CRANFIELD UNIVERSITY

MANUEL ANGEL AMARO CARMONA

SHORT-TERM AIR TRAFFIC FLOW AND CAPACITY MANAGEMENT MEASURES IN MULTI-AIRPORT SYSTEMS

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING (SATM)

PhD
Academic Year: 2016 - 2019

Supervisor: Dr. Francisco Saez Nieto
Associate Supervisor: Dr. Huamin Jia
May 2019

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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

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ABSTRACT

Dynamic Demand and Capacity Balancing (dDCB) focuses on reducing the existent gap between the Air Traffic Flow and Capacity Management (ATFCM) and the Air Traffic Control (ATC) activities by introducing a more dynamic management of the airspace resources. This dynamism could be achieved by the application of Short-Term ATFCM Measures (STAM) that consists of detecting potential hotspots, identifying the flights producing the complexity, and applying minor changes to selected flights.

This thesis presents a research about the application of STAM in a Multi-Airport System (MAS). Firstly, it is proposed an Operational Concept (OpsCon) designed to apply those STAMs that suggest changes in the take-off time of selected flights (temporal displacements in the planned trajectory).

The operational concept is tested by real-time simulations (including the human-in-the-loop) with the objective of evaluating the performance of the ground ATCOs while dealing with most of the uncertainties produced *before take-off*.

Subsequently, it is proposed a methodology that characterizes and evaluates the performance of the aircraft operation in a complex systemized TMA based on the study of its standard routes and their actual traffic in order to reduce the uncertainties *after take-off*.

The process is composed of two main components. The first component identifies recurrent deviation patterns by comparing the Spatio-Temporal (S-T) differences between the actual and planned trajectories.

The second component identifies and characterizes concurrence events based on the analysis of the standard routes and the along-track deviation derived from the first component with the objective to analyze the causes that produce recurrent patterns in the terminal airspace.

The developed framework is applied to a study case of a representative MAS. The quantitative effectiveness of the framework is derived by simulations using historical traffic data samples of the London TMA.

Keywords:

Dynamic Demand and Capacity Balancing (dDCB), Air Traffic Management (ATM), Trajectory-Based Operations (TBO), Terminal Manouvering Area (TMA)

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LIST OF ABBREVIATIONS

Acronym	Description
AIP	Aeronautical Information Publication
AIRC	Airspace Integration Research Centre
AMAN	Arrival Manager
ANSP	Air Navigation Service Provider
AOBT	Actual Off-Block Time
ASM	The Airspace Management
ATC	Air Traffic Control
ATCC	Air Traffic Control Centres
ATFCM	Traffic Flow And Capacity Management
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
ATMS	Air Traffic Management System
ATOT	Actual Take Off Time
ATS	Air Traffic Services
AXOT	Actual Taxi-Out Time
CDM	Collaborative Decision Making
CTFM	Current Tactical Flight Model
CTOT	Calculated Take-Off Time
DBC	Demand and Capacity Balancing

DDR2	The Demand Data Repository
DMAN	Departure Manager
DSAS	Departure Sensitive Arrival Spacing
DST	Decision Support Tool
EGBB	Bristol Airport
EGGL	Birmingham Airport
EGGW	Luton Airport
EGKK	Gatwick Airport
EGLC	London City Airport
EGLL	Heathrow Airport
EGSS	Stansted Airport
EP	Exit Points
ETOT	Estimated Take Off Time
FMP	Flow Management Positions
FOC	Flight Operations Centres
FOCS	Flight Object Creator System
FSX	Microsoft Flight Simulator X
GANP	Global Air Navigation Plan
HITL	Human In The Loop
HPT	Holding Point Time
HT	Holding Time
IAF	Initial Approach Fix

IDM	Integrated Demand Management
ISA	Instantaneous Self-Assessment
KPI	Key Performance Indicators
LDTL	Actual Landing Time
LTMA	London Terminal Manoeuvring Area
MAS	Multi Airport System
MDI	Minimum Departure Intervals
MINIT	Minutes In-Trail
MIT	Miles In-Trail
NFLC	National Flying Laboratory Centre
NM	Network Manager
NMOC	Network Manager Operations Centre
PARTAKE	Cooperative Departures for a Competitive ATM Network Service
RBT	Reference Business Trajectory
RTFM	Regulated Tactical Flight Model
SATM	School of Aerospace, Transport and Manufacturing
STAM	Short Term ATFCM Measures
STAR	Standard Arrival
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
TMA	Terminal Manoeuvring Area

UDPP	User-Driven Prioritization Process
V&V	Verification & Validation
VFR	Visual Flight Rules

1 Introduction

The big change in air transport was marked by the "*Jet Age*", after World War II (1939-1945). Jet passenger travel began in the decade of 1950s, when all the technologies that were developed during WWII became available for civil air transport leading to develop new aircraft concepts. In the late 1970s, a more developed air transport system led to a prominent economic growth supported by bigger and more efficient aircraft. Consequently, new systems for air traffic control and aircraft separation procedures had to be developed to ensure a safe air transport system. Nowadays, air transport is an important enabler that facilitates social development and integration into the global economy.

Today, long-distance passenger movements are carried out almost exclusively due to air transport. This is evidenced by the permanently increasing number of passengers carried every year. Continuing the recovery trend since the global financial crisis of 2008, approximately 4.1 billion passengers and 56 million tonnes of freight were carried in 2017 (ICAO, 2017).

The air transport system is fast and efficient. However, the limited capacity of the existent airports represents the major bottle-neck of the system (Ma *et al.*, 2019). The increasing air traffic demand and the limited capacity of the current airports result in the *construction* of new airports or the *emergence* of secondary airports creating the so-called Multi-Airport Systems (MAS). A MAS is defined as a set of close-located airports that serve the air traffic demand of a large metropolitan area (e.g. New York, London or Paris).

A MAS airspace is characterized by a Terminal Manoeuvring Area (TMA) that allocates the traffic demand of many airports. However, the complexity that characterizes the TMA-MAS leads to a lack of capacity that is evidenced by an increased number of flight delays and regulations (Murça, 2017).

This thesis explores the application of the so-called *Short-Term Air Traffic Flow and Capacity Management Measures (STAM)* to improve the efficiency of a MAS terminal airspace.

The objective of this chapter is to present the background to the problem, to define the objectives of the research and the methodology followed in this thesis.

The section 1.1 presents the background of the problem and the general context of this thesis. The section 1.2 defines the aim and objectives of this thesis in relation to the problem presented. The section 1.3 presents the structures of this document. Finally, the section 1.4 presents the methodology followed during this research.

1.1 Background to the problem

The Air Traffic Management System (ATMS) is a socio-technical complex system composed of different stakeholders. These being the Airspace Users (AUs) that includes civil and military aviation. The airports' operators that provide services to aircraft, passengers and airlines. The Air Navigation Service Providers (ANSPs) that ensure the airspace users are provided with routes and services to flight in controlled airspace. The system is coordinated at European level from the Network Manager Operations Centre (NMOC), which synchronizes all the stakeholders.

The Air Traffic Management (ATM) tasks could be organized into three levels. Firstly, the strategic level focuses mainly on the Airspace Management (ASM) and the Air Traffic Flow and Capacity Management (ATFCM) activities. The Network Manager (NM) and ANSPs set their efforts on allocating the required capacity based on the demand provided by the airlines' Flight Operation Centres (FOC). Then, the pre-tactical phase involves two main tasks of the NMOC that could be summarized in coordinating the definition of a daily plan to optimize the ATM Network and informing to the interested parties about the ATFCM measures that will take place in the European airspace. Finally, the tactical phase focuses more on Air Traffic Control (ATC) activities while the NMOC monitors and shares the ATFCM situation in real-time with the involved partners.

In order to cope with the expected traffic demand, the ATMS is being modernized with new solutions that ensure more efficient and safe management of the airspace. In this context, the uncertainties related to the planning process, performed at strategic level, leads to a conservative management of the system resources that could result in over-limiting the air traffic demand and over-releasing the airspace. To overcome this, *dynamic* Demand and Capacity Balancing (dDCB) focuses on reducing this existent *gap* between the ATFCM and the ATC, by introducing a more dynamic management of the airspace resources (Eurocontrol, 2013). An example of these activities are the *Short-Term ATFCM Measures (STAM)*.

The objective of STAM is to keep the overall demand within capacity limits when unexpected heavy traffic is likely to produce bottle-necks. The procedure consists of detecting potentially pre-regulation hotspots, identifying the flights involved in the bottle-neck and applying minor changes to those flights a few hours/minutes before the sector entry-time. The measures proposed by STAM could include minor ground delays, re-routing, flight level capping or slot-swapping (Eurocontrol, 2018c).

Currently, the role of the Flight Management Position (FMP) is to establish an interface between the Air Traffic Control Centre (ATCC) and the NMOC in order to provide relevant information regarding the air traffic flow management service. STAM extends the key role of the FMPs to reduce the gap between the ATFCM activities at strategic level and the ATC activities at tactical level by analyzing the predicted traffic, anticipating the Air Traffic Controllers (ATCOs) taskload and issuing actions to reduce the air traffic complexity.

Moreover, the efficient management of the arrival/departure sequence is performed in some airports by the Arrival Manager (AMAN) and Departure Manager (DMAN), respectively. However, the departure sequence is often managed, at operational level, by relying largely on the experience of the ATCOs. The management of the take-off events are focused on increasing the efficiency of the terminal, runway and taxi operations by using the "*first in, first out*" paradigm, which is sometimes altered depending on the "*wake turbulence category"* (ICAO, 2001) criteria and/or the number of aircraft in the runway.

Among the different STAM strategies, of particular interest for this thesis are the ones that produce *temporal displacements* to the trajectories of the flights involved in the complexity, by suggesting minor changes in the Estimated Take-Off Time (ETOT).

The concept focuses on applying changes in the take-off time of selected flights, with the objective to obtain a more distributed traffic demand and a reduction of ATC interventions on air. In exchange, these could require an additional taskload to the ground ATCOs modifying the airport departure sequence.

Although the key functions are performed at the ATCC and Control Towers, as a Collaborative Decision Making (CDM) process, it is required a proper coordination between airports, air traffic controllers and airspace users.

Assuming that ETOT changes are executed to produce an effect downstream, the effectiveness of this methodology relies on the management of uncertainties that could be produced at different levels of the flight.

This thesis explores the application of STAM in a MAS-TMA, focusing on operational procedures, the synchronization between different agents and the uncertainties that could be produced while applying these measures. In this sense, the contribution of this research could be organized into three main points. Firstly, it is proposed an operational concept for STAM application in which it is detailed the fundamentals to apply short-term temporal displacement on the grounds taking into account the dDCB/TBO concepts. Moreover, it is discussed the robustness of this idea, which leads to understand and group the uncertainties that could affect the operational concept. Secondly, by exploring the uncertainties that could be produced *before take-off*, which are important to ensure a minimum take-off time error. Lastly, by exploring the uncertainties produced *after take-off,* to ensure that the affected flights adhere to the predicted trajectory and the effect of reducing the airspace complexity downstream is produced.

1.2 Aim and Objectives

This thesis aims at understanding the effects of STAM in the de-confliction of aircraft trajectories in Multi-Airport Systems. Hence, the essential research question to be addressed by this thesis is:

How the short-term ATFCM measures (temporal displacements) can be applied to improve the dynamic Demand Capacity-Balancing and reduce the complexity of the traffic flows in a Multi-Airport Systems?

To answer the question proposed, the following objectives are proposed:

1. Characterize and evaluate the performance of the terminal manoeuvring area of a multi-airport system.
2. Develop a novel framework that supports the analysis and evaluation of the terminal manoeuvring area.
3. Identify the key elements and precursors for the application of STAM in a terminal manoeuvring area.
4. Test and evaluate the models developed and analyze the effects of STAM in the de-confliction of aircraft trajectories.

This thesis makes use of the London Terminal Manoeuvring Area (LTMA), as a case of study to test and evaluate the efficiency of the developed framework.

Additionally, part of this research supported the ConOps, Verification & Validation (V&V) activities of the "*Cooperative Departures for a Competitive ATM Network Service (PARTAKE)*" project sponsored by SESAR Joint Undertaking (SESAR-JU) (PARTAKE, 2015).

1.3 Outline of the thesis

This manuscript is organized into eight (8) chapters.

Chapter 1, provides the background of the problem and introduces the objectives and methodology of the thesis.

Chapter 2 provides an overview of the ATMS in Europe and the operations in a multi-airport system.

Chapter 3 reviews the STAM concept and alternative existing solutions. Particular attention is paid to the PARTAKE-STAM methodology endorsed by the operational concept proposed in this thesis.

Chapter 4 presents an operational concept designed to explain the interaction of different agents required to apply a STAM methodology. Subsequently, it is analyzed the different agents and roles that take part in the operations. Finally, it is explained the sources of uncertainties that determine the efficiency of the concept presented.

Chapter 5 presents a real-time simulation in order to understand how the suggested departure sequence could be managed in the presence of different sources of uncertainties produced *before take-off*. Those that affect this STAM methodology are mainly related to the airport operations (e.g. ATC tactical interventions on the ground, airport complex taxi procedures, airline operations, last-minute passengers, crew procedures, etc.). To this end, it focuses on testing the effectiveness of the operational concept proposed and evaluates the performance of the local and ground ATCOs while absorbing most of the mentioned uncertainties produced during the push-back, taxi, holding and take-off procedures.

Chapter 6 presents a methodological framework to characterize and evaluate the performance of the aircraft operation in complex systemized terminal manoeuvring areas in order to assess the sources of uncertainties produced *after take-off*. The framework, which is divided into two components, studies the standard routes structure and their actual traffic. The first component estimates the 4D adherence to the standard routes and flight plan based on the comparison of the Spatio-temporal differences between the actual and planned trajectories. The second component identifies and characterizes concurrence events based on the analysis of the standard routes and the along-track deviation derived from the first component.

Chapter 7, presents a case of study that analyzes the London TMA using the framework described in the previous chapter. The study uses two examples of standard routes (LAM3A and LORE2S) to evaluate the effectiveness of the framework developed. Additionally, it identifies the most relevant standard routes characterized by high-adherence/primary recurrent patterns and low-adherence/secondary recurrent patterns. Finally, the framework is used to identify the LTMA standard routes interdependences and concurrence events associated to the routes selected.

Chapter 8 reviews the conclusions of this thesis and concludes by identifying the limits of this research and provides recommendations about the future work.

1.4 Methodology

To achieve the proposed objectives, a comprehensive research approach was developed and implemented. The methodology is presented in the Figure 1-1, which is explained in the following sections 1.4.1 and 1.4.2.

A literature review is carried out to provide an initial understanding of the ATMS and MAS-TMA. Additionally, it ensures a correct understanding of the STAM concept and the current STAM solutions that applied in some airports (see chapter 2 and 3, respectively).

The development part of this thesis is focused on understanding the key elements for STAM application in a MAS-TMA. In this sense, the development of this project has been divided in two (2) main phases.

1.4.1 Phase I: MAS-TMA Diagnosis

The Phase I focuses on understanding the aircraft operations in a MAS-TMA, which is described in the Chapter 6 of this manuscript (top part of the Figure 1-1).

The first part of this phase is the development of a *data-driven 4D-adherence calculation method*, which is detailed in the section 6.2. This method is developed to perform a trajectory analysis that leads to understand the TMA standard routes structure and to identify the key elements that contribute to reduce the uncertainties of the terminal airspace operations. It is designed to understand *how* it is produced the traffic deviation from the standard routes with the goal to determine recurrent traffic patterns that could help to assess the application of STAM in a MAS-TMA.

The second part of this phase is the *determination of concurrence events,* which is described in the section 6.3, and it is a heuristic approach that focuses on the identification of hotspots in a terminal manoeuvring area. The main objective is to understand *when* and *why* it is produced the traffic deviation and recurrent patterns determined in the first outcome.

The outcomes obtained in this phase are implemented in a generic methodological framework, which is applied to a study case of London's Terminal Manoeuvring Area (LTMA). This is presented in the chapter 7.

1.4.2 Phase II: STAM OpsCon & Assessment of Ground Operations

The Phase II focuses on understanding the aircraft operations on the ground and the key elements for STAM application (bottom of the Figure 1-1).

Chapter 4 details a STAM Operational Concept (OpsCon) aligned to the TBO concept and the current ATMS. The operational concept focuses on describing the key elements to apply a STAM methodology that suggest temporal displacements on the ground by applying changes in the Estimated Take-Off Time (ETOT) of selected flights.

The effectiveness and robustness of the proposed OpsCon is driven by the capability of the aircraft to take-off at the suggested time and to adhere to the predicted trajectory after take-off. Consequently, the section 4.4 identifies the uncertainties and robustness of the presented concept, which are then explored in the chapters 5 and 6.

The ground operations of the proposed OpsCon, is boarded in the chapter 5. It is described a real-time simulation of the London Stansted (EGSS) airport, that has been carried out by pilots and air traffic controllers (including the human-in-the-loop). The simulation exercise endorses the PARTAKE-STAM methodology (see section 3.5) and it is used to undertake quantitative and qualitative validation of the proposed STAM OpsCon.

In the section 5.8, it is evaluated the performance of the local and ground ATCOs dealing with most of the uncertainties that could arise during the push-back, taxi and hold procedures. Additionally, it evaluates some of the effects on human performance when is modified the departure sequence of selected flights.

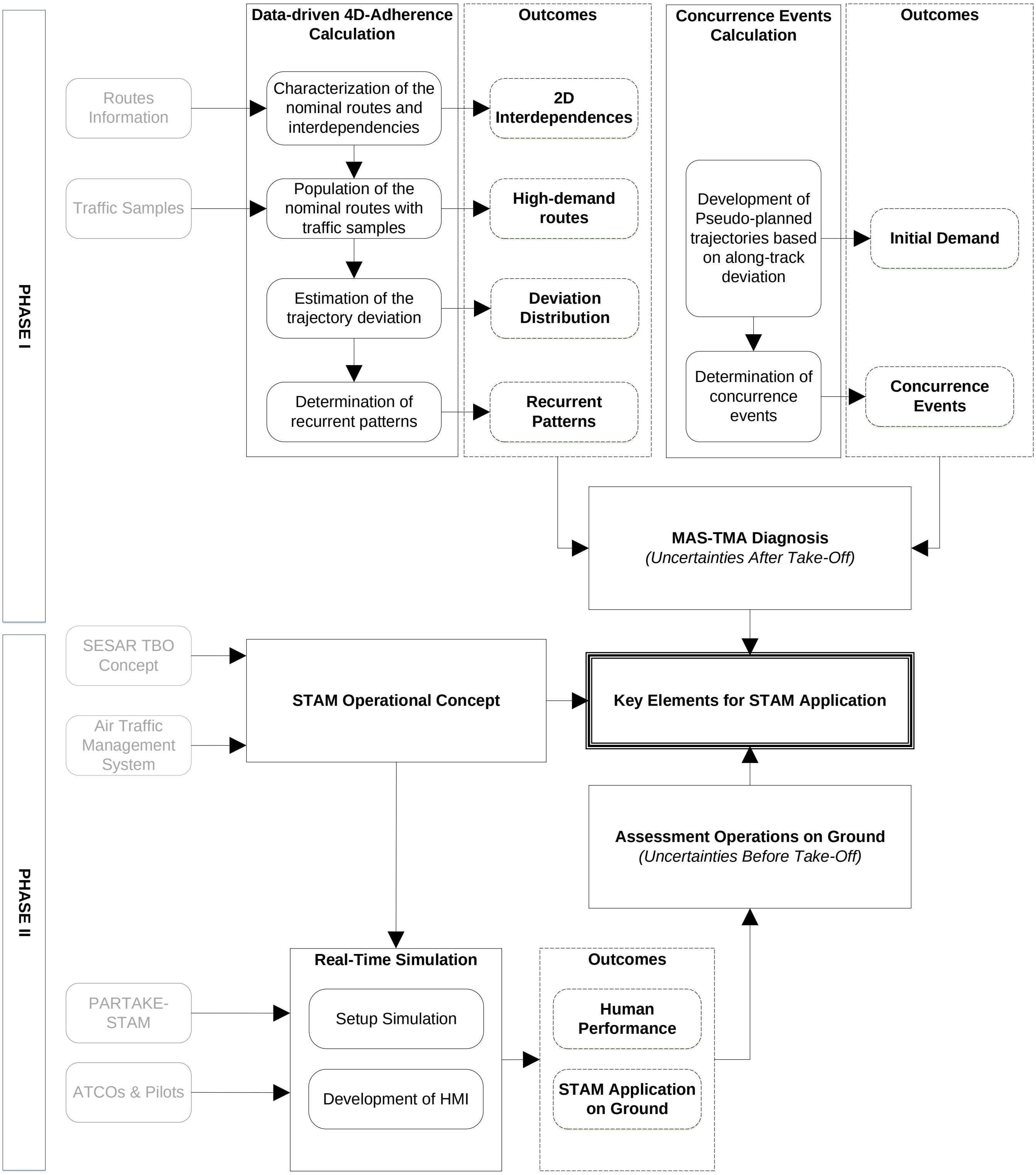

Figure 1-1: Flow chart of methodology and thesis structure

2 Air Traffic Management in Multi-Airport Systems

The use of STAM to reduce the airspace complexity requires a prediction of demand-related information. The operations performed in a TMA often include tactical interventions in order to separate, merge and metering the traffic, which is evidenced by a lack of adherence observed in some standard routes. This process is even more complex in Multi-Airport Systems (MAS) because the traffic density is higher and the airports are close located. Identifying the elements that contribute to applying ATFCM tactical measures in terminal airspace requires a detailed understanding of the ATMS and the MAS-TMA.

This chapter contributes to this by reviewing the different tasks and agents that compose the European Air Traffic Management System, providing an overview of Multi-Airport Systems and describing the most relevant elements that compose a TMA.

The Figure 2-1 summarizes the review methodology followed in this chapter starting by understanding the three main pillars that compose the ATMS and describing the MAS like a component of the Airspace Management (ASM). Moreover, the STAM concept, which could be considered as a sub-component of the Air Traffic Flow and Capacity Management (ATFCM), is described in the chapter 3.

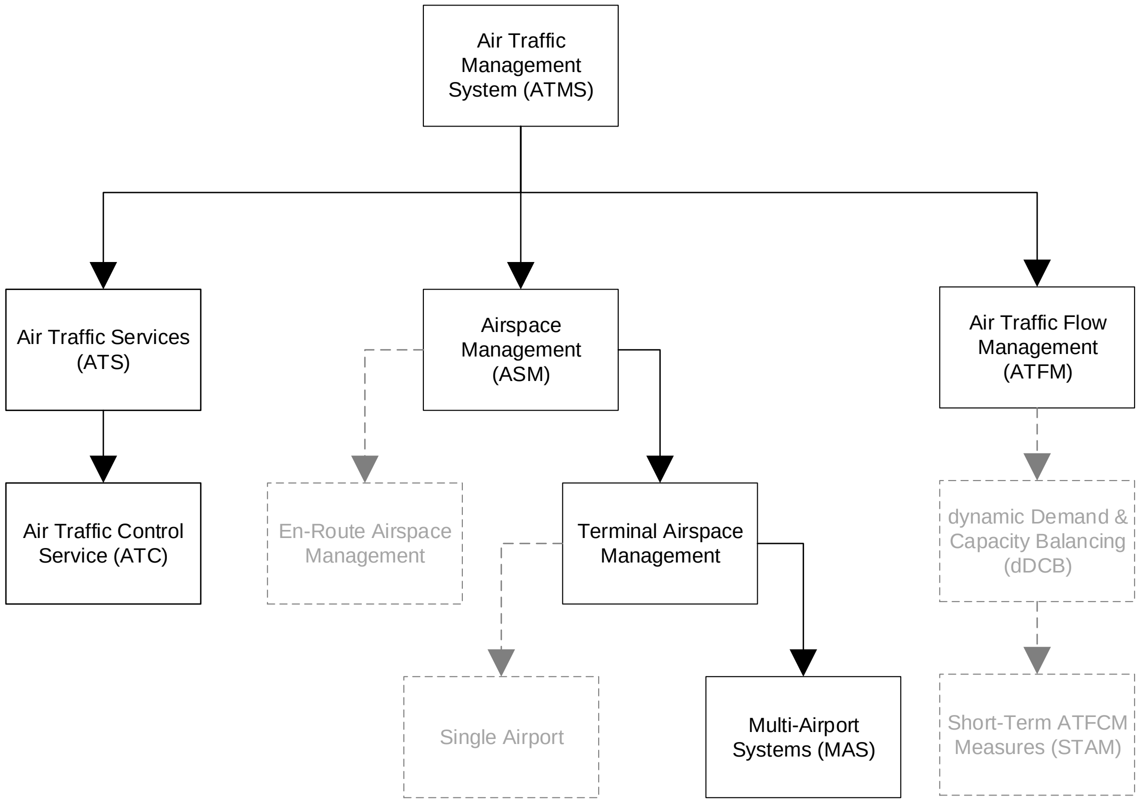

Figure 2-1: Overview of concepts described in chapter 2

2.1 Air Traffic Management

The Air Traffic Management consists of three (3) main functions: Air Traffic Flow Management (ATFM), Air Traffic Services (ATS), and Airspace Management (ASM) (ICAO, 2001).

2.1.1 Air Traffic Services (ATS)

The Air Traffic Services (ATS) comprises the following services (ICAO, 2001):

- Flight information service: A service provided for the purpose of giving advice and information useful for the safe and efficient conduct of flights.
- Alerting service: A service provided to notify appropriate organizations regarding aircraft in need of search and rescue aid, and assist such organizations as required.
- Air traffic advisory service: A service provided within advisory airspace to ensure separation, in so far as practical, between aircraft which are operating on IFR flight plans.

- Air traffic control service: a service provided for the purpose of preventing collisions and maintaining an orderly flow of air traffic.

2.1.2 Air Traffic Control Service (ATC)

Included in the ATS function is the Air Traffic Control (ATC) service, whose primary purpose is to ensure a safe and efficient operation of the air traffic.

The service is provided by Air Traffic Controllers (ATCOs) that directs aircraft on the ground and through controlled airspace (or provides advisory in non-controlled airspace). The purpose of the ATC service is to perform the following tasks (ICAO, 2001):

a) Preventing aircraft-to-aircraft collisions, and on the manoeuvring area, preventing aircraft-to-obstructions collisions.
b) Expediting and maintaining an orderly flow of air traffic.

2.1.3 Air Traffic Flow Management (ATFM)

The Air Traffic Flow Management ensures that ATC capacity is utilized to the maximum extent possible and the traffic volume is compatible with the capacities declared by the appropriate ATS authority (ICAO, 2001). The ATFM is referred as Air Traffic Flow and Capacity Management (ATFCM) in Europe. The service is developed and implemented as a centralized ATFM organization supported by Flow Management Positions (FMP) located at the Air Traffic Control Centres (ATCC).

The main function of the ATFM service, the Demand and Capacity Balancing (DBC), is implemented when the traffic demand exceeds the defined ATC capacity in a specific airspace.

The ATFM procedures are classified depending on three different phases depending on the time the action is carried out:

- Strategic planning: "*if the action is carried out more than one day before the day on which it will take effect*" (ICAO, 2001). The Air Navigation Service Providers (ANSP) and the Network Manager Operation Centre (NMOC) define the ATC capacity requirements. A plan is created in order to resolve the demand/capacity imbalance by taking different steps such as arranging with the ATC authority to provide the required capacity at certain place and time, re-orientate the traffic flows, re-scheduling flights and identifying the needs for tactical ATFM measures.

- Pre-tactical planning: *"if the action is carried out on the day before the day on which it will take effect"* (ICAO, 2001). During this phase, certain traffic flows may be re-routed, tactical measures are decided and an ATFM plan for the following day is shared with all the interested parties.
- Tactical operations: *"if the action is taken on the day on which it will take effect"* (ICAO, 2001). These actions include the execution of ATFM tactical measures where demand exceeds the available capacity, monitoring of the air traffic situation to ensure that the ATFM measures applied are taking effect and initiate remedial actions where long delays are reported or to utilize the ATC capacity to a maximum extent.

2.1.4 Airspace Management (ASM)

Airspace Management (ASM) includes the design of the airspace. Similarly to the ATFM, the ASM operates at three different levels:

- Strategic level: it includes the main functions of the ASM that are the design of:
    - Airspace structures: this includes the airports, terminal areas, sectors and sector configurations, and airspace classifications.
    - Standard routes: includes air traffic services routes, standard arrivals, standard departures and instrument procedures to/from airports.
    - Restricted areas: includes temporary segregated airspaces, reserved areas, danger and prohibited areas
- Pre-tactical level: the ASM is responsible for allocating the airspace structures to meet the airspace user's requirements according to the design performed at strategic level.

- Tactical level: it is monitored of the current status of the system. If required, it is performed dynamic management of the airspace structures (e.g. real-time re-allocation of the airspace structures).

2.2 Controlled Airspace

The controlled airspace is divided depending on the location and function in upper air routes, airways, control areas and control zones. Figure 2-2 presents a profile representation of the controlled airspace (NATS, 2017b).

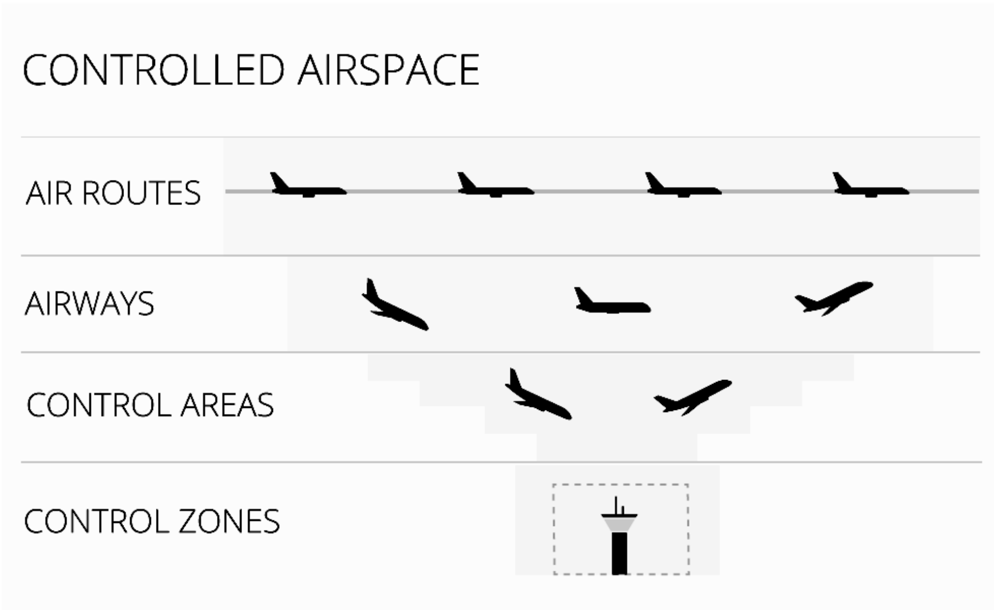

Figure 2-2: Profile representation of the controlled airspace (NATS, 2017b)

Of particular interest for this thesis is the structure of the control areas, also referred to as Terminal Manoeuvring Area (TMA)[1], which is detailed in the following section 2.3.

[1] In the US and Canada, the TMA is referred to as *Terminal Control Area (TCA)*. In this manuscript, the TMA is also addressed as *terminal airspace*.

2.3 Terminal Manoeuvring Area (TMA)

The TMA refers to the volume of airspace established at the confluence of the ATS routes in the vicinity of the airports. The volume is used to allocate traffic performing the last part of the descent phase, approach, landing, take-off and the initial part of the climb phase.

Depending on the demand, the terminal airspace volume is usually sub-divided into different sectors.

The air traffic control service is provided by the approach ATCOs that are essential to maintain the efficiency of the terminal airspace and airports. Additionally, standard routes are defined to reduce the flight interdependences and ATCOs taskload.

2.3.1 Terminal airspace standard routes

ICAO defines two different types of standard routes that are used to direct the traffic within the terminal airspace (ICAO, 2016a):

The *Standard Instrumental Departures (SIDs)* define the procedures to be followed by an aircraft after the take-off is completed. The SIDs are assigned in advance according to the first waypoint of the flight plan and the active runway. The procedures are composed of a set of waypoints that guide the pilot to exit the terminal airspace towards the en-route phase. Additionally, SIDs specify a vertical limit in the climb profile to ensure a minimal safety separation with other routes.

The *Standard Terminal Arrival Routes (STARs)* define the procedures to be followed by aircraft that enter in the terminal airspace. STARs are assigned before entering into the TMA volume and are selected according to the last waypoint of the cruise phase and the active runway. Similarly to the departures procedures, the STARs are composed of a set of waypoints that guide the pilot to an Initial Approach Fix (IAF). Additionally, the arrival procedures could contain holding patterns, speed, descending rate and altitude limitations.

The STARs and SIDs are published by the aeronautical information service (e.g. Aeronautical Information Publication (AIP) in the United Kingdom (NATS, 2017a)).

Traffic following the standard routes is often merged at their last waypoint. In the case of standard arrivals, the initial approach fixes are often *protected* by holding patterns that delay the aircraft in flight under high-demand peaks. In this sense, the traffic is sequenced to maintain a minimum distance required to complete the final approach and landing. In the case of standard departures, the Exit Points (EP) could merge traffic following SID's from different airports.

The Figure 2-3 presents standard arrival procedures to London Heathrow airport. The last waypoint is represented by the Ockham (OCK) fix, which is protected by a holding pattern. The STAR/SID procedures that are published by the AIP indicate further information about the holding speeds, descent planning, navigation aids and courses.

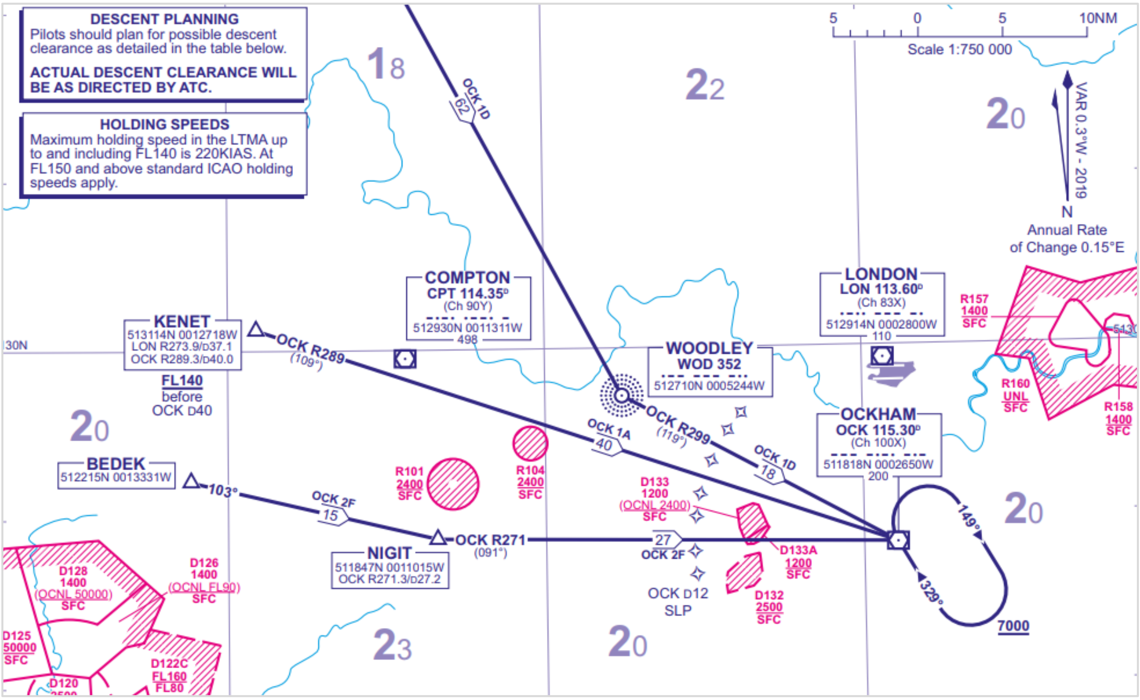

Figure 2-3: Standard Arrival (STAR) procedure to London Heathrow Airport (NATS, 2017a)

2.3.2 Holding patterns

The holding patterns are structures used to order and control the arrival traffic flow. A holding procedure is defined as a *“predetermined manoeuvre which keeps an aircraft within a specified airspace while awaiting further clearance*” (ICAO, 2006). These are used during high-demand conditions in order to maintain the aircraft in the same airspace until they are sequenced and authorized to land.

Holding patterns are defined by an *inbound leg*, *outbound leg* and an entry-point represented by a reference *holding fix* (see Figure 2-4).

An aircraft is required to overfly the holding fix and turn (to the direction indicated by the holding side) in order to intercept the outbound leg. At this point the reference heading is maintained for a period of time (from sixty to ninety seconds, depending on the altitude). Then, it is required a second turn to intercept the inbound leg and holding fix.

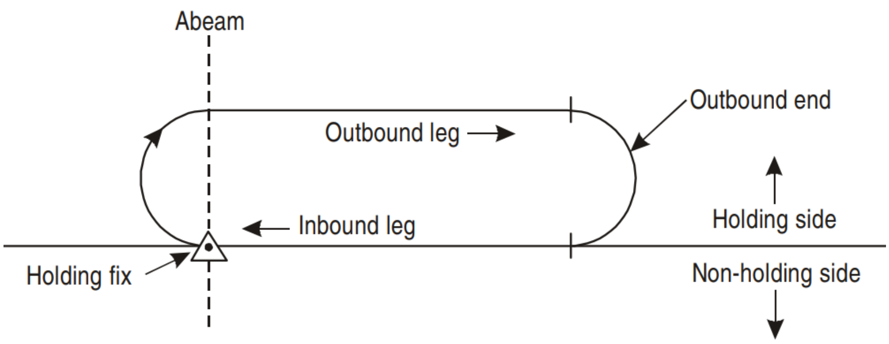

Figure 2-4: Holding procedure (ICAO, 2006)

2.3.3 Visual Flight Rules (VFR) routes

The Visual Flight Rules (VFR) routes are designed mainly for light general aviation aircraft. The routes are airspace volumes that are dedicated to VFR operations.

2.4 Multi-Airport Systems (MAS)

A multi-airport system is a set of two or more significant airports that serves a particular metropolitan area.

(Bonnefoy, de Neufville and Hansman, 2010) identifies 59 multi-airport systems around the world using data from ICAO and FAA. Examples of MAS are presented in the Figure 2-5, including 25 in Europe and 18 in North America. Additionally, the study describes the mechanisms that govern the evolution of multi-airport system, resulting in two fundamental causes:

- The emergence of a secondary airport through the use of an existing airport.
- The construction of a new airport that serves a metropolitan area.

Figure 2-5: Multi-airport systems in the world (Bonnefoy, de Neufville and Hansman, 2010)

Usually, a MAS is characterized by having at least one primary or dominant airport that manages high constant levels of traffic. Secondary airports tend to have more volatile traffic as they rely on low-cost carriers that specialize in specific market segments with relatively lowers fares, which stimulates the traffic.

In North America and Europe, the carrier Southwest Airlines and Ryanair played an important role in the emergence of new airports, respectively. This fact is evidenced by a dominant presence of low-cost carriers and other airlines in secondary airports around the world, as shown in the Table 2-1.

Table 2-1: Presence of low-cost/other airlines carriers at multi-airport systems worldwide (OAG, 2005)

World region	Primary airports	Secondary airports
Asia-Pacific	9%	50%
Europe	19%	44%
Latin America	9%	43%
North America	12%	21%
Middle East	7%	7%

2.5 Terminal airspace in a multi-airport system

A MAS performance is influenced by many factors such as the runway and airspace geometry, the separation minima standards, the weather conditions and the traffic demand. Runway and terminal airspace configuration are shared, therefore the decisions are coordinated in order to de-conflict the arrival and departure flows cooperatively, as a system (Clarke *et al.*, 2012).

A factor that characterizes the terminal airspace in multi-airport systems is the evident limitation to address the traffic interdependences. Spatial displacement is limited due to reduced airspace to perform vectoring procedures increasing the ATCOs taskload during high-traffic demand. In contrast, the temporal displacement (speed limits or take-off time delays) seems a more appropriate method to handle the traffic flows interdependences, although it could has a direct impact on the runway throughput or in the airlines' cost index.

The routes structure of a terminal manoeuvring area of a multi-airport system is characterized by a complex net of standard procedures that direct traffic to/from a set of close located airports.

The arrival standard procedures are used by convergent traffic that is merged at some point, usually to unique *feeders* that serve more than one airport (e.g. the IAPs referred as LOREL and ASKEY serve both, Luton and Stansted airports in

London MAS) (NATS, 2017a). Consequently, the bottle-neck effect produced by airports' runway capacity is more predominant in multi-airport systems.

The departure standard procedures are used by divergent traffic that is often restricted by altitude and speed (e.g. 250kts below FL100). The approach ATCOs issue clearances to authorize the ascending of the aircraft after intercepting the SIDs exit waypoint in their transition to the airways.

Due to the exceptional amount of traffic in shared terminal airspace, the standard routes are often moved away from the most efficient path. In some cases, the standard routes of the primary airports are governing the terminal structure while the secondary airports are adapted to this primary structure.

The Figure 2-6 shows an example of the inbound traffic flow distribution in London MAS. It is observed the centralized routes that arrive at Heathrow airport (blue) defining the primary routes structure of the TMA. The routes directing traffic to the secondary airports, such as Gatwick, City and Luton/Stansted is adapted to fit around the dominant set of routes of Heathrow. This effect is especially observed in the traffic to London City that represents the lowest traffic (highlighted in red). These routes are moved away from the airport's direct (and most efficient) path, merging with some routes of the Stansted/Luton airports.

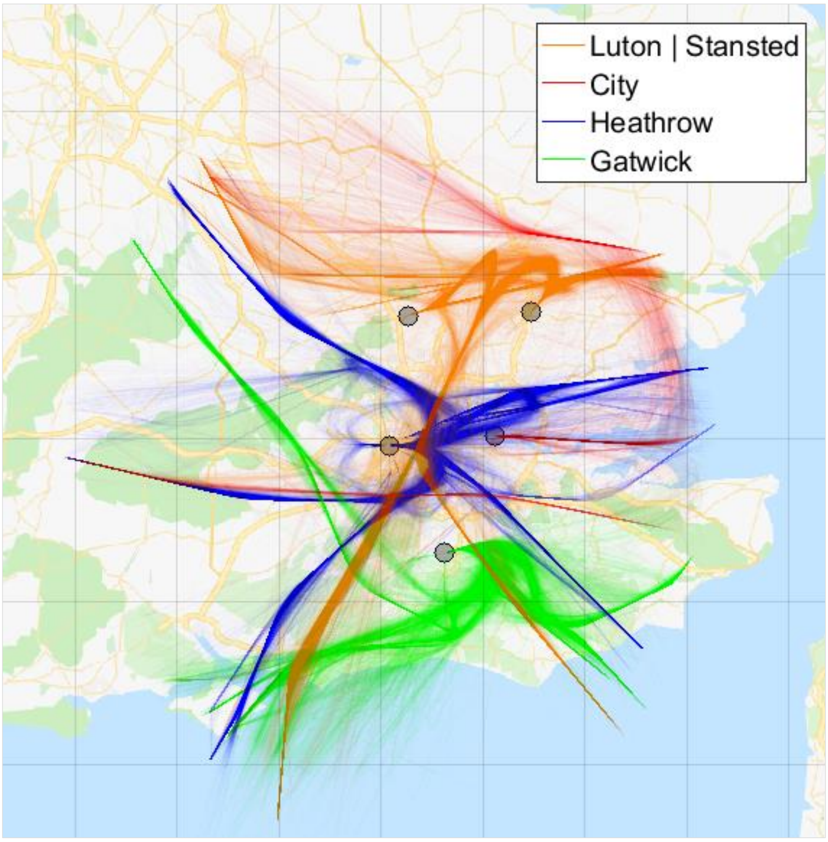

Figure 2-6: London MAS inbound traffic distribution[2]

[2] Data source from the Demand Data Repository (DDR2) (Eurocontrol, 2018b)

3 Short-Term ATFCM Measures (STAM)

The previous chapter introduced the fundamentals of air traffic management in multi-airport systems. It described the most relevant components of the air traffic management system and provided a review of the terminal airspace structures that compose a MAS.

This chapter describes the *Short-Term ATFCM Measures (STAM)*. In this context, the section 3.1 presents a background of the dynamic Demand and Capacity Balancing (dDCB), a strategy developed by SESAR that serves as the foundation for the STAM concept of operations.

Subsequently, section 3.2 describes the different STAM methodologies. Particular interest is provided to current solutions used at the ATCC that exist before STAM and is designed to fine-tune the traffic flow and address traffic interdependencies through a temporal displacement in selected aircraft trajectories (e.g. change in departure sequence). In this context, Minimum Departure Intervals (MDI) and Miles-In-Trail (MIT) / Minutes in Trail (MINIT) are described in the sections 3.3 and 3.4, respectively.

The section 3.5 describes in detail the PARTAKE-STAM methodology, which is used as a technical solution to test and validate the STAM operational concept proposed in next chapter (Chapter 4). Additionally, a sensitivity analysis of the parameters used by this methodology is performed to address some uncertainties produced during the flight in the next chapter.

3.1 Dynamic Demand and Capacity Balancing (dDCB)

Among the main functions of the ATM system, the ATFCM aims at optimizing the traffic flow. The air traffic demand is specified as scheduled flight plans provided by the airlines. These flight plans are following routes through volumes of airspace, which are linked to sectors. The sectors’ capacity is constrained by the ATCOs taskload, the size of the sector and sometimes the complexity of the traffic. The ATFCM balances the number of flights per sector based on the capacity declared at the Air Traffic Control Centres (ATCC). This process is addressed as *Demand and Capacity Balancing (DCB).*

Since the planning is performed at a strategic level, it is exposed to uncertainties that could result in differences between the planned and the actual operations. This is evidenced by the number of tactical regulations that are applied as remedial actions to limit the traffic demand, producing delays in flights and increasing the complexity of airport operations.

Consequently, the DCB process is carried out to ensure *conservative management* of the system resources, which often results in over-limiting the air traffic demand, over-releasing the airspace and wasting the capacity of the system.

The Figure 3-1 presents a brief of the ANSP/NMOC operations to address the traffic demand. The DCB process is performed up to 30 minutes before the estimated time at which the aircraft initiates the movement associated with departure. The demand at this point is measured using the entry-counts and occupancy of the sectors.

Subsequently, the role of the ATFCM is carried out by the FMP that performs *isolated* actions based on local traffic metrics with the aim of reducing the traffic complexity.

Finally, the remaining traffic interdependences are addressed by the ATCOs by performing tactical interventions, which increase their taskload.

There is evidence of a gap between the operations performed by the ATFCM and the actual operations. In response to this problem, SESAR has proposed a more dynamic process that switches from the current hour-based traffic limitations to minute-based actions at sector level by extending the capacity management up to few minutes before the ATC interventions (see Figure 3-2).

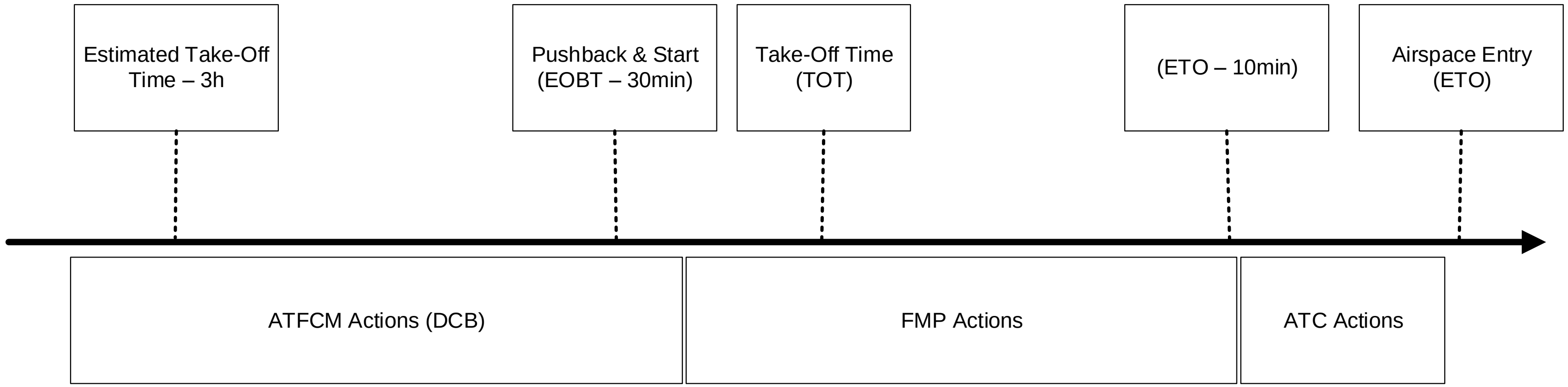

Figure 3-1: Current capacity management process (Richard, 2013)

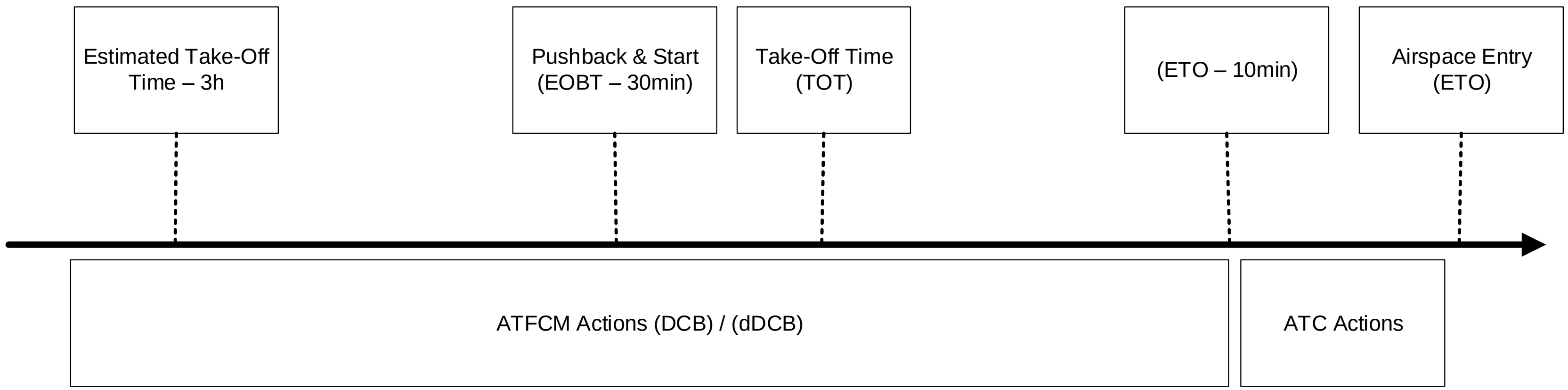

Figure 3-2: Capacity management process based on DCB & dDCB (Richard, 2013)

The foundation of dDCB is to make use of a more refined level of accuracy and granularity to predict traffic. Then, it is performed an iterative process that consists of the following steps (Eurocontrol, 2015a):

- **Detection of demand-capacity imbalances:** the traffic is monitored by the FMPs over their area of responsibility. The monitoring values are adjusted to each sector to detect potential traffic peaks.
- **Network view:** the FMPs provide their advisory information to a network that is accessible by Aircraft Operators (AOs) and NMOC to identify coordinated solutions.
- **Complexity assessment and preparation of STAM:** the impact of the traffic in the ATCOs taskload is analyzed using different metrics. A STAM solution is investigated seeking minimum impact on the AOs.
- **Coordination of proposed STAM:** the selected STAM solution is coordinated with the relevant actors (airspace users, ATCC, etc.) through the FMPs.
- **STAM implementation:** the implementation process uses systematic flight data updates to the network systems. Feedback is provided to the network for stability and traffic prediction.

3.2 Short-Term ATFCM Measures (STAM)

STAM has been introduced by SESAR (Eurocontrol, 2013). The main idea was to transform capacity strategic management to short-term (minute/hour-based) management at sector level. The measures proposed by STAM could include minor ground delays, re-routing, flight level capping or slot-swapping. These measures are described in detail in this section.

STAM concept was enhanced by the introduction of *Advanced STAM* solution (SESAR, 2015), a set of automated tools executed at network level, capable to detect conflicts in advance and disseminate the information to the ATCCs.

Initially, these tools were used in the test “*VP522*”, a live-trial designed to validate a harmonized STAM procedure covering a large part of the European airspace. (Choroba and Hoorn, 2016) summarizes the live-trial results, and have shown that elementary tasks related to STAM, such as the identification of hotspots or network performance were straightforward using the tools developed for the experiment. However, it was necessary to improve the application of STAM at operational level since the role and responsibility of some agents such as the FMPs and NMOC were not clearly defined in the scenario. Successive trials and local tools functionalities tests have been performed during the "*VP700*", resulting in a set of recommendations and key points of improvement of the solutions summarized in (SESAR, 2017).

Some authors have contributed to improving the ATFCM performance using short-term measures, (Bijarbooneh, Flener and Pearson, 2009) presented a study that used constraint-based local search to balance the traffic demand by applying minor changes in the departure sequence. (Nosedal *et al.*, 2014) have developed an algorithm to fine-tune the Calculated Take-Off Time (CTOT) of selected flights to mitigate trajectories interdependencies. The ground-holding scheme proposed was tested by simulations considering a realistic scenario and evaluated relevant KPIs. (Schefers, Ramos and Nosedal, 2016) developed an efficient constraint programming model to suggest efficient flight departures. Other authors have studied related concepts to STAM that aims at introducing speed control or airspace/airport configurations to improve ATFCM performance. (Delgado and Prats, 2014) developed an alternative solution to ground delays using fuel-based cruise speed reduction, in which the aircraft is encouraged to fly slower (at a specific speed) to reduce the amount of unrecovered delay. Similarly, (Xu and Prats, 2017) introduced an strategy to include linear holding, together with typical ground and airborne holding measures in order to improve the performance of the ATFCM. (Jones, Lovell and Ball, 2018) propose a speed control model to reduce the number of delaying manoeuvres (e.g. holding patterns) in the terminal airspace. (Rey *et al.*, 2016) proposed minor speed adjustments as a conflict resolution strategy in order to reduce the ATCOs taskload. (Smith *et al.*, 2016) described a proof-of-concept human-in-the-loop experiment of the Integrated Demand Management (IDM) strategy that proposes different solutions based on Time-based operations in order to improve the air traffic management system when the capacity is insufficient. (Jacquillat, Odoni and Webster, 2016) propose a dynamic programming model that adjusts the airport runways configuration to minimize congestion costs. (Lee *et al.*, 2015) developed a solution for departure-sensitive arrival spacing to improve the runway throughput and reduce departure delays at La Guardia airport.

The selection of STAM begins once a complexity assessment is performed to analyze the impact of the traffic in the ATCOs taskload. Different solutions are explored to mitigate the interdependencies and reduce traffic complexity. The proposed solutions can involve dynamic configuration of the airspace, negotiations with military authorities or cherry-picking actions applied to specific flights (Eurocontrol, 2015a). The following subsections summarize the different actions (STAM) used to reduce the air traffic flow complexity.

3.2.1 Route changes

STAMs that comprise route changes aim at adjusting the trajectory of one or more flights. A route change consists of minor spatial displacements to avoid specific concurrence events or major changes in the flight plan that are previously negotiated with the AOs.

3.2.2 Flight level changes/restrictions

Changes in the flight level consists of a reassignment of the planned altitude to reduce the traffic demand in a sector with high complexity. In contrast, restrictions in the flight level (also known as level-capping) aims at limiting the traffic demand in the airspace above or below a pre-determined flight level by assigning an altitude constraint to relevant flights.

3.2.3 Changes in the departure sequence

Changes in the departure sequence aim at producing a temporal displacement of the trajectories that create the complexity. The changes are produced by modifying the actual take-off time or negotiating with the AOs, an eventual interchange of departure slots between on-time and potentially delayed flights.

3.2.4 Interventions on airborne flights

As last resort, it is considered changes on airborne flights such as restricting speeds by assigning arrival times, route changes or flight level changes through tactical operations.

3.3 Minimum Departure Intervals (MDI)

The most STAM-like current methodology associated to temporal displacements in the context of ground delays is the Minimum Departure Intervals, which consists of applying a fixed minima time-separation to all the flights assigned to a common SID with the goal of reducing the entry-count of a congested sector (Eurocontrol, 2011).

MDI is a measure taken at the ATCC, either due to weather, staff shortage or high demand. In order to apply a MDI, the FMP determines the airspace complexity in the TMA sectors using the expected demand. When the traffic complexity or demand is expected to have an important impact in the ATCOs taskload, it is applied a time restriction in the departure sequence to the target sector.

The result is produced as a take-off interval restriction that is placed in selected airports during a given amount of time (e.g. the affected airport can depart only 1 flight every 10 minutes).

During this interval, the departure controller authorizes the affected flights on a *first-come, first-served* paradigm. Consequently, the restriction inputs additional complexity to the departure sequence affecting the runway throughput. In exchange, the entry-count of the congested sector is reduced.

3.4 Miles-in-Trail (MIT) / Minutes-in-Trail (MINIT)

Miles-In-Trail (MIT) is a metering and sequencing measure that consists on imposing "*a specified distance between aircraft, normally, in the same stratum associated with the same destination or route of flight*" (Eurocontrol, 2014). The measure aims at reducing a sector's entry-count by applying a spatial separation to all the flights that are expected to cross the target volume at a given time.

Similarly, Minutes-in-Trail (MINIT) impose a specified amount of time between aircraft.

MIT/MINIT could be considered a more general version of the MDI used by ATC to fine-tune the traffic flow, extending its application to other phases of the flight (en-route, descending, etc.).

A preliminary analysis of MIT assessed the impact of this strategy on NAS flight operations, resulting in some restrictions that did not have the desired effect on the traffic demand (Myers *et al.*, 2005).

3.5 PARTAKE

A more efficient and granular solution to MDI, is proposed by Cooperative Departures for a Competitive ATM Network Service (PARTAKE), a SESAR JU project that aims at reducing the number of tactical interventions on-air (PARTAKE, 2015).

The solution aims at evaluating the complexity of a sector to suggest minor changes in the ETOT of selected flights (within the 15-minutes CTOT window). The idea is to produce a more efficient departure sequence that distributes the sector demand in exchange for an increased amount of tactical interventions on the ground. The main difference with MDI is a more granulated analysis of the trajectories interdependencies with the objective to propose a solution that targets only those flights that increase the traffic complexity.

PARTAKE is composed by a three-step process that is presented in the Figure 3-3 and described more in detail below.

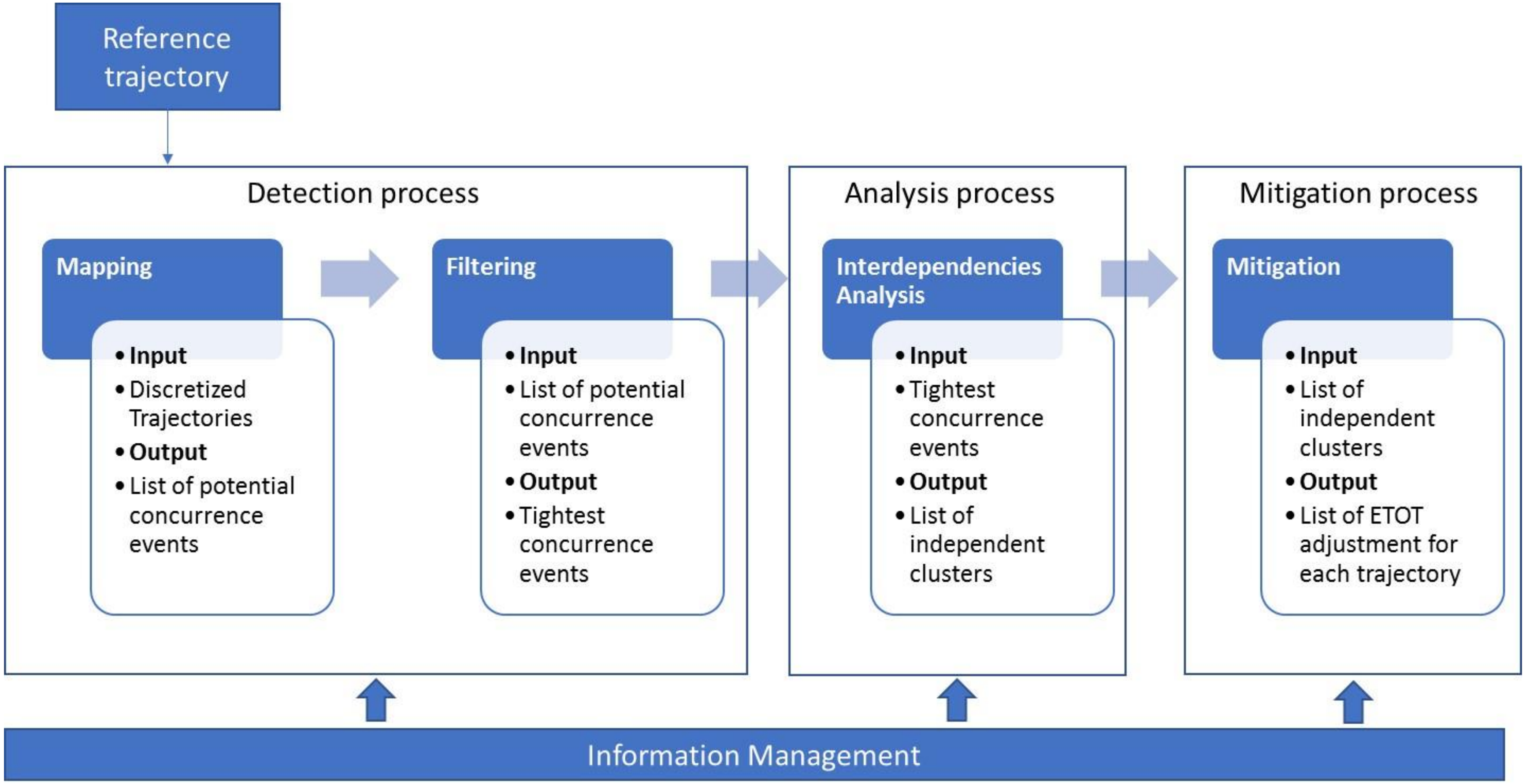

Figure 3-3: PARTAKE Modular Structure (PARTAKE, 2015)

The *detection process* is used to analyze a set of traffic (predicted trajectories) and determine their interdependences (concurrence events). The detection process is based on a first step that maps the predicted trajectories to a multi-layer grid of cells covering the determined airspace. The process detects a list of potential concurrence events by searching those cells that contain more than one flight at a common time interval. Subsequently, the concurrence events are filtered by those flights that have a time separation below 15 minutes (CTOT window).

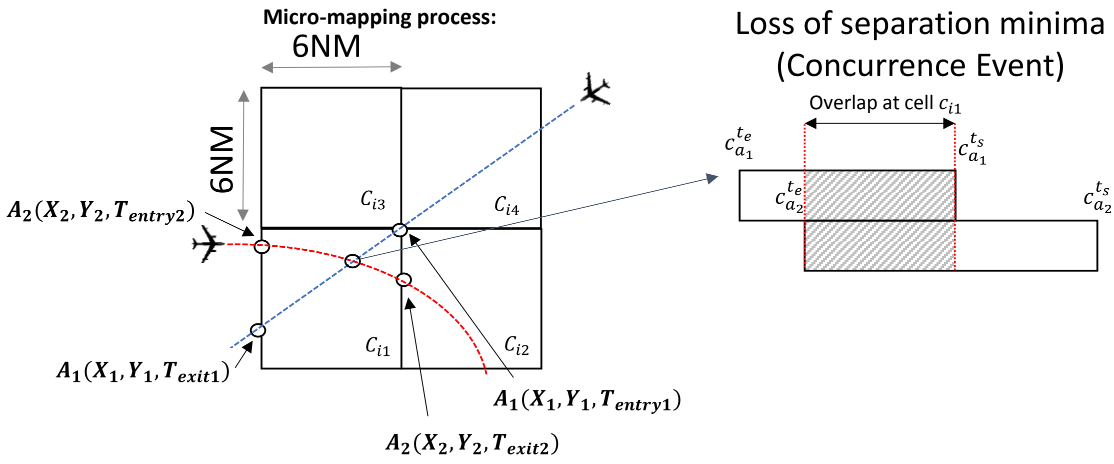

Figure 3-4: PARTAKE detection process (PARTAKE, 2015)

The output of the detection process is a set of concurrence events that are used by an *analysis process* to find groups of interdependences that increase the complexity of the traffic flow. In this context, the clustering process is focused on identifying those cells that contain more than one flight or those flights involved in more than one concurrence event. This is referred as *concurrence* interdependences which are graphically represented in the Figure 3-5, respectively.

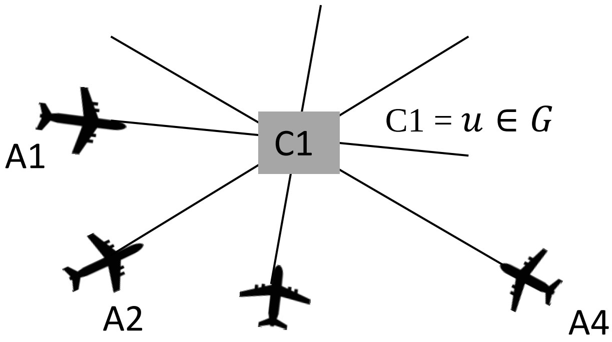

Figure 3-5: Concurrence interdependence (PARTAKE, 2015)

Finally, the *mitigation process* aims at analyzing the interdependent clusters in order to suggest a temporal displacement in the S-T distribution of the flights creating the concurrence event. This is achieved by suggesting a new ETOT within the -5/+10 CTOT window. The process is formulated as an optimization process that ensures that no other conflicts are produced when the temporal displacement of the trajectory is performed.

4 Operational Concept for STAM Application

The previous chapter introduced the concept of STAM within dDCB. Subsequently, it identified the different STAM methodologies based on the changes performed on the flight trajectories creating the complexity. Particular interest was provided to measures that apply a temporal/spatial displacement of aircraft on the ground such as MDI, MIT/MINIT and PARTAKE.

This chapter presents an operational concept to apply STAM which represents the fundamental context of this thesis. The concept is focused on measures that suggest changes in the departure sequence of selected aircraft (temporal displacements produced as ground delays on selected flights).

The operational concept is aligned with the current ATFCM and ATC procedures and relies on the Trajectories-Based Operations (TBO) concept to support the trajectory prediction. The roles and agents that contribute to the operations are described in the section 4.2. The section 4.3 describes the operational concept and the STAM system. Finally, the section 4.4 identifies and groups the main sources of uncertainties that could impact the effectiveness of the solution. The classification performed to the most relevant uncertainties of the OpsCon are especially relevant to understand the content of the next chapters 5, 6 and 7.

4.1 Introduction

The operational concept presented in this thesis describes the operations and synchronization required by different agents of the ATM to apply STAM.

Complexity metrics could be considered by the dDCB process as an indicator of the ATC taskload. In the proposed operational concept, the term *“Complexity*” is used to refer the number of concurrence events produced in the terminal manoeuvring area of a multi-airport system.

In the subsequent chapters, the term "*STAM*" is used to refer to those STAM methodologies that specifically aims at reducing the traffic complexity in a terminal manoeuvring area by *suggesting new take-off times for selected flights (temporal displacements in the planned trajectory)*. The Figure 4-1 presents the interactions between the different agents that contribute to the process. This process is described in the following sections.

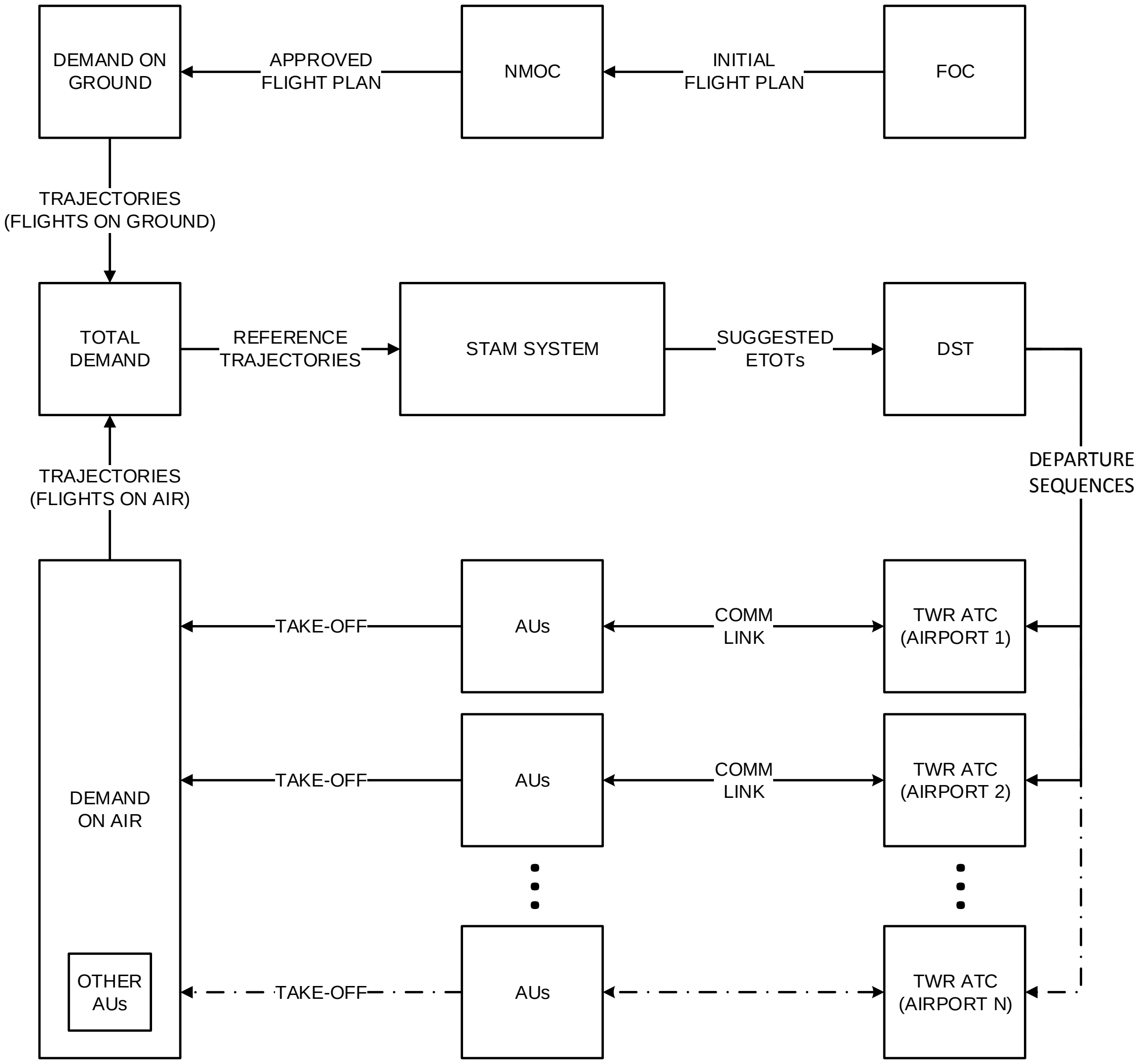

Figure 4-1: Operational concept for STAM application

4.2 Agents and roles

The operational concept proposed is aligned with the current ATMS operations. Before describing the OpsCon, this section describes the agents that contribute to the different operations:

Network Manager Operations Centre (NMOC): It is responsible for delivering Flow and Capacity Management and Flight Planning Operations. Additionally, the NM function includes operational services like information management, post-operation analysis, and contingency management. The NM function provides the required demand information to the STAM system. In this context, the flight trajectory information, which comprises the detailed route of the aircraft defined in four dimensions, could be shared by making use of a System Wide Information Management (SWIM) network.

Airspace User (AU): The airspace user is the organization operating the aircraft and their pilots (Eurocontrol, 2014).

Air Traffic Controller (ATCO): The air traffic controller is the person responsible to provide air traffic control services. The ATCO role is extended to authorize and perform changes in the departure sequence of selected flights.

Flow Management Position (FMP): It is a working position, whose main role is to provide an interface between the central management unit and the air traffic control units (Eurocontrol, 2014).

4.3 Operational Concept (OpsCon)

The airspace users organize their fleet and daily operations in the Flight Operations Centres (FOC). FOC looks for the optimization of the company resources to cope with the scheduled flights. The main role of the FOC, from the ATM point of view, is to submit their flight plans to the Network Manager (NMOC) and obtain an approved planned trajectory and a cleared take-off time. This is a negotiation process, in which the NM performs a DCB process that approves or requires to amend the submitted flight plans depending on the capacity of the system.

Once the FOC obtains an approved flight plan, the demand is submitted to the Air Traffic Control Centres (ATCC) by the NMOC. At this point, the flight plans could be visualized as a *prediction of the aircraft trajectory* that will be used by the core of this OpsCon.

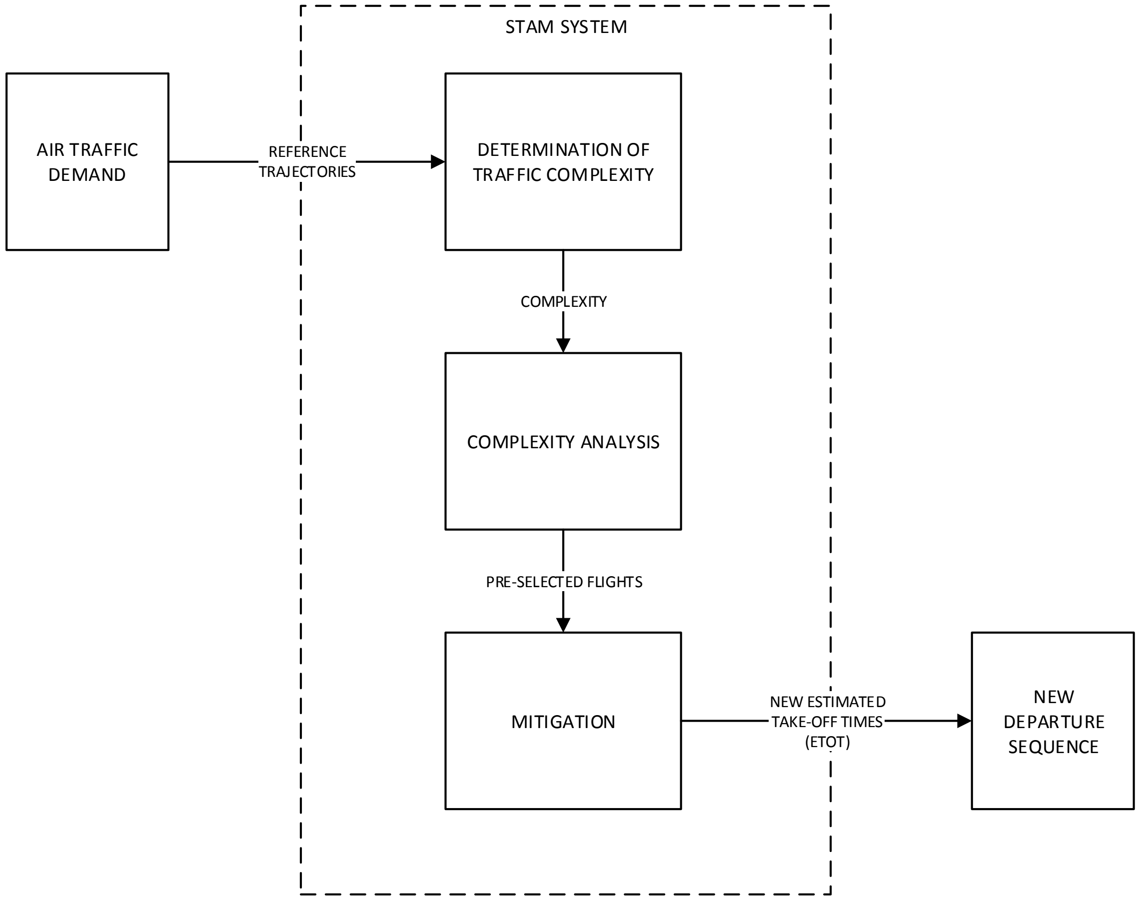

Figure 4-2: STAM System

The core of the OpsCon is a functionality that will be referred as *STAM System*, and it is presented in the Figure 4-2. This functionality is executed locally, at the ATCC, and requires to synchronize with the ground/delivery services of selected airports. The STAM system is based on a methodological process that recursively suggests a more efficient departure sequence with the goal of reducing the traffic complexity of the target airspace (e.g. a given sector or volume).

The OpsCon is aligned with the vision of the future ATMS. In this context, the Global Air Traffic Management (ATM) Operational Concept, defines one of the significant changes of the ATM system to adopt a new conceptual vision in which the system "*considers the trajectory of a manned or unmanned vehicle during all phases of flight and manages the interaction of that trajectory with other trajectories or hazards to achieve the optimum system outcome, with minimal deviation from the user-requested flight trajectory, whenever possible*" (ICAO, 2005).

This significant change is supported by the Trajectory-Based Operations (TBO), "*a concept enabling globally consistent performance-based 4D trajectory management by sharing and managing trajectory information*" (ICAO, 2001).

In the context of TBO, the airspace user intentions, which could be represented by a Spatio-Temporal (S-T) distribution of an aircraft trajectory, are available to all the interested parties. SESAR created the concept of Reference Business Trajectory (RBT) to refer to the trajectory that the airspace user agrees to fly and the ANSP/airport agrees to facilitate (SESAR, 2012).

The main input of the STAM system is a set of predicted trajectories that represents the intentions of the airspace users expected to cross the target airspace (which could be represented by the Reference Business Trajectories).

Following the methodological approach of the dDCB process, it is performed a complexity assessment and preparation of STAM (Eurocontrol, 2015a). The traffic complexity is estimated by detecting interdependencies using the S-T distribution of the reference trajectories. A trajectory interdependency is a condition in which a pair of flights reduces their 4D separation below minimum pre-defined criteria, producing a *concurrence event*[3].

Subsequently, the STAM system compares the S-T distributions of all the flights that are expected to cross the target airspace (within a given look-ahead time interval) and detects situations defined by a high number of trajectories interdependencies. This step looks for identifying the flights that are producing

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[3] The term "*conflict*" is also widely used by other authors to refer to the term "*concurrence event*". Since there is not an official standard terminology, this manuscript makes use of the term concurrence event.

the complexity and pre-selected them for potential temporal displacements on the ground.

The main objective is to release the most thigh trajectory interdependencies by shifting the ETOT of the flights producing the concurrence events. Consequently, the output of the STAM system is a new set of ETOTs (contained within the CTOT's 15-min interval) that are transmitted to the ground/delivery service of each airport some minutes before the push-back & start, modifying the airport's departure sequence.

At this point, the focus of the operation is handled to the control towers. The local and ground ATC roles are extended to ensure the departure sequence is completed according to the suggested take-off times.

4.4 Uncertainties and Robustness

The effectiveness of the temporal displacement measures on the ground is driven by the capability of air traffic controllers to complete the suggested departure sequence and the aircraft to adhere to the predicted trajectory. However, uncertainties produced by the airport procedures, complex taxiways and ATC tactical interventions on air could impact the trajectory conformance.

This section aims at identifying the uncertainties of the OpsCon, which represent the context of the following chapters of this thesis.

4.4.1 Uncertainties on the ground operations

An important part of the robustness of this concept relies on the management of the uncertainties on the ground, which are produced *before take-off.*

The uncertainties produced *before take-off* have their source in all the operations carried out from the push-back process to the take-off. These uncertainties include all the operations performed at ground level such as last-minute passengers, delays in the push-back & start procedures or complex taxi operations. The Figure 4-3 presents the most relevant uncertainties produced during ground operations.

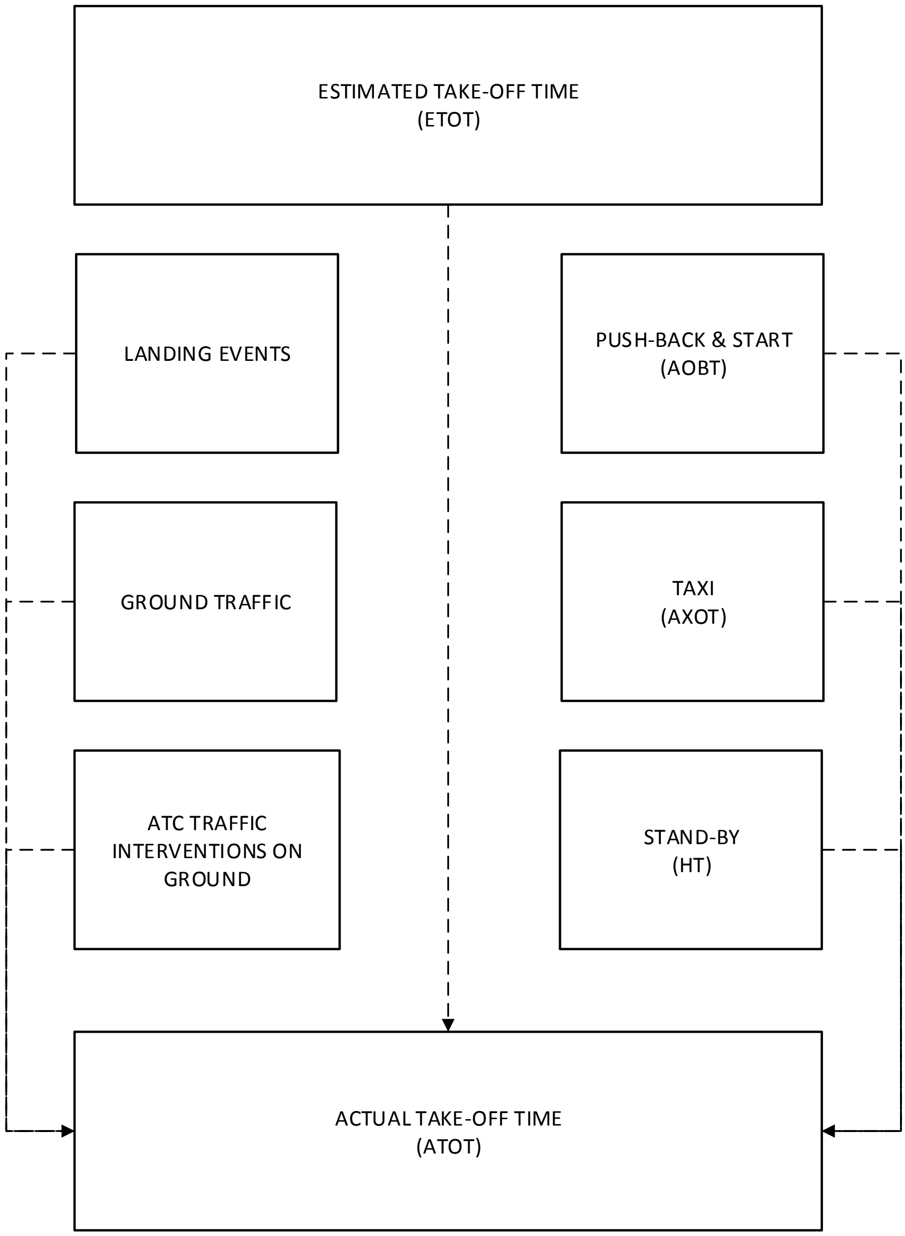

Figure 4-3: Uncertainties on the ground operations

These actions could input disturbances in the system that result in an increased difference between the suggested ETOT and the Actual Take-Off Time (ATOT).

Therefore, the suggested take-off times shall be properly balanced within a time interval that absorbs minor delays produced by the natural air traffic controllers' tasks to direct the selected flights to the active runway.

The first step to tackle this issue is to include an interval of time to the suggested ETOTs that contribute to absorbing the delays produced during the ATC operations on the ground.

However, the full management of these uncertainties is still unclear because this interval of time increases the minimum clearance distance required to mitigate concurrence events. Therefore, defining an unnecessary long interval of time between take-offs reduces the runway throughput and over-releases the ATC interventions on air. Consequently, the chapter 5 evaluates the uncertainties *before take-off*, by simulating this operational concept from a tactical point of view and evaluates the operations of the air traffic controllers on the ground to apply the departure sequence as suggested.

The effects of the new departure sequence could have an impact on the ATCOs taskload that require to balance their efforts in order to maintain a runway throughput and reduces the take-off time error. Therefore, a taskload assessment is also presented in the chapter 5.

4.4.2 Uncertainties in the terminal airspace

The uncertainties produced *after take-off* have their source in all the operations carried out from the take-off to the concurrence event position. The Figure 4-4 presents the main sources of uncertainties in the terminal airspace.

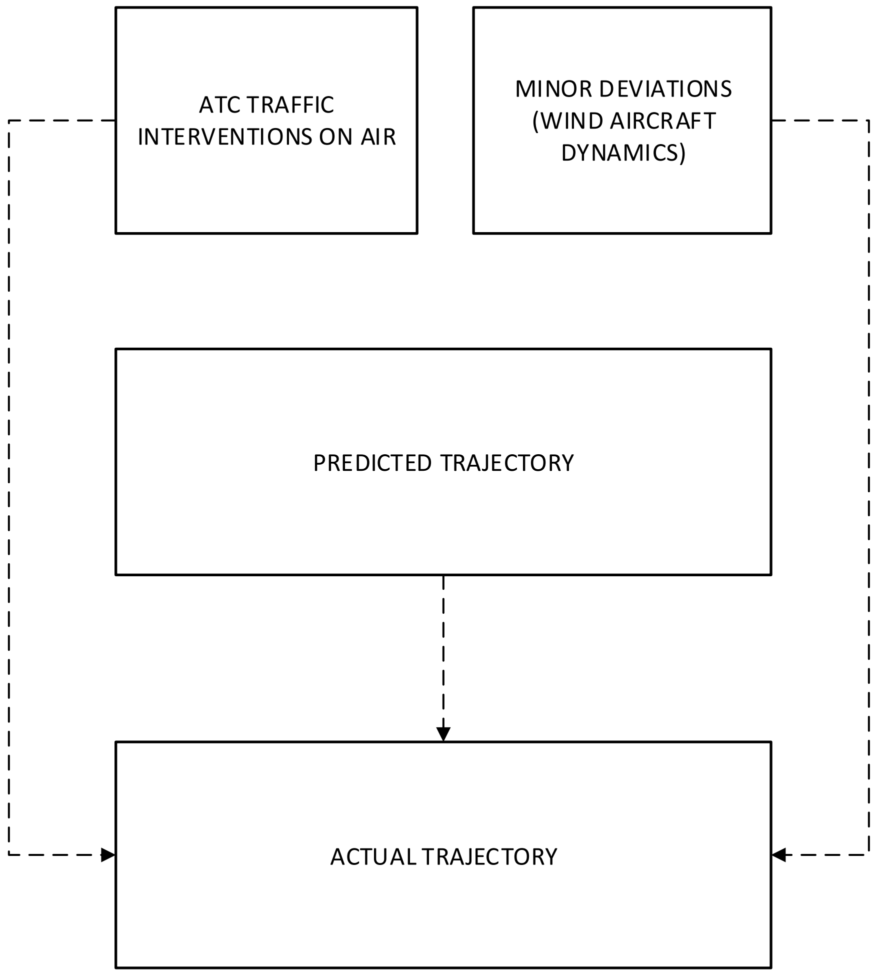

Figure 4-4: Uncertainties in a terminal airspace

During this phase, the aircraft could be affected by wind and operational procedures that produce a lack of adherence to the standard route. The methodology endorsed by this thesis has been designed to minimize these uncertainties by fine-tuning the 4D separation criteria used to detect concurrence events. The PARTAKE approach proposes a cell-based methodology to detect concurrence events, in which minor deviations produced by wind or aircraft dynamics could be neglected for the uncertainties assessment (PARTAKE, 2016).

It is assumed that the horizontal and vertical separation criteria are adjusted to absorb uncertainties produced by wind conditions and minor deviations from the standard route by defining cell-sizes above 2NM.

In highly-vectorised airspace like a MAS-TMA, the assessment of uncertainties focuses on major deviations of the flights from their standard route, which is defined by the SIDs and STARs procedures. Although the flights are required to follow the standard routes, in some cases, tactical interventions of the ATCOs are still required (e.g. clearance for new flight levels or vectoring to shorten the trajectory). Therefore, the main source of uncertainties *after take-off* that could affect the robustness of the solution is input by the TMA ATCOs.

This thesis demonstrates that in a systemized terminal airspace, it is possible to identify high and low adherence standard routes and statistically determine if there exist routes with predictable/recurrent deviation patterns that could be produced by ATC interventions on air. The identification of these routes is boarded in the chapter 6, with the introduction of a framework for the diagnosis of a MAS-TMA that aims at identifying trajectories interdependences, high-demand standard routes, trajectory deviations, recurrent patterns, and temporal analysis to understand the causes of these patterns.

5 A Real-Time Simulation of STAM Operations on ground

The previous chapter presented an operational concept for STAM application. The robustness of the solution is affected by uncertainties that could be produced *before take-off* (e.g. taxi operations) and *after take-off* (e.g. ATC interventions on air).

This chapter is the first step to assess those uncertainties. It aims at exploring the uncertainties produced by operations *before take-off*. The main source of uncertainties is generated during ground operations, when the aircraft is performing push-back, start, holding, taxi and take-off procedures.

5.1 Introduction

In order to explore the uncertainties and test the operational concept proposed in the previous chapter, it has been designed and executed a real-time simulation including the Human-In-The-Loop (HITL) in which changes in the departure sequence of selected flights are performed.

The concept is tested quantitatively by defining a set of Key Performance Indicators (KPI) that are described in the section 5.2. Subsequently, it has been designed a simulation scenario that includes traffic, elements, and structures from a representative multi-airport system (section 5.3). The section 5.4 describes the simulation setup and describes the roles of the actors. The section 5.5 describes the tools developed and implemented to overcome the technical challenges of the real-time simulation.

The results were compared to a baseline scenario. Therefore, a first session has been designed to simulate the airport operations including no restrictions in the take-off departure. Subsequently, it has been included restrictions in the departure sequence, by assigning suggested ETOTs to a set of selected flights. These sessions, limits, and assumptions are detailed in the section 5.7.

The results for each session have been quantitatively compared by measuring the defined KPIs. Additionally, qualitatively results regarding the human performance have been obtained during de-briefing sessions. These results are detailed in the section 5.8.

5.2 Key Performance Indicators (KPI)

The different exercises are compared quantitatively according to the following key performance indicators:

Take-Off Time Error (Δ_{TOT}): a key objective of the methodology is to reduce the difference between the suggested ETOT and the ATOT. The Take-Off Time Error is defined as the difference between these two times. The suggested ETOT is provided to the air traffic controller. The ATOT represents the time when the aircraft takes-off.

$$\Delta_{TOT} = ATOT - ETOT \tag{5-1}$$

Holding Time (HT): according to the standard operations, once a flight is on hold at the runway threshold and the runway is available, a take-off clearance is given immediately. This KPI has been defined in order to evaluate if the restrictions in the departure sequence could require longer holding times to achieve the suggested ETOT. The holding time is the period between the aircraft stops at the holding point (referred to Holding Point Time (HPT)) and the ATOT.

$$HT = ATOT - HPT \tag{5-2}$$

Actual Taxi-Out Time (AXOT): The AXOT is the period between the aircraft pushes-back (AOBT) and the actual take-off time (ATOT), (Eurocontrol, 2010). The AXOT is affected by the taxiways, the aircraft operation, and the airport traffic. This KPI has been defined to measure the uncertainties on the ground produced by the taxi procedures.

$$AXOT = ATOT - AOBT \tag{5-3}$$

ATC Taskload: the air traffic demand is distributed along the time, reducing the ATC interventions on air. In exchange, it is expected an increase in the ATC taskload on the ground due to an increased number of instructions to delay or expedite the AXOT. This KPI has been defined to measure the additional effort performed by the ATCOs while achieving the suggested departure sequence. It has been measured based on the Instantaneous Self-Assessment (ISA) taskload scale (Kirwan *et al.*, 1997) presented in the Table 5-1.

Table 5-1: Instantaneous Self-Assessment (ISA) taskload scale (Kirwan *et al.*, 1997)

Level	Taskload Heading	Description
5	Excessive	Behind on tasks; losing track of the full picture.
4	High	Non-essential tasks suffering. Could not work at this level very long.
3	Comfortable	All tasks well in hand. Busy but stimulating pace. It could keep going continuously at this level.
2	Relaxed	More than enough time for all tasks. Active on ATC task less than 50% of the time.
1	Under-Utilised	Nothing to do. Rather boring

5.3 LTMA Scenery

The operational concept aims at reducing the ATC interventions in the terminal airspace. The standard routes, the sectors and the airports selected define the complexity of the operations. The target scenario of the operational concept is a terminal manoeuvring area of a multi-airport system, where the sector complexity is characterized by outbound traffic from two or more airports that is merged by the standard routes.

The London FIR airspace is controlled from Swanwick's Air Traffic Control Centre. It is divided into two main volumes, London AC (en-route airspace, "LAC") and London TC (designed to manage traffic arriving and departing from London Heathrow (EGLL), Gatwick (EGKK), Luton (EGGW), Stansted (EGSS), City (EGLC) as well as Birmingham (EGGL), Bristol (EGBB) and smaller airfields in the region. This airspace will be referred to "LTMA").

The LTMA is a systemized airspace characterized by standard routes combined with highly-predictable planning to reduce the air traffic controller interventions. Some of the standard routes are characterized by high-adherence recurrent patterns and ATC interventions. The Figure 5-1 presents a simplified plan representation of the LTMA and the airports' locations.

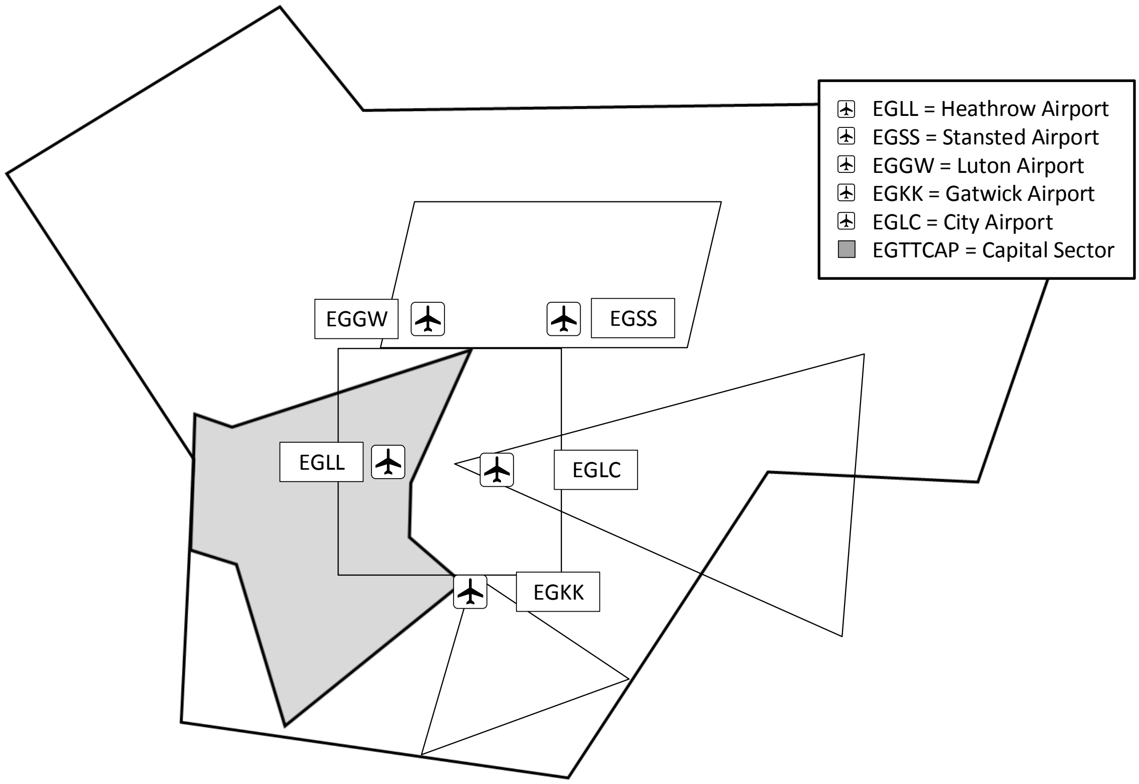

Figure 5-1: Simplified plan representation of the LTMA

The sessions are designed to simulate the operational concept applied in Stansted and Luton airports while serving traffic to the "Capital" sector of the LTMA (referred as EGTTCAP). According to historical data (Eurocontrol, 2018b), the EGTTCAP has been the target of several regulations, which indicates the existence of demand and capacity imbalances.

In order, to represent these imbalances, it has been transformed a historical traffic sample collected from the Demand Data Repository (DDR2) (Eurocontrol, 2018b) to simulate an increase of traffic in Stansted and Luton airports departing towards EGTTCAP, while maintaining the original runway throughput of the airports.

The Table 5-2 shows details of the simulated scenario, the time interval used to detect concurrence events and the historical traffic data.

Table 5-2: LTMA Scenery Details

Airports	EGSS, EGGW
Target sector	EGTTCAP
Date (Base DDR2 File)	July 19th, 2017
Time Interval	5:45am – 6:30am
Total expected departures	26 (15 EGSS + 11 EGGW)

5.4 Simulation Setup

The ATM Laboratory located of the Airspace Integration Research Centre (AIRC) at Cranfield University is composed by a full control tower simulator, four (4) pseudo-pilot positions (referred as "PP") to manage the traffic simulated and other two (2) positions to record and control the simulation as well as to obtain data for further post-processing.

The simulation has been designed to replicate a simplified version of the start, push-back, taxi, holding and take-off procedures of Stansted airport.

Additionally, it is included the take-off procedures of Luton airport as a secondary objective to study the interdependences between these two airports in the LTMA. The laboratory has been setup according to the diagram provided in the Figure 5-2.

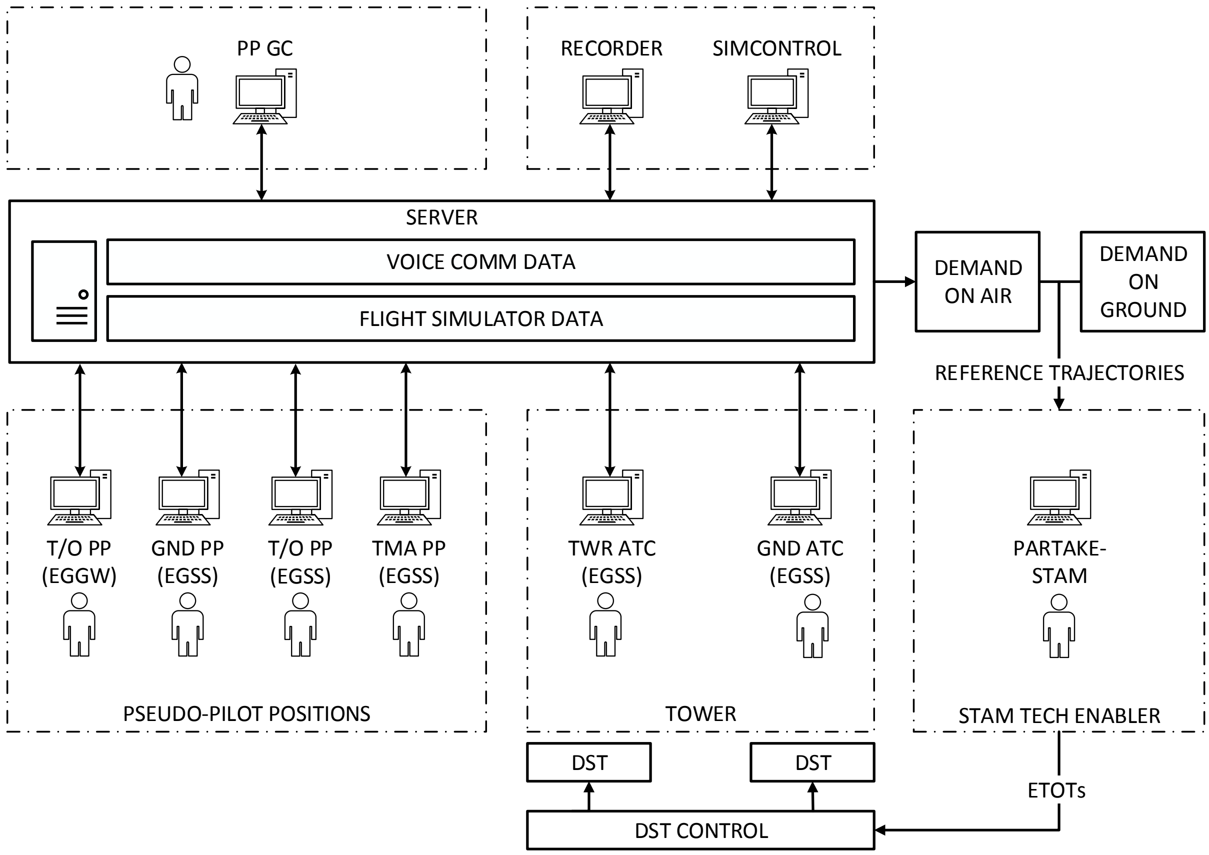

Figure 5-2: Laboratory Setup for the simulation

TWR Controller (EGSS): the role of this position is defined by ICAO as: "*normally responsible for the operations on the runway and aircraft flying within the area of responsibility of the aerodrome control tower*" (ICAO, 2001). The local (or tower) ATC is responsible for the take-off and landing procedures at Stansted airport. This role has been performed by a certified TWR air traffic controller.

GND Controller (EGSS): the role of this position is defined by ICAO as: "*normally responsible for traffic on the manoeuvring area with the exception of runways*" (ICAO, 2001). The ground ATC is responsible for the push-back & start, taxi procedures at Stansted airport. This role has been performed by a certified GND air traffic controller.

GND PP (EGSS): the role of this position is to perform the starting, push-back and taxi procedures according to the instructions provided by the GND Controller (EGSS). For each flight, the function of this pseudo-pilot is completed once the aircraft is handed over to the TWR Controller (EGSS). This role has been performed by a certified ATPL pilot.

T/O PP (EGSS): the role of this position is to perform the line-up from holding position and take-off as instructed by the TWR Controller (EGSS). For each flight, the function of this pseudo-pilot is completed once the aircraft took-off and it is handed over to the departure controller. Additionally, the T/O PP is responsible to remove of the simulation those aircraft that landed and vacated the runway. This role has been performed by a certified Private pilot.

TMA PP (EGSS): the role of this position is to perform the final approach and landing operations as instructed by the TWR Controller. The traffic is served automatically to the Initial Approach Fixes LOREL and ASKEY. For each flight, the function of this pseudo-pilot is completed once the aircraft is directed to land.

T/O PP (EGGW): the role of this position is to perform the line-up and take-off procedures of the Luton airport. For each flight, the function of this pseudo-pilot is completed once the aircraft takes-off.

5.5 Tools and human-machine interfaces

The technological solution used to generate a more efficient departure sequence is based on the tools developed by the Cooperatives Departures for a Competitive ATM Network Service (PARTAKE) project. PARTAKE focused on developing a methodology to distribute the air traffic demand in a sector by detecting concurrence events, analyzing and identifying the most complex interdependences and suggesting changes in the ETOTs of selected flights (within the 15-min CTOT window) in order to mitigate the conflicts (PARTAKE, 2016).

The tools are integrated in the laboratory through a conceptual Decision Support Tool (DST) that was responsible for sending the reference trajectories from the simulator to the tool, receiving new suggested ETOTs and broadcasting the updated departure sequence to the ATCOs of each airport (Figure 5-3). The Appendix A presents the Software, Hardware and Equipment used including the DST ATC Module’s UI and the DST Control Tool concept.

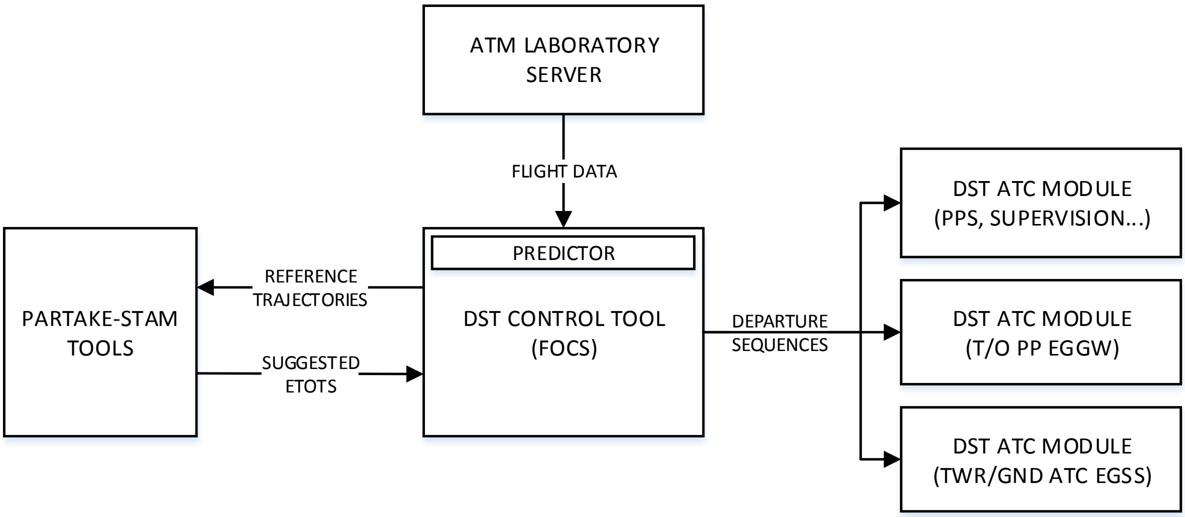

Figure 5-3: PARTAKE Tools integration with the ATM Laboratory

Additionally, the PARTAKE software has been adapted to operate in the LTMA-EGTTCAP sector. The parameters for detecting concurrence events and generate new ETOTs are adjusted by relying on the ATCOs experience during the briefing sessions of the simulation. The software provided new suggested ETOTs periodically (every 5 minutes). The pre-departure sequence was obtained 15-minutes in advance to the take-off time, so the ATCOs had enough time to complete the taxi procedures for the selected airport. The Table 5-3 shows details of the parameters used for the PARTAKE tool (PARTAKE, 2016).

Table 5-3: PARTAKE Tool parameters setup

Parameter	Value
Start Time	6:00am
Look-ahead time	60 min
Cell-size (horizontal)	3 NM
Cell-size (vertical)	500 ft
ATC time	15 min
Execution period	5 min

5.6 PARTAKE-STAM sensitivity analysis

In the real-time simulation, the parameters of PARTAKE tools have been adjusted empirically based on the ATCOs experience. Nevertheless, it has been performed a sensitivity analysis in order to determine *ideal* operating values for the most relevant parameters of the PARTAKE tool's algorithm: cell-size, look-ahead time and the number of airports. These are defined in the Table 5-4.

Table 5-4: PARTAKE most relevant parameters

Parameter	Description
Cell-size[4]	Represents the dimensions of a 2-dimensional square cell used to detect concurrence events. A concurrence event is detected when two or more aircraft share the same cell during a given interval of time (overlap time).
Look-ahead time	The time horizon within which all aircraft positions are projected to explore the existence of potential conflicts.
Number of airports	Number of airports in which temporal displacements on the ground flights will be considered to mitigate the concurrence events

The sensitivity analysis consists of a set of fast-time simulations in which the PARTAKE tools have been executed using a traffic sample of the LTMA.

Considering the characteristics of the parameters, the experiments have been divided into two (2) groups:

- **Group I (experiments E1-E10)**: this group of experiments tests the influence of the cell-size towards the percentage of concurrence events that can be mitigated using the proposed methodology.

[4] In the PARTAKE sensitivity analysis, the cell-size refers to the horizontal separation minima, while the vertical minima is fixed in 500ft.

In this set of tests, it is adjusted the cell-size and number of airports, while fixing the look-ahead time. In this context, the cell-size ranges from 2NM to 6NM (and 500ft), which represent acceptable levels of separation for terminal airspace. In the other hand, the number of airports in which the PARTAKE methodology is implemented is 2 or 4.

Following the scenario used in the real-time simulation, it is chosen for the tests E1-E5 the two (2) main airports that serve traffic to the EGTTCAP sector (Luton and Stansted). While for the tests E6-E10 it was selected a configuration of 4 airports that included the Birmingham and Bristol airports since they feed an important amount of traffic to the studied sector.

- **Group II (experiments E11-E16)**: this group of experiments is designed to analyze the impact of the look-ahead time in the number of concurrence events mitigated. The cell-size and the number of airports are fixed in 3NM and 2 airports, respectively.

The cell-size, look-ahead time and number of airports selected for each experiment are detailed in the Table 5-5.

LTMA has been the target of an important number of regulations during the summer of 2017 (Eurocontrol, 2018b). Most regulations occurring in the traffic peak period between 6:00am and 7:00am. Consequently, it has been chosen as a traffic sample of July 19th, 2017 from 6am to 7am.

The most remarkable result to emerge from the analysis of the cell-size (experiments E1-E10) is that the percentage of solved concurrence events is maximum for cell-size of 2 and 3 NM.

Regarding to the number of operating airports. The mode of operation using either 2 (EGGW and EGSS) or 4 airports (EGGW, EGSS, EGBB and EGGD) seems not to influence significantly on the mitigation possibilities for small cell-sizes for the selected traffic sample. The reason for this is that for the sample of the experiment, EGGW and EGSS provide higher traffic volume, whereas EGBB and EGGD have a lower traffic volume.

Lastly, the number of concurrence events detected increases according to longer look-ahead times until a saturation level is reached. The number of concurrence events detected increased significantly applying a look-ahead time parameter greater to 60 minutes. However, the selection of this parameter incurs in a trade-off between the effectiveness of the detection functionality and the uncertainties. A short look-ahead time improves the effectiveness of the method to solve concurrence events. In contrast, a long look-ahead time causes an increase of the uncertainties. Consequently, further analysis is required to evaluate the uncertainties in the temporal distribution of the reference trajectories.

Table 5-5: Experiments performed in the sensitivity analysis of PARTAKE parameters

		Cell-size					Airports		Look-Ahead Time		
Group	Experiment	2NM	3NM	4NM	5NM	6NM	2	4	45	60	75
I	E-1	✓					✓			✓	
	E-2		✓				✓			✓	
	E-3			✓			✓			✓	
	E-4				✓		✓			✓	
	E-5					✓	✓			✓	
	E-6	✓						✓		✓	
	E-7		✓					✓		✓	
	E-8			✓				✓		✓	
	E-9				✓			✓		✓	
	E-10					✓		✓		✓	
II	E-11	✓					✓		✓		
	E-12	✓					✓			✓	
	E-13	✓					✓				✓
	E-14		✓				✓		✓		
	E-15		✓				✓			✓	
	E-16		✓				✓				✓

5.7 Sessions, limits and assumptions

The exercise has been carried out in three 45-min sessions presented in the Table 5-6. The first session emulated the classic ground operations *without* the STAM procedures. The second and third sessions emulated the ground operations *with* STAM procedures.

The main differences between the last two sessions focused on the balance of different tasks between the TWR and GND ATCOs (EGSS). One session prioritizes the runway throughput, relying most of the tasks on the GND ATC (EGSS). The other session aimed at synchronizing the different agents, maximizing the use of holding points and prioritizing the suggested ETOT, in exchange for a longer holding time when possible.

Disruptions given by adverse weather conditions have been discarded in the simulation. A fixed runway configuration has been assumed during the exercise (RWY22). Stansted airport is characterized by hosting an increased number of Wake Turbulence Category (M) aircraft (e.g. A319, A320, A321 and B737), therefore, it is assumed that all the traffic was contained inside this category. The aircraft flight dynamics for ground and air operations have been simulated based on the used software. However, the taxi speed was adjusted between 15 and 30 kts according to the GND PP (EGSS) requirements.

Although the roles of TWR and GND ATC (EGSS) were performed by certified ATCOs, the controllers were not familiar with real Stansted airport operations. Therefore, the communications maintained during the exercise were limited to *generic* start, push-back, taxi, holding and take-off procedures. The pseudo-pilots applied disturbances by simulating realistic situations (e.g. requesting a few minutes more to start the push-back or requesting an earlier push-back & start procedure when possible).

Table 5-6: Real-Time Simulation Sessions

Session	STAM	Highlights
P-S1	No	**Priority to runway throughput** ▪ Emulated the classic procedures without restrictions in the departure time. ▪ Suggested ETOTs were not considered by the pilots nor ATCOs.
P-S2	Yes	**Priority to runway throughput** ▪ Aircraft on holding position was cleared to take-off once the runway is available (prioritized the runway throughput). ▪ Since suggested ETOTs were considered, the GND ATC role focused on regulating the time the aircraft reached the holding position. ▪ GND & T/O PPs (EGSS) are provided with suggested ETOTs.
P-S3	Yes	**Priority to departure sequence** ▪ Aircraft on holding positions were cleared to take-off, when possible, prioritizing the suggested ETOT. ▪ ATCOs were instructed to maximize the use of two holding points to manage the take-off sequence. ▪ TWR ATC role focused on reducing the Take-Off Time Error while GND ATC role focused on direct aircraft to the holding point on time. ▪ TMA PP was provided with the departure sequence and synchronized landings with TWR ATC. ▪ GND & T/O PPs (EGSS) were provided with suggested ETOTs.

5.8 Results

5.8.1 Data Processing

The KPIs have been calculated based on the time measures obtained during the simulation exercise. The ATOT, AOBT and HPT have been recorded following a pre-defined procedure that included digital and manual procedures as shown in the Table 5-7.

The digital records have been obtained through the use of the DST ATC module provided to the TWR ATC (EGSS). The manual records have been obtained through the use of flight strips. Additionally, the T/O PP (EGSS) and T/O PP (EGGW) recorded the ATOT of each flight (for redundancy purposes).

Table 5-7: Data acquisition for defined KPIs

Metric	Flight Strips	DST Module (ATC)	DST Module (PP)	Record
ETOT	✓	✓	✓	✓
ATOT	✓	✓	✓	✓
AOBT				✓
HPT	✓			✓

The ATC taskload has been manually logged by a taskload assessor who was positioned behind the TWR and GND ATCOs (see Figure 5-4). A new taskload entry for each ATC was recorded every 5 minutes.

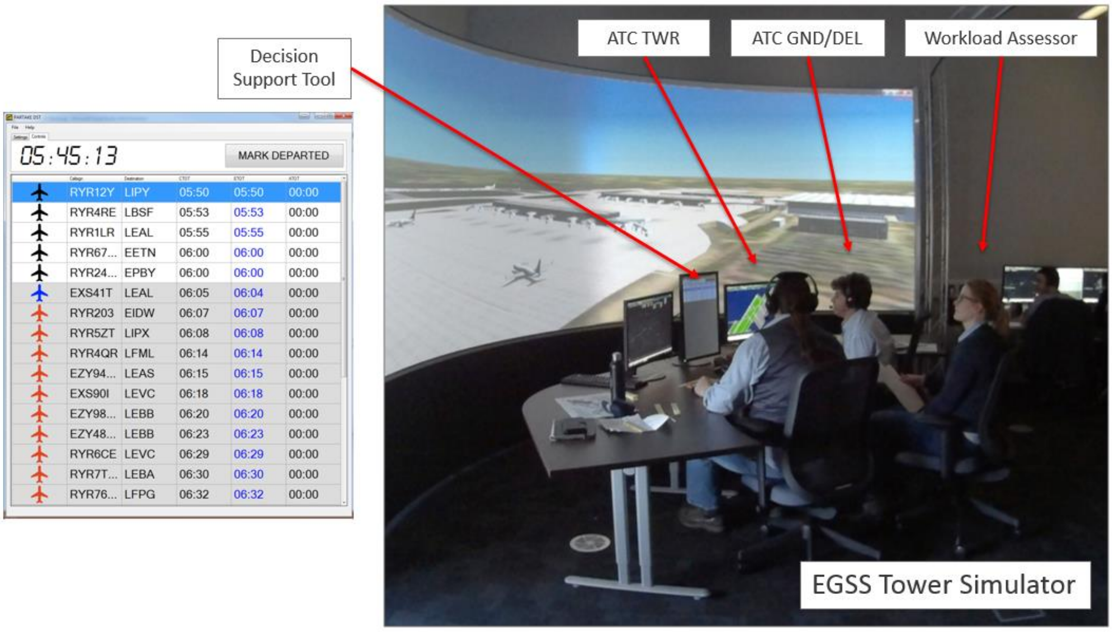

Figure 5-4: Tower Simulator and roles

5.8.2 Results on Take-Off Time Error

The take-off time error indicates the ultimate performance of the ATCOs to absorb the uncertainties on the ground of the operational concept proposed. The Figure 5-5 presents the take-off time error (Δ_{TOT}) for each session. It is observed a Δ_{TOT} below the ±300 seconds in the P-S1. Although the P-S2 included restrictions of the departure sequence, it was obtained a similar take-off error. In contrast, the P-S3 presents a Δ_{TOT} below ±50 seconds.

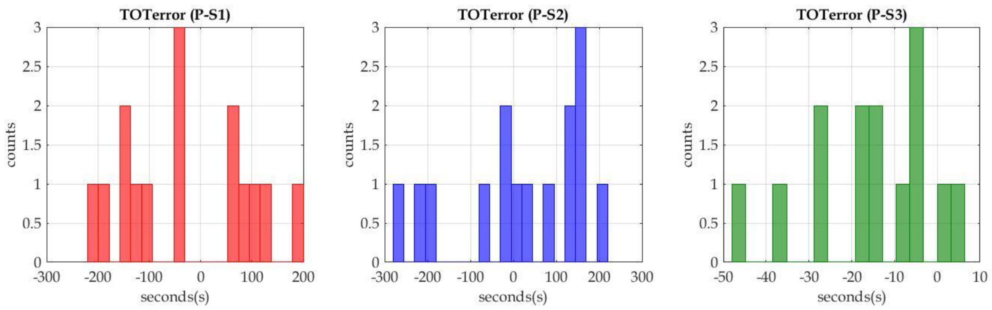

Figure 5-5: Take-Off Time Error (Δ_{TOT}) | P-S1 | P-S2 | P-S3

The Figure 5-6 shows the distributions of the landing events produced at the Actual Landing Time (LDTL) compared to the suggested ETOT and the ATOT obtained in the P-S2.

When compared the estimated (top) with the actual (bottom) take-off times, it is observed that the local ATCOs were prioritizing the runway throughput over the suggested ETOTs. Some departure events (ETOTs → 5:50, 6:02, 6:12, 6:14, 6:23 and 6:25) were produced before than suggested times when no landing events were produced at a similar time. However, other take-off events (5:53, 6:05, 6:19 and 6:29) were shifted due to landing events produced at similar times.

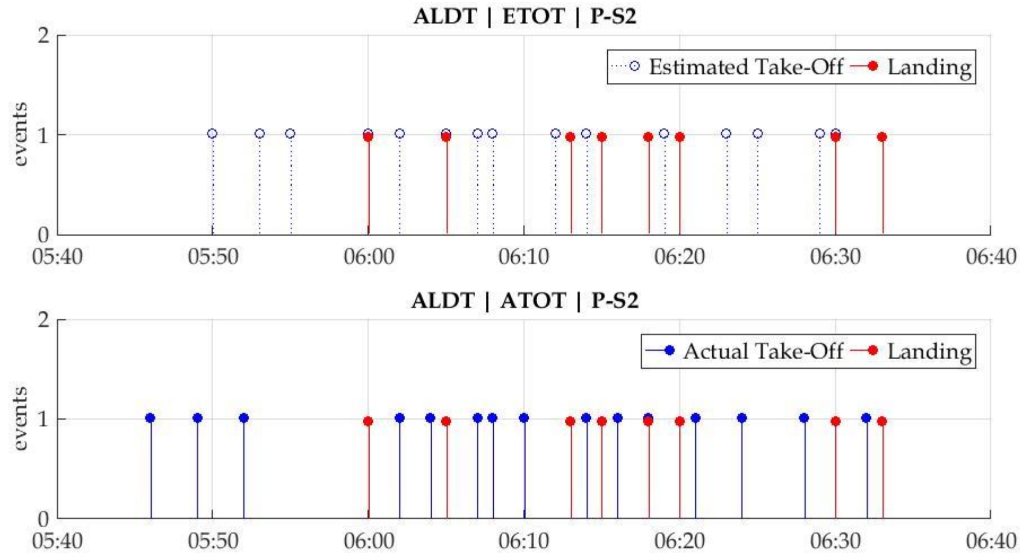

Figure 5-6: Landings and (Estimated | Actual) Take-Off Events | P-S2

A different result is observed in the PS-3. The Figure 5-7 shows that most of the flights were delayed (when possible) at the holding point, even that the runway was available. The result is reflected in a lower take-off time error. The landing separation was increased due to the TMA-PP was aware of the departure times (emulating a TMA-TWR ATC synchronization). Although some LDTL overlapped with the suggested ETOTs (5:53, 6:00, 6:05 and 6:29), it is observed that the flights were cleared right after/before the landing event with the goal of reducing the take-off time error.

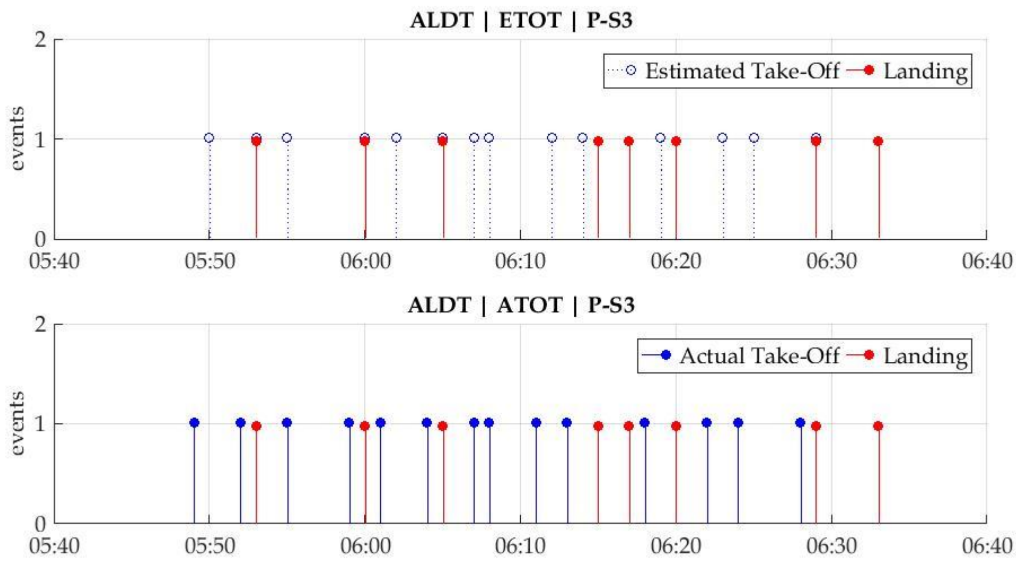

Figure 5-7: Landings and (Estimated | Actual) Take-Off Events | P-S3

5.8.3 Results on holding (HT) and taxi (AXOT) times

The average holding time was similar for all the sessions ($HT_{P-S1} = 295s$, $HT_{P-S2} = 311s$ and $HT_{P-S3} = 300s$). The holdings were balanced according to the events produced in the runway for each session.

Table 5-8: Average Holding Time (HT) & Taxi Time (AXOT)

Session	Avg HT (seconds)	Avg AXOT (seconds)
P-S1	294	606
P-S2	311	670
P-S3	300	630

The results of the Figure 5-8 show a difference in the time distribution. The holding times were more variable in P-S2. Holding times longer than 5 minutes were produced after the landing events at 6:00, 6:05, 6:13 and 6:20.

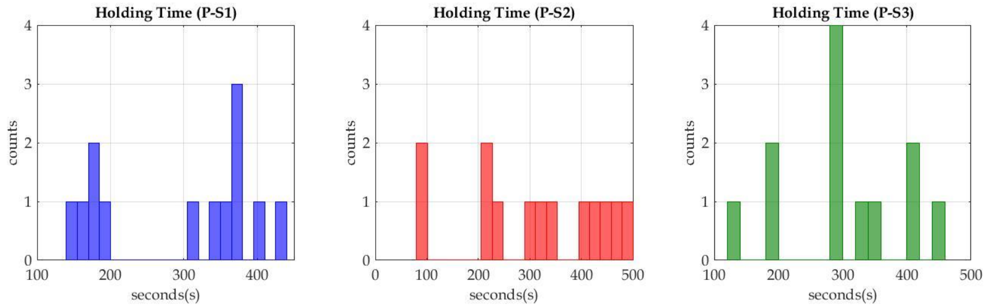

Figure 5-8: Holding Time (HT) | P-S1 | P-S2 | P-S3

In contrast, 50% of the flights maintained a holding time within an interval of 300±50 seconds during the P-S3 session. In the Table 5-8, it is observed a difference in the taxi time (AXOT) for each one of the sessions. During the session P-S2, the ground ATC tried to balance the time the flights achieved the holding point (HPT) by applying minor delays, especially during the push-back and start procedures, which is reflected in the differences of taxi times compared to P-S3. Other delays were the result of disturbances applied by the crew before the AOBT.

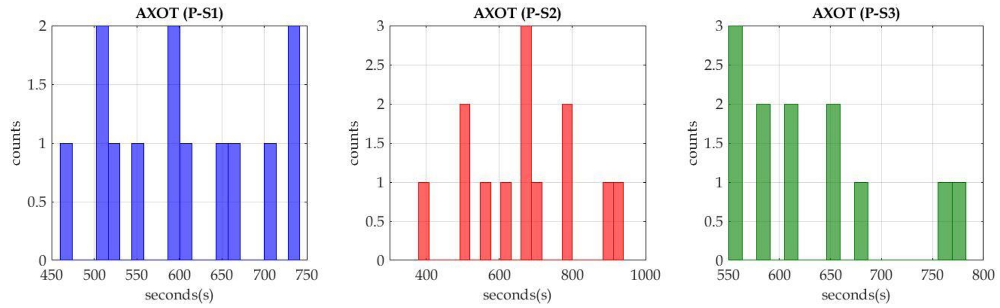

Figure 5-9: Taxi Time (AXOT) | P-S1 | P-S2 | P-S3

5.8.4 Results on human performance

The results presented in the Table 5-9 show that the ground and local ATCOs experienced on average taskload between relaxed (level ISA-2) and comfortable (level ISA-3) heading. The general meaning of these values is affected by the simplified operations simulated for Stansted airport and the 10-minutes warm-up time in which few landing and take-off operations were performed. However, the comparison between simulations demonstrates a balance in the taskload during the P-S3. The fact that the TMA PP was provided with the departure sequence and synchronized the landings with the local ATC reduced significantly the taskload of the ATCOs on the ground.

Table 5-9: Average (Ground | Local) ATC Taskload

Session	Avg Taskload (Ground ATC)	Avg Taskload (Local ATC)
P-S1	2.1	2
P-S2	2	1.7
P-S3	1.4	1.6

The Figure 5-10 shows the ground and local ATCOs taskload for each session. The ground ATC experienced a "*relaxed*" (level ISA-2) taskload most of the time. The most significant taskload peaks (still in *"comfortable"* level ISA-3) were achieved during a 10-minutes interval [6:00, 6:10], in which a set of flights with suggested ETOTs were sequenced (AOBTs → 6:01, 6:06, 6:08). However, these peaks are associated to the number of flights in a sequence rather than the suggested ETOT, since these peaks can be observed during the P-S1, in which no departure restrictions were provided.

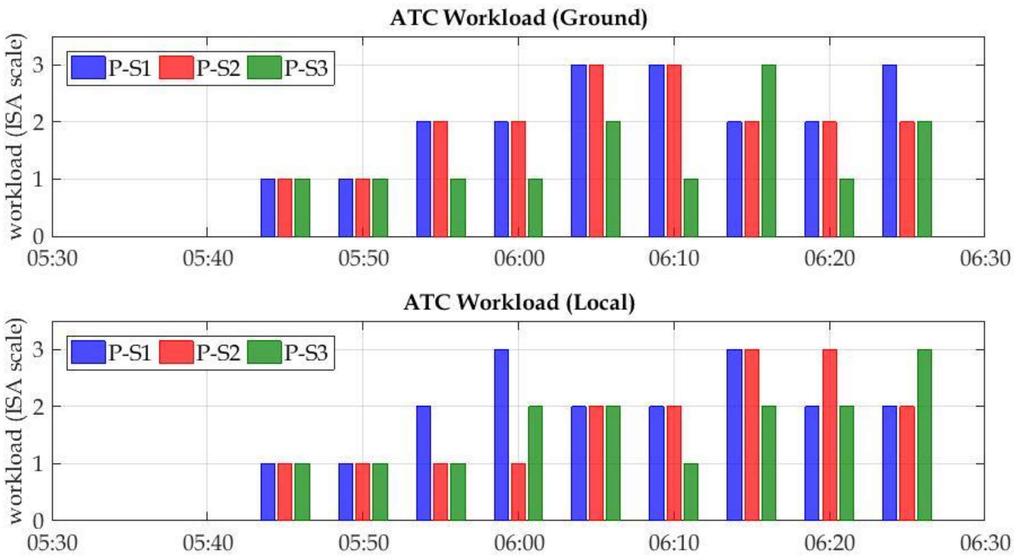

Figure 5-10: (Ground | Local) ATC Taskload | P-S1 | P-S2 | P-S3

In the other hand, the local ATC experienced less taskload, with peaks that could be associated to the number of landing events and flights in the holding points (labeled as *R1*, *Q1* and *S1*) at specific times. During the interval [6:10, 6:20], there were used mostly two (2) holding points and were produced three (3) landing events. The taskload peaks experienced at this interval were reduced in the P-S3 with the synchronization between the local ATC and TMA PP, resulting in a more distributed landing sequence, penalized by increased holding times on air.

Apart from the quantitative assessment based on the KPIs provided, the de-briefing sessions were used to assess qualitative results. In general, the ATC "*did not felt important levels of stress during the three sessions. However, the operations on the ground were comparable to the ones experienced when applied Minimum Departure Intervals (MDI)*".

5.9 Conclusions

Chapter 4 presented a proof-of-concept of the proposed OpsCon for STAM application. The concept aims at applying temporal displacements on selected flights by proposing a new departure sequence (and changing their ETOT). The main goal is to reduce the number of concurrence events and the number of ATC interventions *on-air*, in exchange of a more distributed demand in the sector and an increased number of ATC interventions on the ground.

This chapter, presented a real-time simulation exercise based on the proposed OpsCon. In this context, it has been simulated a simplified version of the Stansted airport scenario, involving the human-in-the loop (HITL) and generic communications for push-back, start, taxi, hold, take-off and landing procedures.

The results show that it has been possible to obtain take-off time errors below ±50 seconds, providing an insight about the uncertainty window (cell-size, clearance time) required to improve the robustness of the endorsed PARTAKE methodology.

Synchronization of local and TMA ATCOs is key to reduce the take-off time error. During the P-S2, the ground controller focused on regulating the taxi operations and the times to arrive at the holding point. These actions were reduced during the P-S3, focusing more on achieving the holding point immediately and handling the pressure to the local ATC. To overcome this, the local ATC synchronized with the TMA PP to take-off flights on time, distributing accordingly the landing events and possibly impacting the runway throughput at peak times. Therefore, the application of this methodology could be ideal for airports with reduced demand that serves traffic to congested MAS-TMA sectors (e.g. Stansted or Luton in the LTMA). The taxi layout and the number of runway feeders is an important factor to consider in this methodology.

The ATC taskload results show that the synchronization between the different ATCOs that intervene in the process is key to reduce the uncertainties on the ground. Additionally, the taxiway layout of the airport improved the management of the departure sequence by making use of two holding points simultaneously. However, the simulation was designed to represent a simplified version of the airport operations, which could have had an impact in the absolute taskload perceived by the ATCOs.

The landing separation obtained in the P-S3, helped the local ATC to manage the suggested departure sequence, reducing their taskload. Therefore, a balance between take-off and landing events is key to achieve low take-off errors, but further analysis is required to evaluate the potential impact of this *balancing* in the TMA operations (e.g. longer holding times on-air/TMA-ATC taskload).

6 A Framework for Diagnosis of a Terminal Manoeuvring Area in MAS

The previous chapter analyzed the uncertainties produced *before take-off* by developing a HITL proof-of-concept and real-time simulation. Quantitative results in terms of take-off time errors, holding time, taxi times and human performance indicators were provided to analyze the operations on the ground.

Following the context provided in section 4.4 of the OpsCon for STAM application, it is proposed to identify those standard routes characterized by recurrent patterns to reduce the uncertainties produced *after take-off*.

Consequently, this chapter presents a data-driven generic methodology that contributes to characterize and evaluate the terminal airspace operations of multi-airports systems by studying the adherence of the actual traffic to standard routes.

The section 6.1 presents a literature review related to the identification of traffic flows, clustering methodologies, and concurrence event detection. The methodology is composed by two main components designed to analyze the main sources of uncertainties produced *after take-off*. A first component that estimates the 4D-adherence of the flights to the standard routes (section 6.2) and a second component that identifies concurrence events in the terminal airspace (section 6.3).

The 4D adherence estimation methodology begins with a preliminary identification and classification of the standard routes interdependencies in section 6.2.1. This is carried out to provide an overview of the traffic flow behavior within the MAS-TMA operations. Subsequently, the 4D deviation distribution is determined by populating the standard routes with real traffic samples (section 6.2.2) and comparing the planned and actual trajectories at segment level (section 6.2.3). Lastly, the section 6.2.4 presents a clustering algorithm designed to determine groups of trajectories with similar deviation, which leads to identifying recurrent traffic patterns at segment level.

The analysis and identification of concurrence events is based on a reverse process that estimates the state of the MAS-TMA before the tactical interventions. The methodology presented in the section 6.3, is designed to detect loss of separation minima events that are then analyzed to identify the potential causes of the lack of adherence and demand conditions of the terminal airspace.

6.1 Background

A. Flight data analysis and traffic patterns identification

Some authors have developed machine-learning/statistical approaches in order to determine recurrent patterns in large-scale data sets. There exists some clustering methods such as *k-means* (Gaffney and Smyth, 1999), BIRCH (Zhang, Ramakrishnan and Livny, 1996), DBSCAN (Ester *et al.*, 1996), HDBSCAN (Campello, Moulavi and Sander, 2013) and OPTICS (Ankerst *et al.*, 1999) that have been extensively used for this purpose.

In-flight data analysis, the most common approach to identify traffic patterns is the application of clustering techniques to flight radar track data in order to determine groups of trajectories represented by similar Spatio-temporal distributions.

In this context, (Gariel, Srivastava and Feron, 2011) presented a methodology to determine the performance of aircraft trajectories using a density-based clustering algorithm. Similarly, (Verdonk Gallego *et al.*, 2018) applied the same density-based clustering technique to identify traffic flows that were used in a machine-learning algorithm to predicted aircraft trajectory vertical profiles. (Eckstein, 2009) filtered, decomposed and applied clustering to radar flight tracks to understand the performance of individual aircraft trajectories in a terminal manoeuvring area. (Murca *et al.*, 2016) used a density-based clustering algorithm to identify major flight trajectory patterns in the airspace and an ensemble-based classification scheme to detect a lack of adherence in aircraft trajectories. Similarly, (Murca and Hansman, 2018) developed a data-driven framework to identify, characterize and predict traffic flow patterns in the terminal airspace of multi-airport systems that is based on a machine learning method that uses flight tracks data, weather and runway configuration information. The process is based on an initial layer of clustering at a spatial scale to determine the airspace structures and the second layer of clustering at a temporal scale to determine flow patterns. (Rehm, 2010) relied in hierarchical clustering to identify spatial traffic patterns. (Enriquez, 2013) used spectral clusterization for large, time-varying air traffic datasets to perform a temporal characterization of air traffic flows. (Sabhnani *et al.*, 2010) developed a grid-based algorithm that extracts standard flows, conflicts and merging points from a given set of 4D trajectories. (Arneson *et al.*, 2017) applies a density-based clustering technique to identify the dominant routing structure between Fort Worth and New York centres in a given time interval. The identification extracts relevant weather data and quantifies the impact of convective weather on the routing structure. (Delahaye *et al.*, 2017) introduced a new metric to calculate the distance between trajectories and then applied a hierarchical clusterization algorithm to flight data samples of French airspace for the goal of extracting traffic flows. (Andrienko *et al.*, 2018) proposed an analytical workflow for clustering of flight trajectories that has resulted in a suite for clustering, visualize and support data analysis. (Sidiropoulos *et al.*, 2016) proposed a framework for the robust identification of relevant air traffic flow patterns in the terminal airspace in which it is applied a clustering algorithm to determine the spatial and temporal distribution of flights in the New York multi-airport system. (Lee, Han and Whang, 2007) proposed a partition-and-group framework for clustering general data trajectories in which the trajectory is split into different parts that are then grouped in similar line segments with the objective to identify common sub-trajectories from real trajectory data.

The clustering process presented in this thesis adopts an alternative approach that aims at grouping aircraft trajectories with similar deviations gradients at segment level. Although the general results could lead to similar results than clustering the actual trajectories, this approach extends the trajectory analysis to a *higher level of granularity* by determining not only trajectory deviations at segment level but also by identifying those segments of the standard routes where the initial/final lack of adherence is produced. Additionally, clustering algorithms are sensitive to parameters that could be difficult to associate with operational parameters. The clustering method proposed in this thesis uses a similar approach used by the OPTICS algorithm (Ankerst *et al.*, 1999) to determine the peak values of the reachability distance distribution, but in this case, it is applied to determine local maximum and minimum in the deviation data distribution. Consequently, the method presented in this thesis is based on two parameters. The bin-width ($\tau_{i+1} - \tau_i$), which is directly associated with an operational requirement of the route (horizontal separation minima) and the threshold (T_{peak}), which represents the number of trajectories that are considered *acceptable* to determine a recurrent pattern.

B. Analysis of terminal airspace in multi-airport systems

The framework developed in this thesis is intended to determine 2D interdependencies in standard routes, determine the lack of adherence of traffic and identify recurrent patterns in terminal airspace of a multi-airport system. The concept of multi-airport system (or metroplex) has emerged as a response of the increase of demand to/from metropolitan areas, which produce an emergence or construction of secondary airports (Bonnefoy, de Neufville and Hansman, 2010). The operations in a terminal manoeuvring area are more complex in multi-airport systems because a limited airspace volume is intended to allocate the traffic of several close located airports. Few authors have investigated the interdependences and performance of the MAS-TMA. (Clarke *et al.*, 2012) developed a framework for evaluating concepts for improving multi-airport system terminal area airspace. The framework is then used to identify a range of multi-airport system issues and inefficiencies and quantify potential benefits of both, generic and New York TRACON (N90) Metroplex configurations. The operations of four (4) representative U.S multi-airport systems have been compared in the study of (Ren *et al.*, 2009), in which twelve critical issues and six types of airspace interdependencies have been identified. (Donaldson and Hansman, 2011) studied the New York airports' capacity as a whole and compared with the individual capacity of each airport. The shared resources of the multi-airport system produce a significant impact on the capacity of the involved airports. (Murça *et al.*, 2018) applied a flight trajectory data analytics framework to determine structural, operational and performance differences between three representative multi-airport systems (New York, Hong-Kong and Sao Paulo). The framework is based on two modules that identify spatial patterns of aircraft movement using a density-based clustering algorithm and a trajectory classification scheme to match flight trajectories to the identified airspace structures. (Histon and Hansman, 2002) analyzed the co-located and non-co-located merging points in real traffic interdependences.

The approach followed in this thesis to identify concurrence events is focused in a *heuristic method* that makes use of a pseudo-planned trajectory representing the state of the terminal manoeuvring area before the tactical interventions. The method is used to determine concurrence events and analyze their relationship with the lack of adherence to a specific standard route. Consequently, other strategies like the one used by NEST tools (Eurocontrol, 2012) for conflict detection based on analysis of flight tracks could be compatible with the analysis method proposed in this chapter.

6.2 Data-driven 4D adherence calculation method

This section proposes a method for the estimation of the adherence based on the comparison of the Spatio-Temporal (S-T) distribution of the actual and planned trajectories of the terminal airspace. The technique is proposed as a set of five (5) steps that are presented in the Figure 6-1.

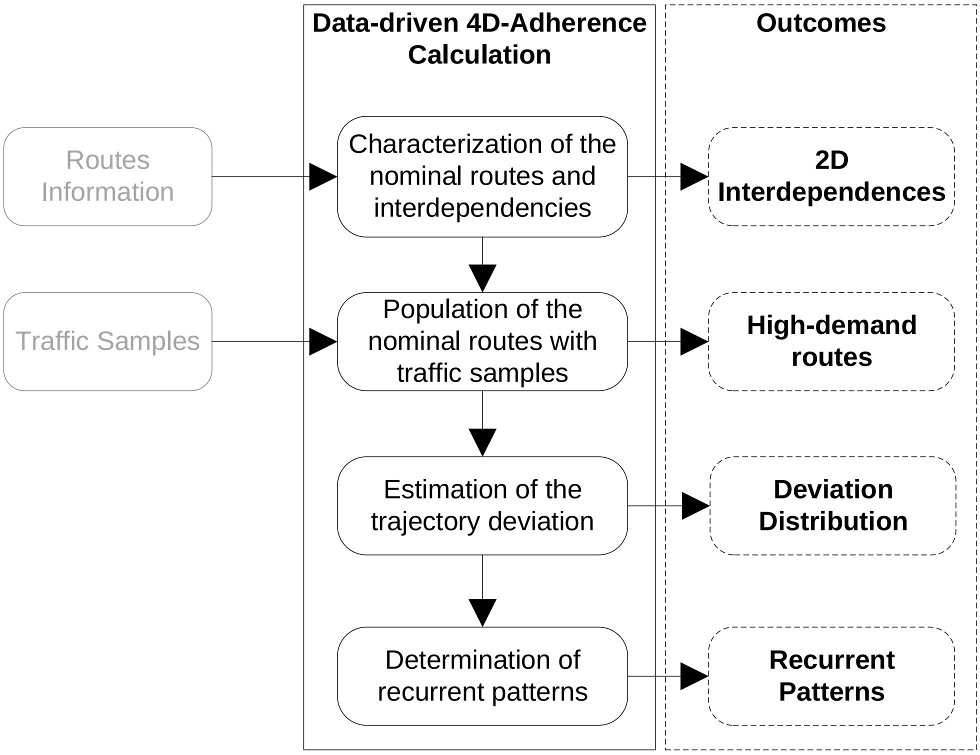

Figure 6-1: Methodology to calculate 4D adherence and recurrent patterns

6.2.1 Identification of the standard routes and interdependencies

The method determines the 2D interdependencies between the different standard routes as a first step to understand the operations of a TMA. Three types of interdependences are defined (Figure 6-2):

- **Two-dimensional crossing point (Type I):** the two routes have a crossing point.
- **Merging waypoint (Type II):** a waypoint where the routes merge into one common route (II) or simply in the last waypoint of the route (IIa). This case is common in routes that share the same IAF/EP.
- **Different routes share a common segment (Type III):** if there exists an intermediate waypoint where the routes are merged but the routes do not share the same IAF/EP.

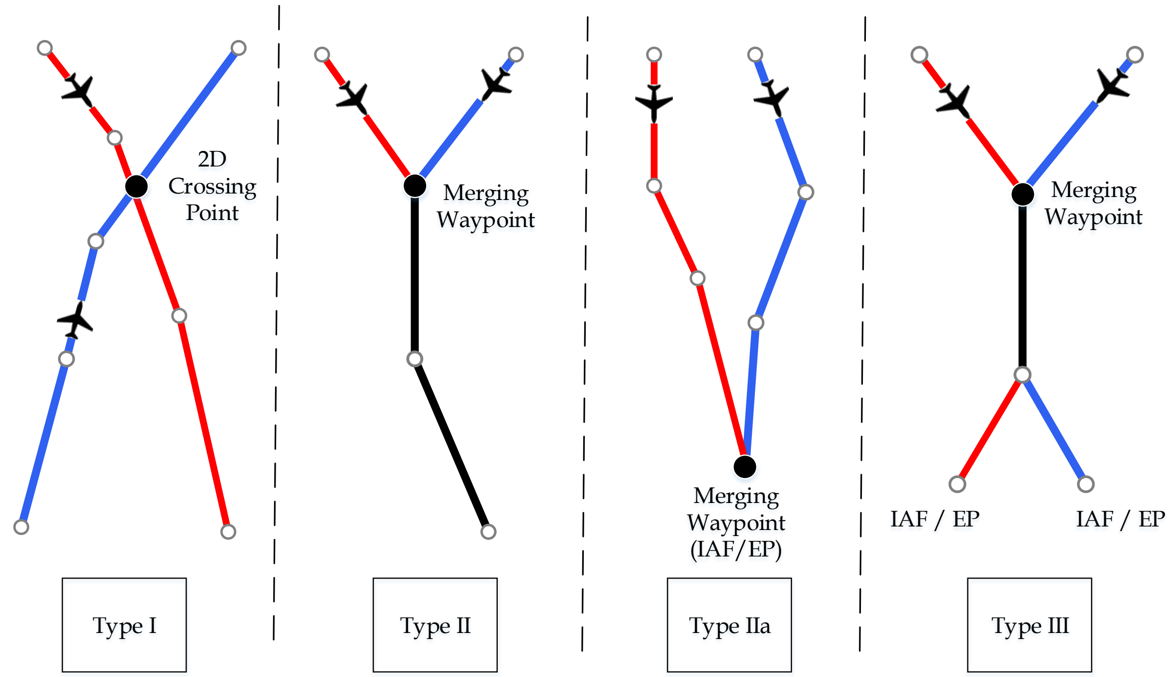

Figure 6-2: Types of 2D Interdependences

6.2.2 Population of standard routes with real traffic data

Having classified the standard routes interdependencies, it is proposed a trajectory analysis method that uses planned and actual trajectories samples to estimate the 4D adherence to the standard routes.

Definition of standard routes

The most basic element to define a standard route is a waypoint. (ICAO, 2006) defines a waypoint as "*a specified geographical location used to define an area navigation route or the flight path of an aircraft employing area navigation*". Consequently, it is considered a two-dimensional waypoint as a pair of ordered coordinates that represent a geographical location defined by a longitude x, and a latitude y:

$$wp(x, y) \tag{6-1}$$

Moreover, a standard route (R) is defined as a set of ordered waypoints that are joint by a great circle arc:

$$R = \{wp_1^R, wp_2^R, wp_3^R \dots wp_n^R\} \tag{6-2}$$

A segment is a subset of R represented by two adjacent waypoints. Hence, each segment is composed by its initial waypoint and its final waypoint:

$$S^R = \{wp_i, wp_f\} \tag{6-3}$$

Given that each segment is a subset of R, then a standard route could also be represented by the union of its segments:

$$R = \bigcup_{i=1}^{n-1} S_i^T \tag{6-4}$$

It is considered that for each multi-airport system, there exists a set of *standard routes* that represents the SID and STAR procedures of its terminal manoeuvring area.

Definition of four-dimensional trajectories

A four-dimensional trajectory point is defined as a 4-upla of ordered numbers that represent a spatio-temporal aircraft position defined by a longitude (x), a latitude (y), an altitude (z) and a time (t).

$$tp(x, y, z, t) \tag{6-5}$$

A four-dimensional trajectory is defined as a set of ordered trajectory points that are spatially joint by a great circle arc:

$$T = \{tp_1, tp_2, tp_3 \dots tp_k\} \tag{6-6}$$

A trajectory segment is a subset of T defined by the joint of two adjacent trajectory points. Hence, each segment is composed by its initial trajectory point and its final trajectory point:

$$S^T = \{tp_i, tp_f\} \tag{6-7}$$

A planned trajectory is defined as a four-dimensional trajectory that represents the flight intent, as described by the flight plan, and constrained by standard procedures (Eurocontrol, 2017a). Consider a set of *planned trajectories* so that its origin or destination airport (at least one) is included in a unique multi-airport system. Each element of the planned trajectories set is defined as:

$$P = \{tp_1^P, tp_2^P, tp_3^P \dots tp_m^P\} \quad (6\text{-}8)$$

It is defined an actual trajectory as a four-dimensional trajectory that represents a flight track of an aircraft in its intent to follow a planned trajectory. Consider a set of *actual trajectories* so that each element of the set is defined as:

$$A = \left\{tp_1^A, tp_2^A, tp_3^A \dots tp_q^A\right\} \quad (6\text{-}9)$$

Since the method proposed uses historical flight data samples, it is considered that there is a one-to-one correspondence between the planned trajectories (P) and actual trajectories (A) sets, so that each element of the planned trajectories set could be paired to one and only one element of the actual trajectories set (Figure 6-3).

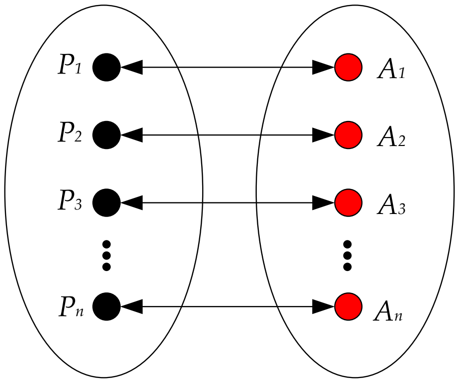

Figure 6-3: Correspondence between planned and actual trajectories

It is used the Regulated Tactical Flight Model (RTFM) and Current Tactical Flight Model (CTFM) as traffic samples for the planned and actual trajectories, respectively (Eurocontrol, 2018b).

Mapping of planned trajectories to standard routes

The mapping process aims at describing a rule that defines a correspondence between the planned trajectories and the standard routes so that each planned trajectory P can be associated with one standard route R (Figure 6-4).

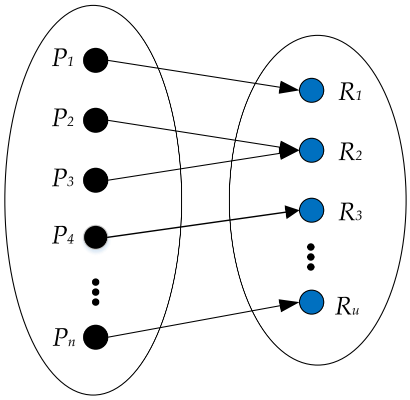

Figure 6-4: Correspondence between planned trajectories and standard routes

The standard routes represent procedures fixed to the terminal airspace and therefore *independent* of the time. In some cases, the standard routes define altitude limits to ensure the separation between different arrival and departure routes. However, not all the waypoints of a standard route are provided with a defined altitude. Hence, it is assumed that a waypoint wp^R is equal to a trajectory point tp^P, if both elements share the same longitude (x) and latitude (y) while discarding the time (t) and altitude (z).

$$x_i^P = x_i^R \tag{6-10}$$

$$y_i^P = y_i^R \tag{6-11}$$

Then, a planned trajectory P is associated to a standard route R if the number of associated waypoints and trajectory points is equivalent to the number of waypoints of R.

$$card(R \cap P) = card(R) \tag{6-12}$$

Point-to-point association of actual trajectories along planned trajectories

The method to estimate the trajectory adherence is preceded by a point-to-point association process that links each actual trajectory point to a planned trajectory point.

The Figure 6-5 (left) shows an example of planned and actual trajectories samples. The actual trajectory represents flight tracks. As can be observed, a direct point-to-point association result in inaccurate results because some actual trajectory points are associated with the same planned trajectory point which is quite far from the geometrically closest point between the two trajectories.

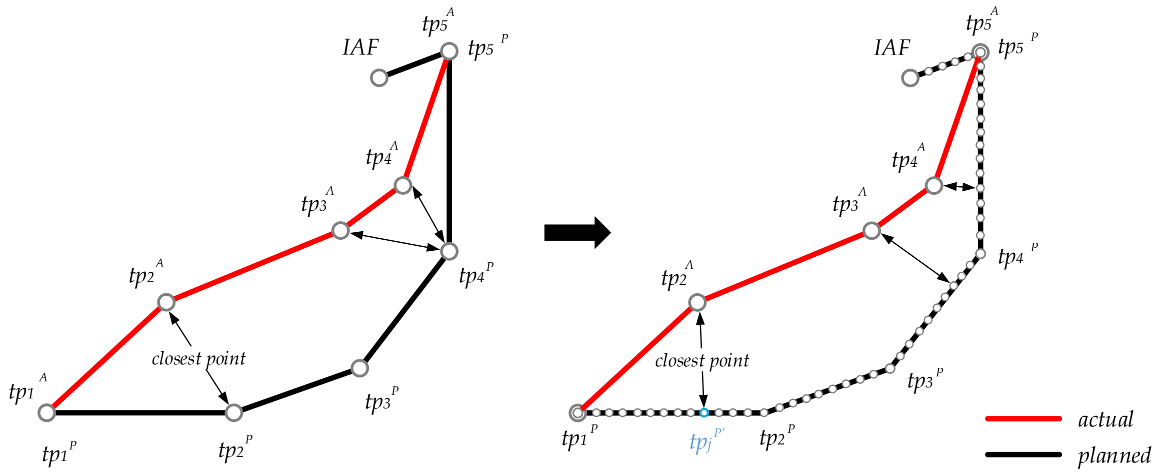

Figure 6-5: Point-to-point trajectories association

To overcome this, it is proposed to adapt the planned trajectory structure to carry out a more accurate point-to-point association. Each segment of the planned trajectory is resampled in k number of interpolated trajectory points. Therefore, each segment (S_i^P) of the trajectory P is now represented by the joint of $k-1$ sub-segments of the trajectory P':

$$S_i^P = \bigcup_{i=1}^{k-1} S_i^{P'}$$

Then, for each pair of trajectory points $tp^A(x_{i,}y_i, z_i, t_i)$ and $tp^{P'}(x_{j,}y_j, z_j, t_j)$, it is calculated their great-circle distance as follows (Inman, 1821):

$$a = \sin(\Delta y/2)^2 + \cos(y_i) \cdot cos(y_j) \cdot \sin(\Delta x/2)^2 \qquad (6\text{-}13)$$

$$d_{ij} = R \cdot (2 \cdot \tan2^{-1}(\sqrt{a}, \sqrt{1-a}) \qquad (6\text{-}14)$$

The goal is to compare the distance of each trajectory point of the sets A with the trajectory points of the set P'. It is determined that a planned trajectory point $tp^A(x_{i,}y_i, z_i, t_i)$ is associated to $tp^{P'}(x_{j,}y_j, z_j, t_j)$, if the distance between them is minimal among all the other possible pairs of $tp^A(x_{j,}y_j, z_j, t_j)$. As a result, the new planned trajectory contains additional trajectory points ($tp^{P'}$).

The approach followed in this section aims at identifying the closest point between both trajectories. Since this is an intermediate step to calculate the trajectory deviation values, this approach could be replaced by an analytical approach (minimum distance between a point and a line) that leads to similar results.

6.2.3 Estimation of trajectory deviations

The next step is to calculate the vertical δ_v, cross-track δ_c and along-track δ_t deviations for each pair of trajectory points. If the $tp^A(x_{i,}y_i, z_i, t_i)$ is associated to the $tp^{P'}(x_{j,}y_j, z_i, t_i)$ then the vertical deviation is the difference of their altitude coordinates:

$$\delta_v = z_i - z_j \tag{6-15}$$

The cross-track deviation is defined by the distance between the actual and planned trajectory points considering one side of the planned segment course. Consequently, it is defined a planned trajectory segment $S^P = (tp_i(x_i, y_i, , z_i, t_i), tp_{i+1}(x_{i+1}, y_{i+1}, z_{i+1}, t_{i+1}))$ and the trajectory point $tp_j{}^A(x_j, y_j, z_j, t_j)$, the cross-track deviation is defined by:

$$\delta_c = \ d_{ij} \cdot \rho \tag{6-16}$$

where ρ is defined by the outer product of $\overrightarrow{tp_i{}^P tp_{i+1}{}^P} \times \overrightarrow{tp_i{}^P tp_j{}^A}$, as follows:

$$l = (x_j - x_i)(y_{i+1} - y_i) - (y_j - y_i)(x_{i+1} - x_i) \tag{6-17}$$

$$\rho = \begin{cases} 1 & if \quad l \geq 0 \\ -1 & if \quad l < 0 \end{cases} \tag{6-18}$$

The along-track deviation represents the time difference between the actual and the planned trajectory:

$$\delta_t = t_i - t_j \tag{6-19}$$

Once the along-track deviation is calculated for each element of the set P, the total trajectory along-track deviation is calculated as the sum of the along-track deviation values at each planned trajectory point:

$$\delta_{t_{total}} = \sum_{i=1}^{q} \delta_{t_i} \tag{6-20}$$

4D adherence by segment

Consider the point-to-point association process with three actual trajectories ($N = 3$) presented in the Figure 6-6. A total of 9 trajectory points (tp) that define the actual trajectories A_1, A_2 and A_3 are associated to trajectory points that define their planned trajectories P_1', P_2' and $P_3{}'$. These planned trajectories are all associated to a standard route (R).

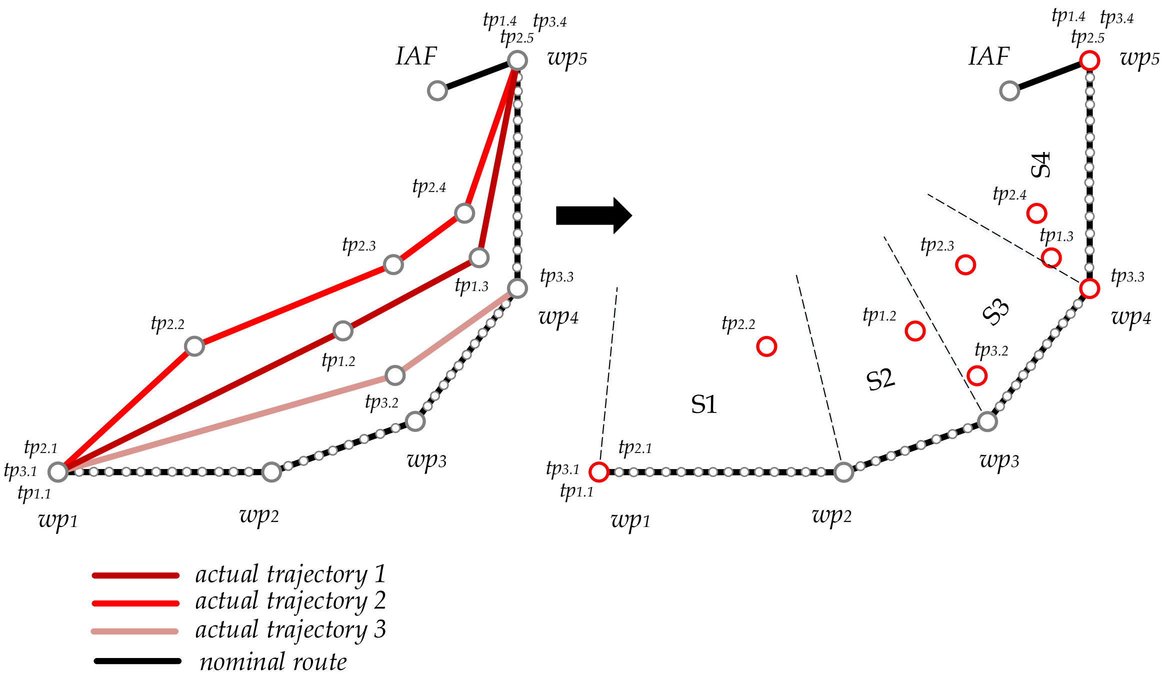

Figure 6-6: Trajectory points association process (*N*=3)

The vertical, cross-track and along-track deviation values can be grouped for each segment of their planned trajectory.

$$P_1 \begin{cases} \{tp_{1.1}\} \rightarrow S_1^{P_1} \\ \{tp_{1.2}\} \rightarrow S_2^{P_1} \\ \{\quad\} \rightarrow S_3^{P_1} \\ \{tp_{1.3}, tp_{1.4}\} \rightarrow S_4^{P_1} \end{cases} \quad P'_2 \begin{cases} \{tp_{2.1}, tp_{2.2}\} \rightarrow S_1^{P_2} \\ \{\quad\} \rightarrow S_2^{P_2} \\ \{tp_{2.3}\} \rightarrow S_3^{P_2} \\ \{tp_{2.4}, tp_{2.5}\} \rightarrow S_4^{P_2} \end{cases} \quad P_3 \begin{cases} \{tp_{3.1}\} \rightarrow S_1^{P_2} \\ \{\quad\} \rightarrow S_2^{P_2} \\ \{tp_{3.2}, tp_{3.3}\} \rightarrow S_3^{P_2} \\ \{tp_{3.4}\} \rightarrow S_4^{P_2} \end{cases}$$

given $\{tp_{1.1}, tp_{1.2}, tp_{1.3}, tp_{1.4}\} \in A_1$, $\{tp_{2.1}, tp_{2.2}, tp_{2.3}, tp_{2.4}, tp_{2.5}\} \in A_2$ and $\{tp_{3.1}, tp_{3.2}, tp_{3.3}, tp_{3.4}\} \in A_3$

Additionally, since each planned trajectory is mapped to a standard route, it is possible to associate the actual trajectory points to each segment of the standard route R:

$$R \begin{cases} \{tp_{1.1}, tp_{2.1}, tp_{2.2}, tp_{3.1}\} \rightarrow S_1^R \\ \{tp_{1.2}\} \rightarrow S_2^R \\ \{tp_{2.2}, tp_{3.2}, tp_{3.3}\} \rightarrow S_3^R \\ \{tp_{1.3}, tp_{1.4}, tp_{2.4}, tp_{3.4}, tp_{2.5}, tp_{3.4}\} \rightarrow S_4^R \end{cases} \tag{6-21}$$

Consider the trajectory point deviation as a variable defined by the vertical (δ_v), cross-track (δ_c) and along-track (δ_t) deviation components:

$$\delta^{tp} = (\delta_v, \delta_c, \delta_t) \tag{6-22}$$

Then, there are defined new sets to represent the deviation of each segment of the route R.

$$\delta^R \begin{cases} \delta^{S_1^R} = \{\delta^{tp_{1.1}}, \delta^{tp_{2.1}}, \delta^{tp_{2.2}}, \delta^{tp_{3.1}}\} \\ \delta^{S_2^R} = \{\delta^{tp_{1.2}}\} \\ \delta^{S_3^R} = \{\delta^{tp_{2.2}}, \delta^{tp_{3.2}}, \delta^{tp_{3.3}}\} \\ \delta^{S_4^R} = \{\delta^{tp_{1.3}}, \delta^{tp_{1.4}}, \delta^{tp_{2.4}}, \delta^{tp_{2.5}}, \delta^{tp_{3.4}}\} \end{cases} \tag{6-23}$$

Generally, the segment deviation is defined by three deviation set components. Each component is defined by the vertical, cross-track and along-track deviations of the trajectory points associated to the segment.

$$\delta^{S^R} \begin{cases} \delta_v{}^{S^R} = \{\delta_v{}^{tp_1}, \delta_v{}^{tp_2}, \delta_v{}^{tp_3} \ldots \delta_v{}^{tp_n}\} \\ \delta_c{}^{S^R} = \{\delta_c{}^{tp_1}, \delta_c{}^{tp_2}, \delta_c{}^{tp_3} \ldots \delta_c{}^{tp_n}\} \\ \delta_t{}^{S^R} = \{\delta_t{}^{tp_1}, \delta_t{}^{tp_2}, \delta_t{}^{tp_3} \ldots \delta_t{}^{tp_n}\} \end{cases} \tag{6-24}$$

Since the number of trajectory points associated with the standard route segments is proportional to the number of trajectories, a high number of trajectories provide enough information to study the deviation distribution for the standard routes.

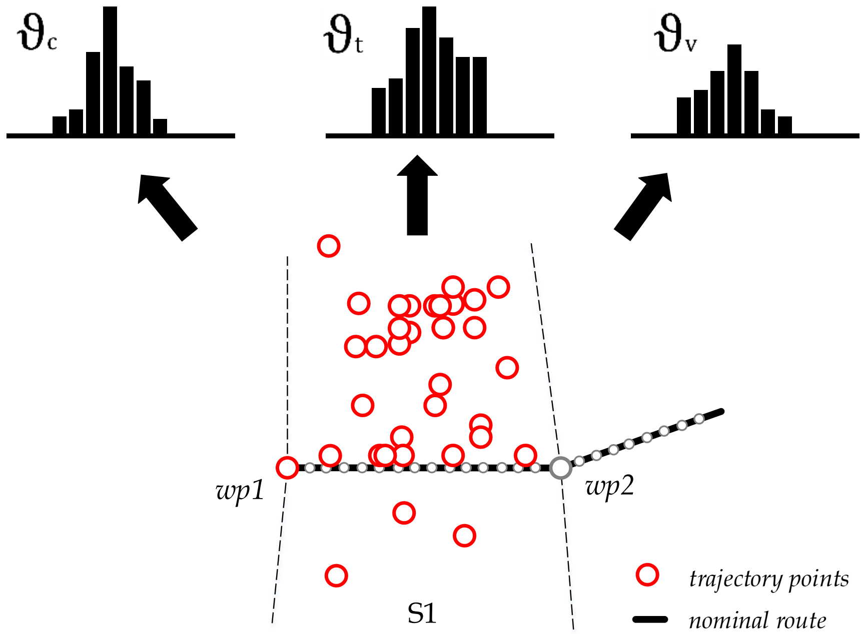

Figure 6-7: Trajectory deviation distribution

Consider δ' as one of the three (3) sets that compose the segment deviation (e.g. δ_v, δ_c or δ_t). It is defined a sample S_δ of values of δ'.

The goal is to collapse the range of δ' values to construct a histogram composed by uniformly distributed *k* bins (Scott, 1979). Therefore, it is defined a new discrete random variable ϑ and select $k-1$ edge values $\tau_1, \tau_2, \tau_3 \ldots \tau_{k-1}$, so that $\min(S_{\delta'}) < \tau_1 < \tau_2 \ldots < \tau_{k-1} \leq \max(S_{\delta'})$.

Hence, each value of the set δ' is mapped to one value of the set ϑ (Figure 6-7). The probability density function of ϑ is defined as:

$$f(\vartheta) = \sum_{i=1}^{k-1} p_i \, \Delta(\vartheta - \tau_i) \qquad (6\text{-}25)$$

where Δ is a dirac delta function (Dirac, 1981) and $p_1 \dots p_n$ are the probabilities associated to the edge values $\tau_1 \dots \tau_{k-1}$.

6.2.4 Determination of recurrent patterns

Having determined the traffic 4D deviation, the next step is to identify and analyze trajectory points with similar deviation values. This thesis proposes a clustering method based on the analysis of the local maximum/minimum values of ϑ. The concept is based on a similar approach used by the hierarchical clustering methodology to determine the peak values of the reachability distance distribution by the OPTICS clustering algorithm (Ankerst *et al.*, 1999).

The recurrent patterns identification is performed using two clustering layers. The first layer identifies subsets of trajectory points with similar *deviation values*. The second layer groups trajectory points that belong to the same trajectory and have similar *deviation gradients*. The Figure 6-8 presents the process for the determination of recurrent patterns.

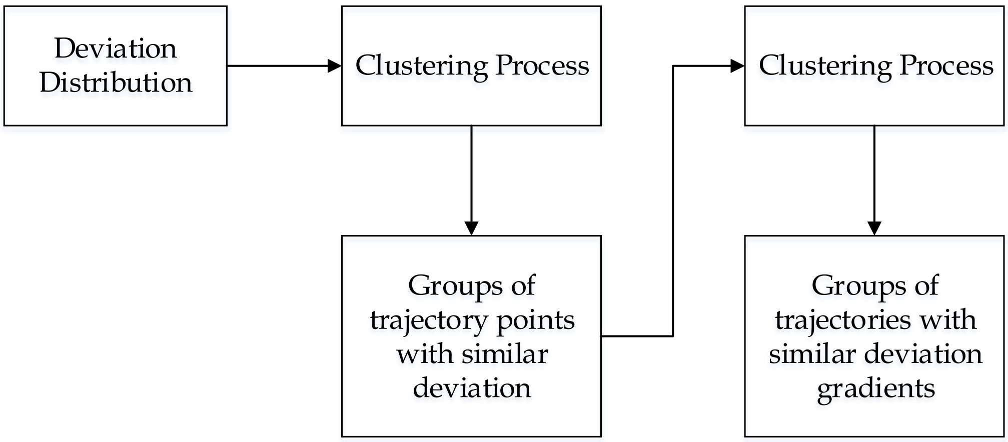

Figure 6-8: Clustering process to determine recurrent patterns

For the first clustering layer, consider the subsets $M = \{\vartheta_{M_1}, \vartheta_{M_2}, \vartheta_{M_3}, \dots \vartheta_{M_n}\}$ and $m = \{\vartheta_{m_1}, \vartheta_{m_2}, \vartheta_{m_3} \dots \vartheta_{m_n}\}$ as a set of deviation values so that $f(\vartheta_{m_i})$ is a local minimum and $f(\vartheta_{M_i})$ is a local maximum. If

$card(m) > 2$, then it is possible to define a subset of deviation values delimited by the interval G_i:

$$G_i = [\vartheta_{m_i}, \vartheta_{m_{i+1}}] \; \forall \; card(S) \; f(\vartheta_{M_i}) \geq T_{peak}: \vartheta_{m_i} < \vartheta_{M_i} < \vartheta_{m_{i+1}} \tag{6-26}$$

Consider the example of data represented by the Figure 6-9. Each subset G_i is represented by a local maximum (or peak) of the data distribution, greater than a T_{peak} and contained in an interval defined within two local minimum values (ϑ_{m_i} and $\vartheta_{m_{i+1}}$).

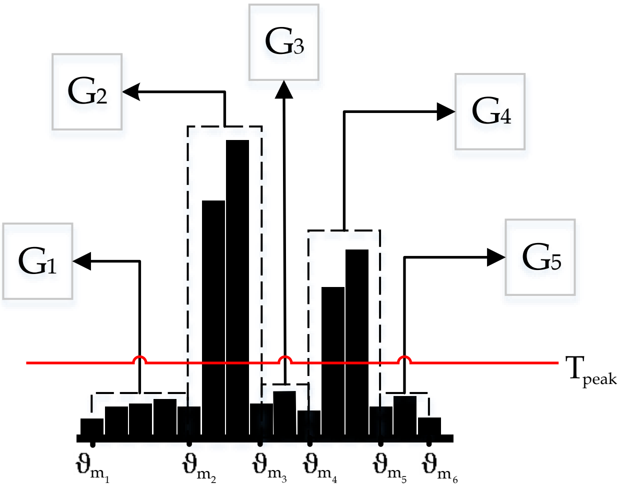

Figure 6-9: Grouping data distribution

It is possible to identify three (3) main subsets of trajectory points that could be defined by the following intervals:

$$\begin{aligned} G_1 &= \{\vartheta \mid \vartheta_{m_1} < \vartheta \leq \vartheta_{m_2}\} \\ G_2 &= \{\vartheta \mid \vartheta_{m_2} < \vartheta \leq \vartheta_{m_3}\} \\ G_3 &= \{\vartheta \mid \vartheta_{m_3} < \vartheta \leq \vartheta_{m_4}\} \\ G_4 &= \{\vartheta \mid \vartheta_{m_4} < \vartheta \leq \vartheta_{m_5}\} \\ G_5 &= \{\vartheta \mid \vartheta_{m_5} < \vartheta \leq \vartheta_{m_6}\} \end{aligned} \tag{6-27}$$

Considering that $\vartheta_{m_2} < 0 < \vartheta_{m_3}$, then, the subset G_2 is representing the trajectory points that adhered to the standard route segment. The subset G_4 represents a number of trajectory points that have a different deviation. The subsets G_1, G_3

and G_5 are discarded as the maximum number of trajectory points is below the threshold considered as T_{peak}.

The recurrent patterns are determined by grouping trajectories with similar deviation gradients. Note that each standard route segment could have points of the same trajectory associated to different deviation subsets. Therefore, a second clustering layer uses the groups identified in the first layer to identify trajectories that combine points located in different deviation groups (e.g. all the flights that in the given segment changed their cross-track deviation from a high-adherence subset G_2 to a low-adherence subset G_4).

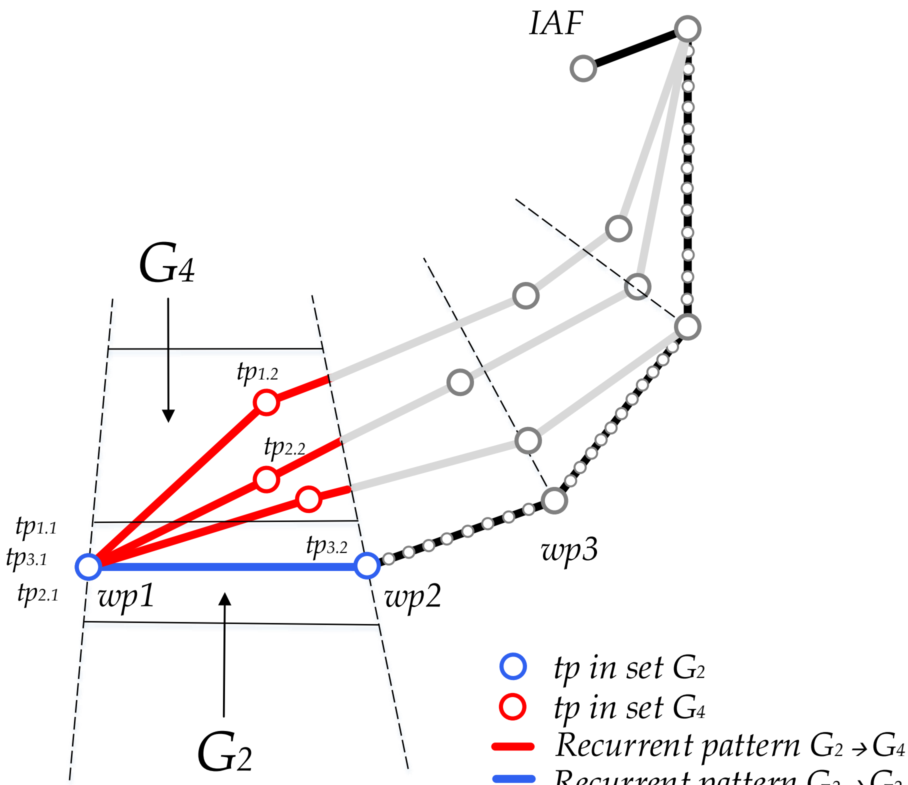

Figure 6-10: Trajectories Clustering

Figure 6-10 presents the case of a set of trajectories that have variable deviations along the same segment. Consider an actual trajectory $A = \{tp_1, tp_2, tp_3, \dots, tp_n\}$. The first trajectory points tp_1 and the second tp_2 have different cross-track deviations, which means that tp_1 is contained in the high-adherence subset G_2 and tp_2 in the low adherence subset G_4. A recurrent pattern is identified when a relevant number of trajectories follows the same *deviation pattern* (e.g. $G_2 \rightarrow G_4$).

The number of possible combinations depends on the trajectories characteristics, the deviation distribution and the amount of traffic associated to standard route. Table 6-1 presents some possible patterns for the segment $S^R = \{wp_1, wp_2\}$:

Table 6-1: Clusters and patterns for the segment $\boldsymbol{S^R}$

Cluster	Pattern	Description
$\boldsymbol{C_1}$	G_2	Trajectories that followed the standard route
$\boldsymbol{C_2}$	G_4	Trajectories parallel to the standard route
$\boldsymbol{C_3}$	$G_2 \rightarrow G_4$	Trajectories that started to deviate from the standard route
$\boldsymbol{C_4}$	$G_4 \rightarrow G_2$	Trajectories that are returning to the standard route

Therefore, in the example provided, there is a recurrent pattern (C_3) composed by three (3) trajectories that, for the first segment, have a sequence of trajectory points contained in the subset G_2 and the subset G_4.

It is assumed that recurrent patterns are usually deviations produced by vector clearances issued to stretch or shorten the aircraft trajectory. The reason to authorize or issue a *shortening vector* or a *direct-to clearance* is related to the safety and efficiency of the airspace. Therefore, it is assumed that there are two (2) main reasons associated to a loss of adherence produced by the ATCOs:

- The ATCOs prioritize the safety of the airspace users and reduces the chances of producing an eventual loss of separation minima by issuing a vector to an airspace user involved in a concurrence event.
- The ATCOs aims at improving the flow efficiency and issues a vector to an airspace user to shorten its trajectory. Sometimes, these actions could also be requested by the flight crew for flight efficiency (e.g. request a vector or change in the flight level).

The method could be adapted depending of the bin-width $(\tau_{i+1} - \tau_i)$, which represents operationally-relevant trajectory deviations and the threshold T_{peak}, which is linked to the probability that these deviations occur.

6.3 Concurrence events localization

In this section, it is estimated the reason behind a recurrent loss of adherence in a standard route. The methodology is composed by two steps presented in the Figure 6-11.

Firstly, it is defined a pseudo-planned trajectory resultant from shifting the flight plan according to the along-track deviation estimated in the section 6.2.3. Secondly, it is determined a set of concurrence events using a heuristic approach.

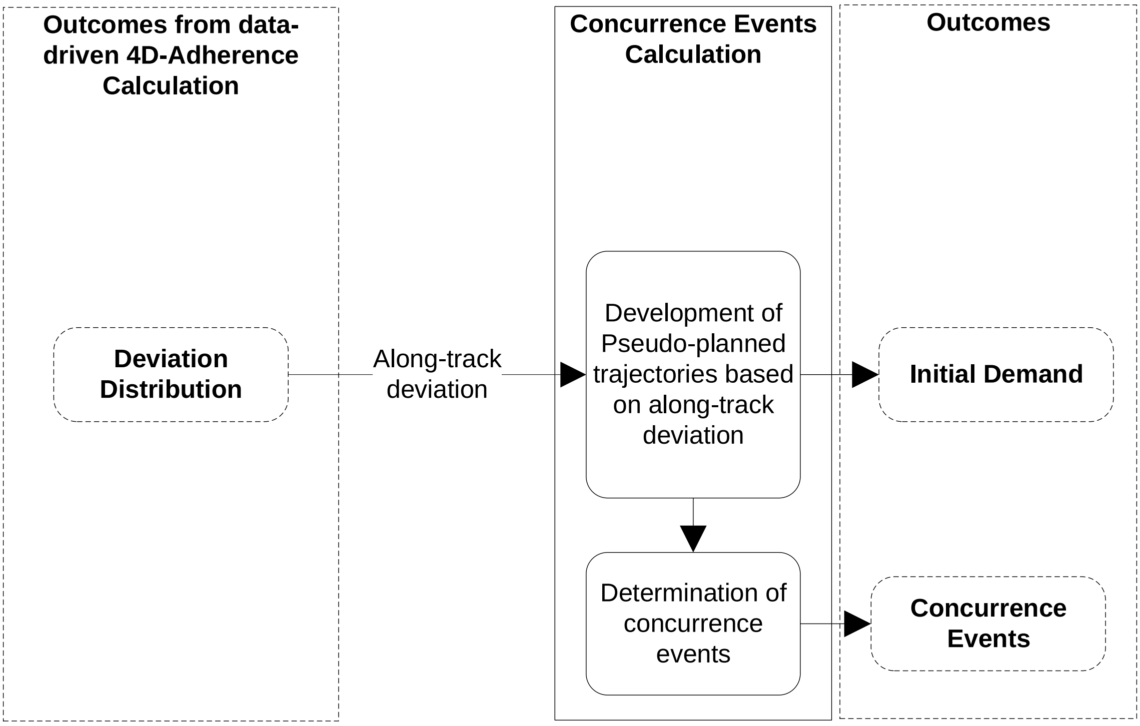

Figure 6-11: Methodology for detection of concurrence events

6.3.1 Definition of a concurrence event

Consider a pair of planned trajectories P_1 and P_2 associated to the standard routes R_1 and R_2, respectively.

A concurrence event occurs if there exists a pair of trajectory points $tp_1(x_1, y_1, z_1, t_1) \in P_1$ and $tp_2(x_2, y_2, z_2, t_2) \in P_2$ so that the following minimum conditions are met:

$|z_2 - z_1| \leq Q_z$ Vertical separation minima condition (C_z) (6-28)

$d_{12} \leq Q_d$ Horizontal separation minima condition (C_d) (6-29)

$|t_2 - t_1| \leq Q_t$ Time separation minima condition (C_t) (6-30)

The distances Q_z and Q_d are separation minima values associated to the terminal airspace. The coefficient Q_t represents the minimal time interval required to define a concurrence event and d_{12} is the great-circle distance between the trajectory points tp_1 and tp_2.

6.3.2 Pseudo-planned trajectory based on the along-track deviation

The trajectory information composed by planned and actual trajectories represents both; the intentions of the airspace users and a track of the actual path followed by the aircraft, respectively. In terminal airspace, the ATCOs input the main source of changes/deviations in the aircraft trajectory. The actual trajectory includes implicit information of the effects produced by tactical ATC interventions, weather conditions, or other decisions taken by the crew. This change is traduced in a difference with respect to the planned trajectory.

Consider the trajectories P_1' and $P_2{}'$ represented in the Figure 6-12. A concurrent event occurs when a pair of trajectories reduces their 4D separation below a minimum defined criteria. If the time of one of the flights is shifted, the concurrent event may be removed. Hence, it could be stated that, if the spatial components are fixed according to the original flight plan, then the existence of a concurrent event is mainly dependent on the temporal component.

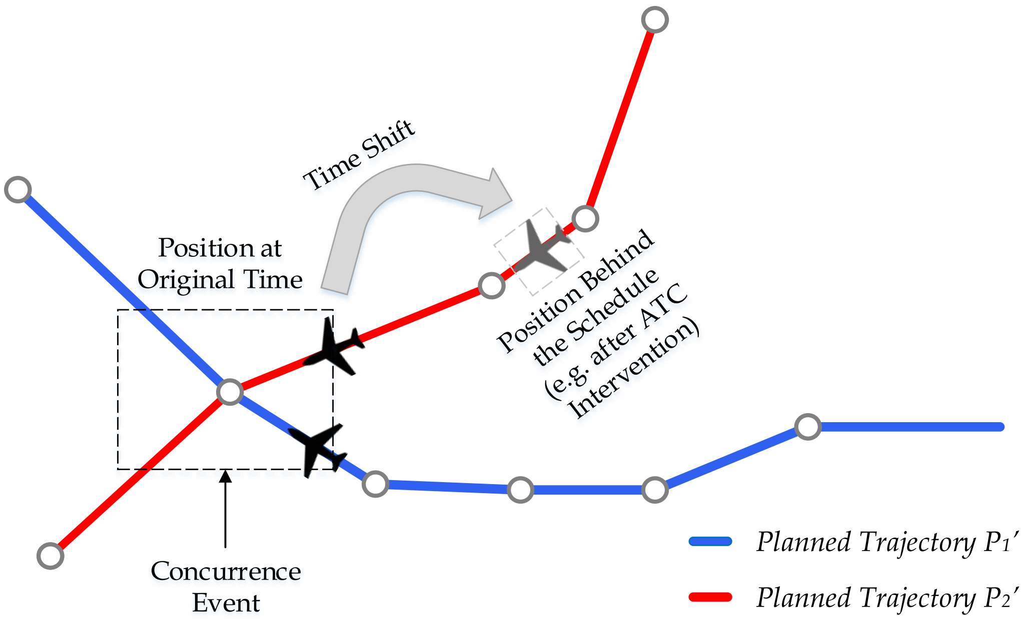

Figure 6-12: Concurrence event and trajectory time-shift event

The method proposes the use of a pseudo-planned trajectory, resultant of shifting the temporal component of the planned trajectory according to the along-track deviation ϑ_{t_1} at the time the flight entered to the terminal airspace (first trajectory point). The goal is to represent the initial conditions of the traffic before the temporal displacement that caused the loss of adherence.

6.3.3 Heuristic method for concurrence events identification

It is proposed a generic method to identify those trajectory points that meet the conditions denoted in the Equation (6-28) and Equation (6-29).

Consider a set of trajectories $P = \{P_1, P_2 \dots P_n\}$ as the sample of planned trajectories. The method for concurrence events calculation is composed of three steps:

- **Pre-processing:** This process prepares the trajectories structure for the algorithm application. It estimates new pseudo-planned trajectories shifted in time according to the along-track deviation of the first trajectory point.
- **Filtering:** For each trajectory in the sample P, it is obtained the time of its first trajectory point as a reference to filter the other trajectories of the sample. This process ensures that each trajectory is compared with only

those trajectories that have similar timestamps. Therefore, for each trajectory of the group P there exists a subset F that contains trajectories so that $|t_1^F - t_1^P| \leq AVG_t$, where AVG_t is the average time of a flight in the terminal manoeuvring area.

- **Searching:** for each trajectory of the subset F, it is compared point by point so that the conditions C_d, C_z and C_t are met. The duplicated events involving the same trajectories in the same points are discarded.

The steps 2 and 3 are repeated for each trajectory interdependence point estimated in the TMA. The result is a set of concurrence events that are then counted to determine *hotspots*. The term "*hotspot*" refers to those areas where recurrent concurrence events are localized and produce changes in the aircraft trajectory.

The main objective of determining concurrence events is to perform a temporal analysis of the recurrent patterns identified in the previous sections by comparing the demand conditions of the system with the number of concurrence events detected.

The following chapter presents a study case in which the current methodology has been implemented in a generic methodological framework and applied to a representative multi-airport system. The study case details the performance of aircraft trajectories in two standard routes of the London terminal airspace by determining high-adherence and low-adherence recurrent patterns. Additionally, it presents a temporal analysis that determines the traffic demand conditions when the recurrent patterns are produced.

7 Case of Study: Analysis of London TMA

The previous chapter proposed a methodology to identify recurrent patterns and concurrence events with the objective to carry out a diagnosis of a MAS-TMA operations. The use of high-adherence routes and recurrent patterns is suggested to reduce the uncertainties produced *after take-off* and to improve the effectiveness of the STAM operations.

In this context, the proposed methodology has been used to implement a *generic framework* that analyzes the MAS-TMA performance. The methodology has been decomposed in ten (10) steps that are structured as follows:

- **Data processing:** the first phases of the framework focus on processing the standard routes and trajectories data. Additionally, it is identified the intersection points that represent the 2D interdependences of the standard routes. A summary of the data processing phases is presented in the Table 7-1.
- **Adherence and concurrence events estimation**: the adherence and concurrence events calculation methodology described in the sections 6.2 and 6.3, respectively, have been implemented in the last phases of the framework. A summary of these phases is presented in Table 7-2.

Subsequently, the developed framework has been tested by carrying out a case of study of the London Terminal Manoeuvring Area (LTMA). This chapter presents an analysis that focuses on estimating the traffic adherence, recurrent patterns and concurrence events of the London's terminal airspace.

The section 7.1 provides a description of the used data and technical aspects of the study case. Then, it is presented the identification of the LTMA 2D interdependences (section 7.2). Section 7.3 focuses on estimating the 4D adherence and recurrent patterns of two selected routes of the LTMA. Lastly, an analysis of the causes of the deviations (based on the analysis of concurrence events) is presented in the section 7.4.

Table 7-1: Framework structure (data processing phases)

	Phase	Description	Main Output
Data Processing	Initial	Reads the initialization variables. Obtains the airport coordinates.	Airports waypoint coordinates
	Phase I	Identifies the SID/STAR ARINC-424 entries of the selected airports and extract the waypoints and navaids involved as well as their sequence.	SID/STAR entries
	Phase II	Obtains the coordinates of the waypoints involved in the identified SID/STAR procedures of the previous phase.	SID/STAR waypoint coordinates
	Phase III	Creates the leg structure for the STAR/SID and plots the procedures in a figure.	Leg data structures for SID/STARs
	Phase IV	Calculates the intersection points between all the SID/STARs and produces a set of interdependencies matrices.	Interdependency matrices and intersection points.
	Phase V	Groups the standard routes by nominal flows for further understanding of the operations.	SID/STAR nominal flows

Table 7-2: Framework structure (adherence and concurrence events calculation phases)

	Phase	Description	Main Output
Adherence	Phase VI	Maps planned trajectories to standard routes, calculates along-track, cross-track, vertical and total along-track deviations.	Facts table with deviations and associated standard routes.
	Phase VII	Calculates the 4D adherence to each segment of the standard routes.	Adherence distributions for each segment
	Phase VIII	Calculates the most recurrent traffic patterns by clustering the cross-track deviation distributions.	Recurrent patterns grouped by the cluster of trajectories
Hotspot	Phase IX	Creates pseudo-planned trajectories shifted in time and search for concurrence events.	Concurrence Events
	Phase X	Filters the trajectory clusters and concurrence events for a given segment/route.	Demand, Concurrence Events, Clusters per segment.

7.1 Data description

The data required for the application of the framework includes historical traffic data composed by planned and actual trajectories limited to inbound and outbound traffic to/from the five (5) major airports of the LTMA: Heathrow (EGLL), Gatwick (EGGW), Stansted (EGSS), Luton (EGGW) and City (EGLC). Each trajectory is defined in terms of 4D trajectory points $tp(x, y, z, t)$. Figure 7-1 shows the location of the main airports and IAFs of LTMA (NATS, 2017a).

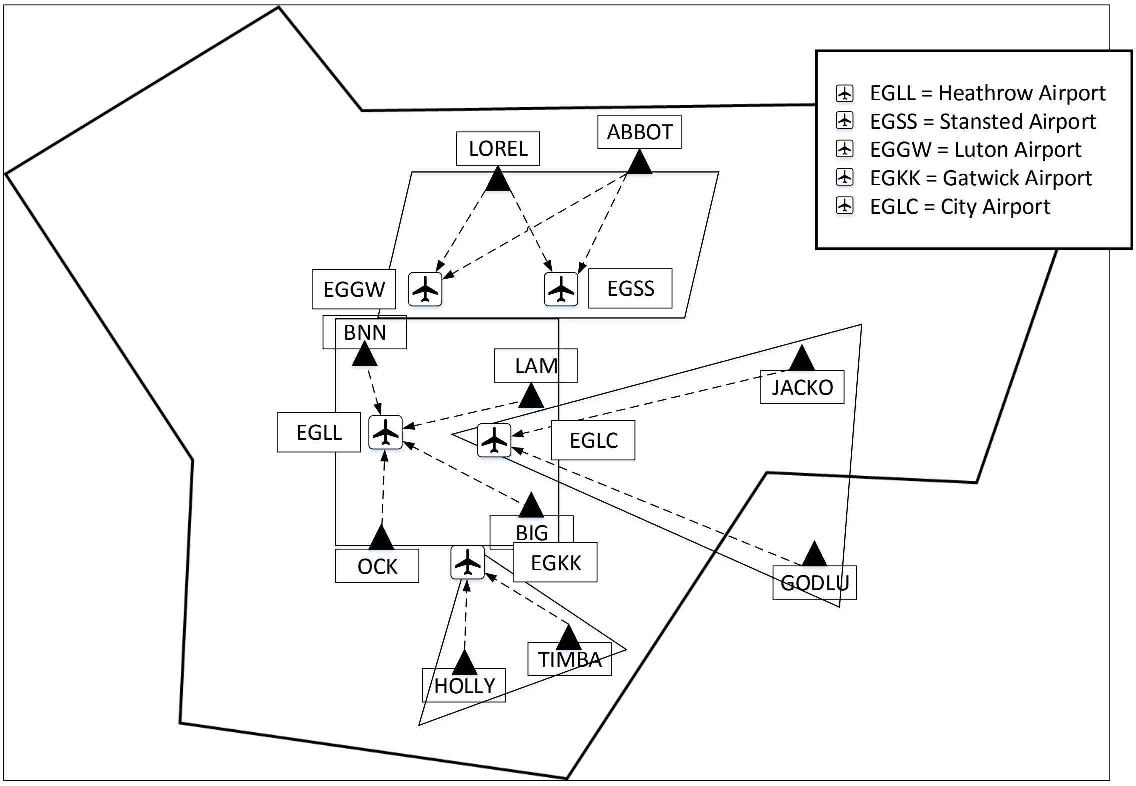

Figure 7-1: Main airports and IAFs the London MAS

The standard routes are populated with real traffic data, which is composed by a total of 53.066 trajectories that belong to the 7th AIRAC, 2017 (Jun 22nd to Jul 10th). The sample has been obtained to maintain a balance between the amounts of data required for the analysis and the available performance resources provided by the hardware used for the tests (CPU at 3.40 GHz / 32GB RAM).

Furthermore, the sample trajectories have been limited to those waypoints inside the LTMA. It has been used the coordinates of Heathrow airport as a reference central point (lat: 51.4775, lon: -0.461389). The flight data tracks are sampled using the DDR2 format, which is detailed in (Eurocontrol, 2018a). Each track point has been recorded based on events that denote *significant changes on the aircraft dynamics* (e.g. a point is tracked when a significant change in the speed, heading or altitude of the aircraft is produced).

Additionally, it has been obtained the standard routes information (waypoints, legs and route names) from ARINC-424 format database that contains a total of 163 arrival procedures (STARs) and 128 (SIDs) departure procedures to/from the five major airports of the London TMA. In normal daily operations, the number of used standard routes depends on the active runway, the navaids availability and the traffic conditions.

7.2 Identification of 2D interdependencies

The standard routes of the airports Luton and Stansted create a cluster of similar trajectories directed to the same IAFs: LOREL/ASKEY and ABBOT/CASEY.

The LTMA main flow distribution is represented by a large number of Type I interdependences between Stansted/Luton and Heathrow, which means that the traffic in the south-north direction is crossing the terminal airspace over Heathrow airport.

Few interdependences exist between Gatwick (located at the south) and the north cluster, and only visible in a few routes associated to the traffic crossing the TMA in the north direction.

The traffic to City airport arrives from the north/south edges and then it is directed to the airport. A large number of Type II interdependences between City and the north airport cluster evidences that the north/west routes are partially merged with Stansted/Luton routes.

The Figure 7-2 presents the location of the interdependences identified in the analysis and provide the first picture of the location of concurrence events. The blue dots represent merging points, and most of them coincide with the geographical location of the EP/IAFs and holding procedures.

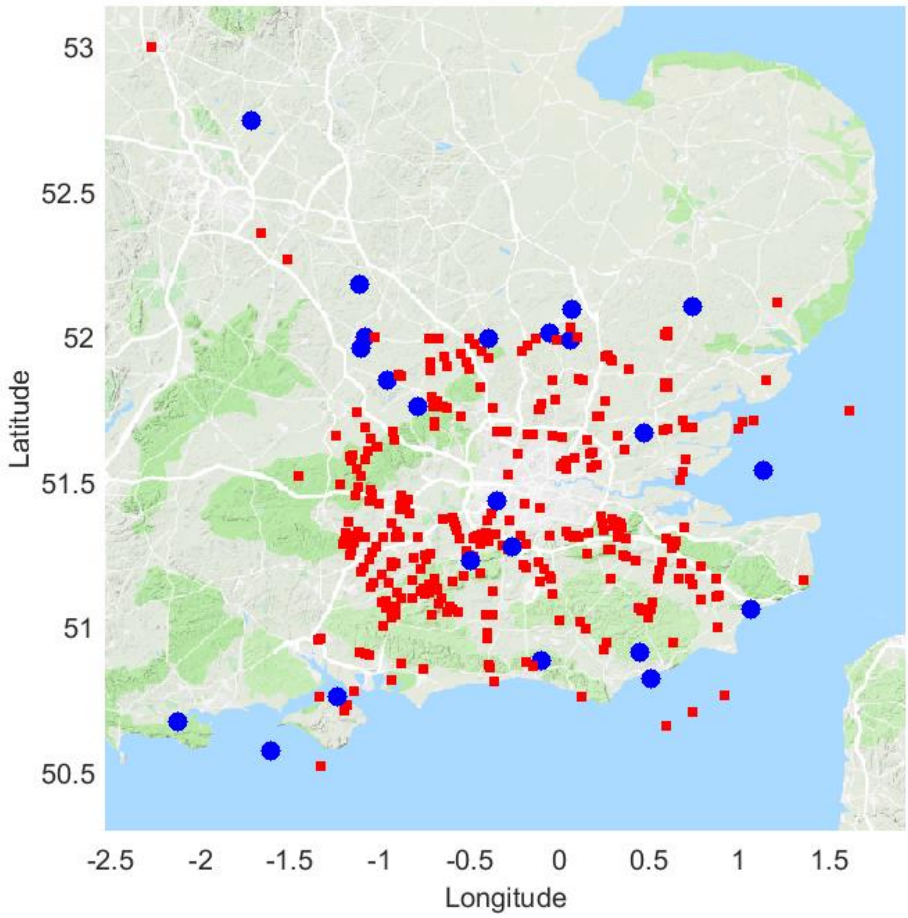

Figure 7-2: Location of standard routes interdependences

7.3 Estimation of 4D adherence and recurrent patterns

A systematic and regular behavior of the system contributes to improving the ATFCM tasks performed at strategic/pre-tactical level. dDCB/STAM are process based on predicted trajectories, which in most of the cases are represented by their flight plan.

A key outcome of this thesis is the capacity to identify, characterize and group those standard routes that are known for having recurrent traffic patterns. At this end, particular interest is given to two different types of routes. Firstly, high-adherence standard routes that are characterized by recurrent traffic patterns with a low cross-track deviation. These routes represent regular traffic that could be highly predicted based on their original flight plan. Secondly, low-adherence standard routes that could contain secondary traffic patterns. These routes represent a systematic behavior although it is not adherent to the standard route.

This behavior could be predicted once identified the situations (why/when) that produced the secondary recurrent patterns.

A point-to-point association is carried out in order to identify the high-demand standard routes. The result shows that the sampled planned trajectories are associated to a total of 45 STARs and 54 SIDs. The Table 7-3 shows the standard routes, the number of actual trajectories and the percentage of traffic associated to each outbound and inbound standard route, respectively.

Table 7-3: High-demand standard routes

Airport	SID	Flights	Percentage (%)
EGLL	'DET2F'	2792	10.5
EGLL	'BPK7F'	2488	9.4
EGSS	'CLN1E'	2037	7.7
EGKK	'CLN8M'	1789	6.7
EGGW	'MATC1B'	1579	5.9
EGLL	'CPT3F'	1482	5.6
EGKK	'SAM1X'	1417	5.3
EGLL	'WOBU3F'	1395	5.2
EGSS	'CPT4R'	1206	4.5
EGGW	'CPT3B'	1125	4.2
EGKK	'BOGN1M'	870	5.0

Airport	STAR	Flights	Percentage (%)
EGLL	'LAM3A'	4693	17.7
EGLL	'BIG3B'	1809	8.6
EGKK	'WILO3D'	1796	6.8
NC	'LORE4C'	1533	6.7
EGLL	'BNN1B'	1441	5.7
EGKK	'LUMB2F'	1218	5.4
NC	'ASKE3G'	948	4.5
NC	'LORE4Q'	880	3.5
EGKK	'ASTR4C'	868	3.3
EGLL	'OCK4B'	740	3.2
EGKK	'WILO3B'	699	2.7

7.3.1 Adherence analysis of the standard route "LAM3A"

It is selected a significant example that shows the arrival route "*LAM3A*", which comprises the 17.7% of the inbound sampled traffic (4693 flights). The standard route directs the arrival traffic from the Central/East Europe and Asia towards Heathrow airport. It is composed by the waypoints *TRIPO*, *SABER*, *BRASO* and *LAM*. The Figure 7-3 shows the planned trajectories associated with the standard route. The Figure 7-4 shows the distribution of actual trajectories for the traffic sample. The transparency factor (MATLAB, 2018) used to produce the figure, emphasizes the density of the patterns that contains more trajectories.

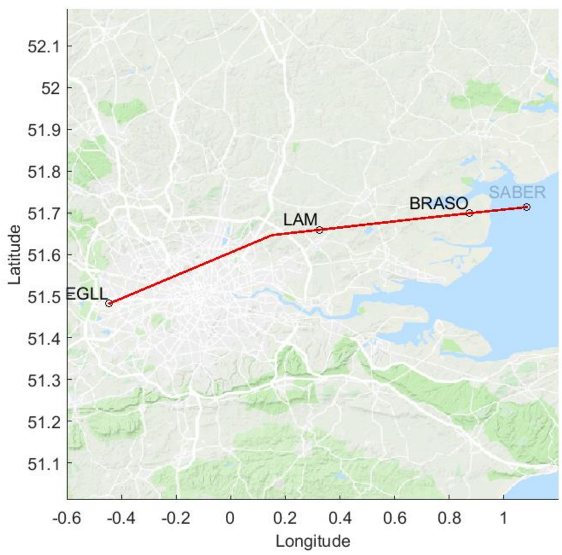

Figure 7-3: Planned Trajectories (*LAM3A*)

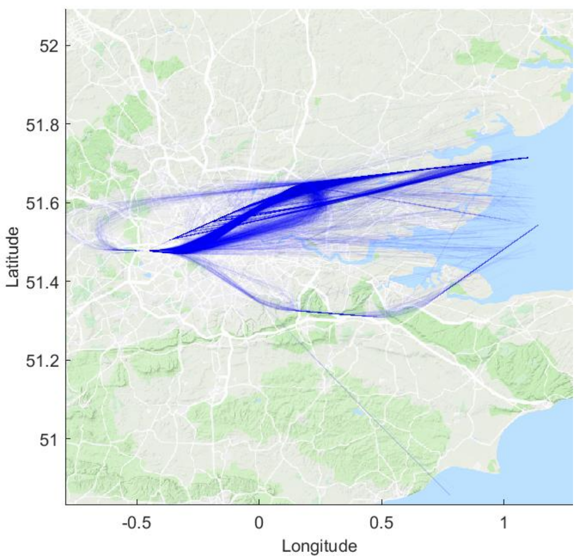

Figure 7-4: Actual Trajectories (*LAM3A*)

The adherence analysis resulted in the estimation of the cross-track, along-track and vertical deviation for *LAM3A*, presented in the Figure 7-5, Figure 7-6 and Figure 7-7, respectively. A logarithmic scale has been used. The horizontal profile indicates that there exist a high-adherence to the standard route with cross-track deviations below ±2NM in most of the cases. There exist lower-demand secondary recurrent patterns determined by the peaks ($\vartheta_c = -15NM$) observed in the segment $S_2^{LAM3A} = \{SABER, BRASO\}$. The cross-track deviation is more distributed in the segment $S_3^{LAM3A} = \{BRASO, LAM\}$ driven by the holding pattern that exists in the last waypoint.

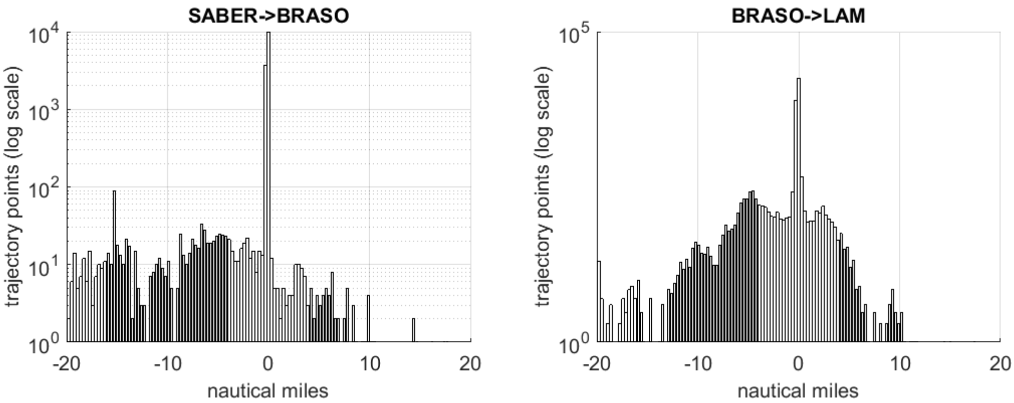

Figure 7-5: Cross-track deviation distribution ($\boldsymbol{\vartheta}_c$)

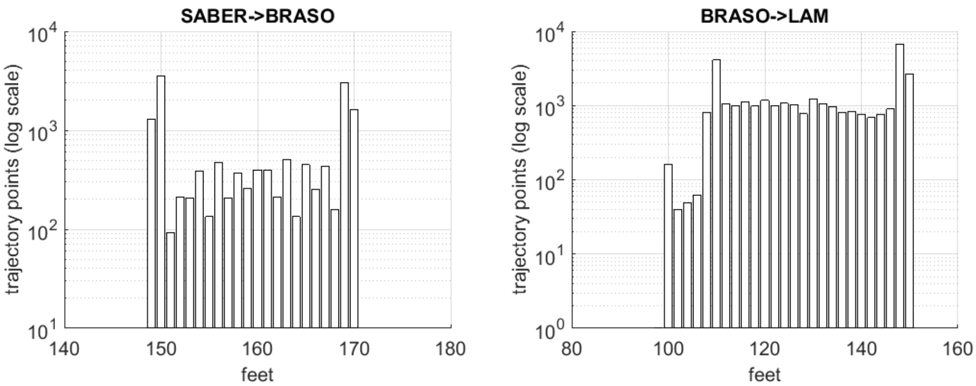

Figure 7-6: Vertical deviation distribution ($\boldsymbol{\vartheta}_v$)

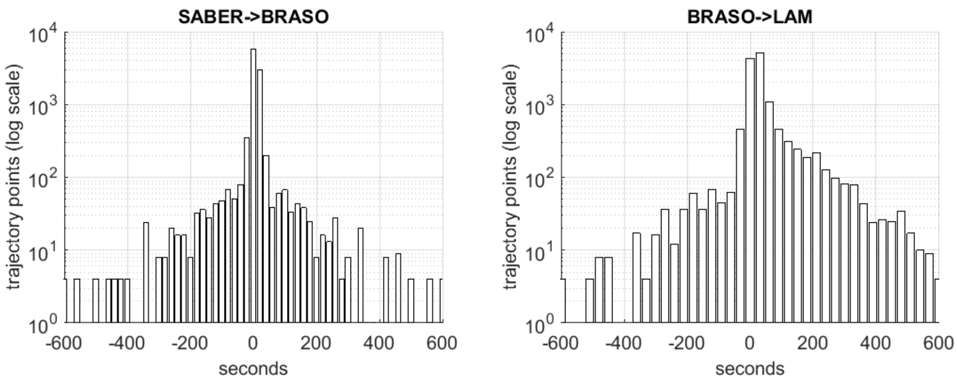

Figure 7-7: Along-track deviation distribution ($\boldsymbol{\vartheta}_t$)

The vertical profile distribution shows deviations within the intervals denoted by the planned flight levels. It can be observed highly distributed vertical deviations (within the flight plan altitude levels) in the segment $S_3^{LAM3A} = \{BRASO, LAM\}$. In this case, the traffic is directed to the LAM holding pattern at FL100 before descending to EGLL. Additionally, the effects of the holding pattern are observed in the along-track deviation. It is observed an increase in the along-track deviation that indicates the traffic experiences a bottle-neck effect.

The analysis applied to the LTMA determined other high-adherence standard routes with results similar to the example provided. The Table 7-4 presents the high-adherence standard routes of the LTMA. The total route adherence level has been measured as the average of traffic associated with the high-adherence clusters of each segment of the route.

Table 7-4: High-Adherence Standard routes

Type	Route	Segments	Adherence (avg %)	Notes
SID	‘CPT3F’	4	97.2	
STAR	‘BNN1B’	3	97	
STAR	'BIG3B'	3	96	
STAR	‘OCK4B’	3	93.3	
SID	‘CLN1E’	4	91.8	
SID	‘BPK7F’	7	90.6	Until BPK
STAR	‘LAM3A’	3	88.6	
SID	‘SAM1X’	4	84.2	

7.3.2 Adherence analysis of the standard route "LORE4Q"

It is selected another example that shows the arrival route "*LORE4Q*", which comprises 880 flights of the inbound sampled traffic. The standard route directs the arrival traffic from the British-Spanish routes (BRESP) to the Northern airports (Luton & Stansted). *LORE4Q* is composed by the waypoints UNDUG, MAY, VATON, *3OCK, BPK, BKY, BUSTA, and LOREL. The Figure 7-8 and Figure 7-9 show the planned and actual trajectories for the sampled traffic, respectively.

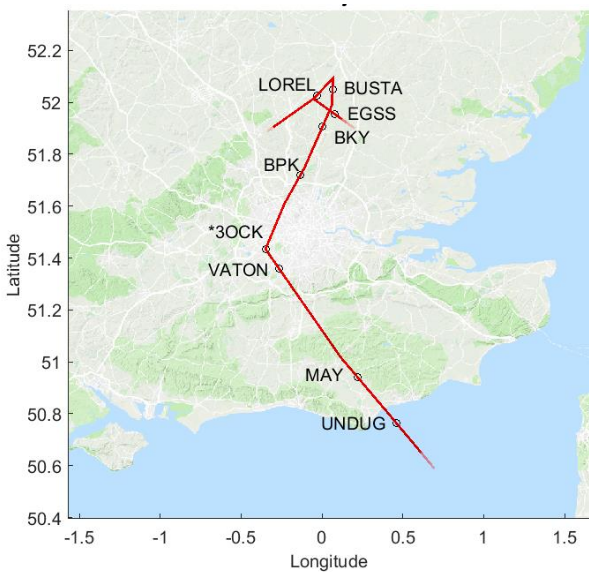

Figure 7-8: Planned Trajectories (*LORE4Q*)

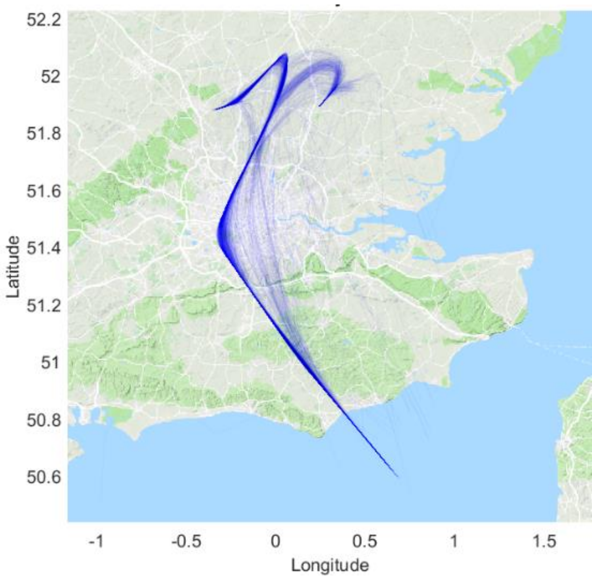

Figure 7-9: Actual Trajectories (*LORE4Q*)

The lower horizontal adherence for *LORE4Q* is supported by the set of trajectories diverged to the right side of the route and a clearly defined cross-track deviation that initiates in the segment $S_2^{LORE4Q} = \{MAY, VATON\}$. Figure 7-10 presents the cross-track distribution for the selected route. There exist segments of the route that are determined by a high-adherence (e.g. $S_1^{LORE4Q} = \{UNDUG, MAY\}$), but in general, there exists an important number of trajectory points with a cross-track deviation greater than ±2NM.

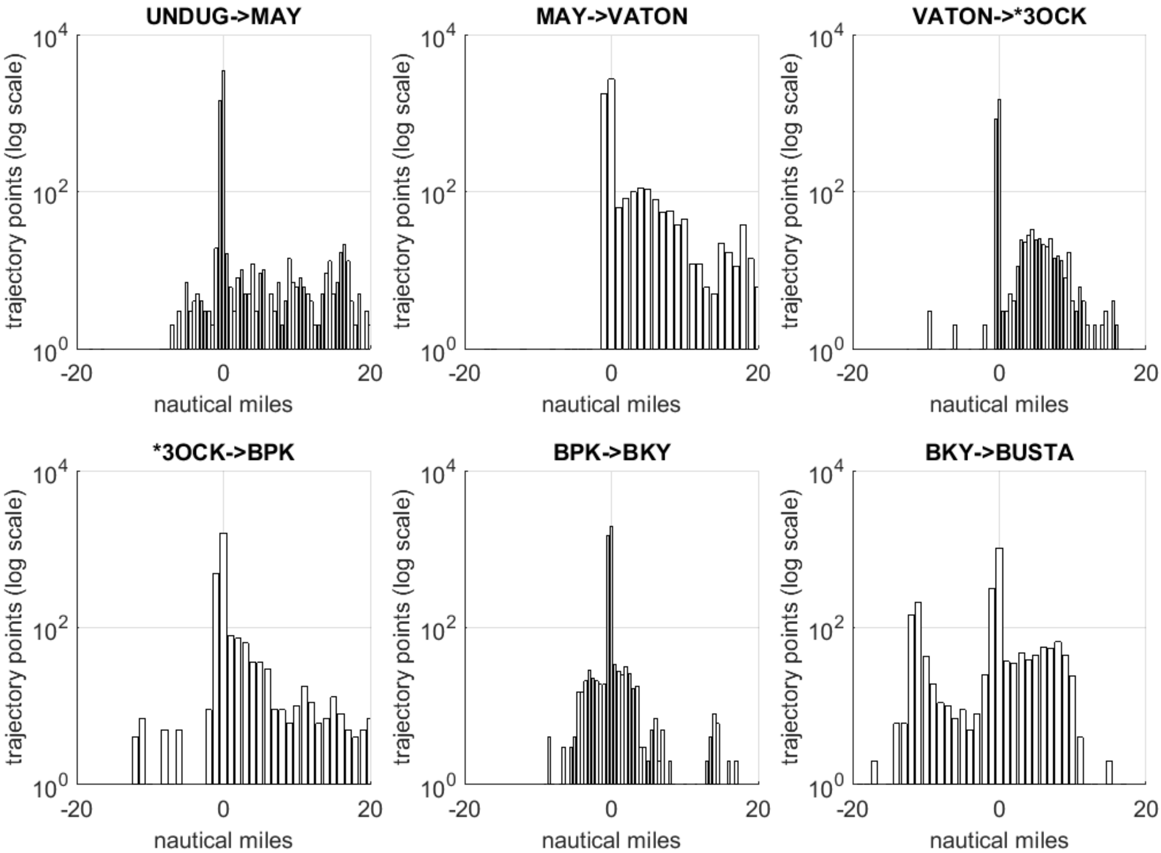

Figure 7-10: Cross-track deviation ($\boldsymbol{\vartheta_c}$)

7.3.3 Determination of recurrent traffic patterns

The clustering algorithm was applied to the cross-track deviation (ϑ_c) distribution data of *LAM3A* and *LORE4Q* samples to determine the existence of recurrent patterns. The number of clusters identified depends on the T_{peak} parameter and the bin-width ($\tau_{i+1} - \tau_i$). For this example, it is adjusted the threshold to consider local maximums (peaks) that are greater or equal to the 1% of the total trajectory points associated to the standard route. Additionally, a minimum value condition $T_{peak} = 50$ was added to those cases with a reduced number of trajectory points associated (filter for low traffic demand patterns). The bin-width has been empirically adjusted depending on the deviation distribution to consider only high-predictable recurrent patterns.

The Table 7-5 shows the results of the clustering process applied to the selected high-adherence route (*LAM3A*). It is determined that most of the trajectories have a high-adherence to the standard route.

Table 7-5: Results of Clustering process (*LAM3A*)

Segment	∂_c Sets (NM)	Mode (*tp*)	Clusters	Flights
$\boldsymbol{TRIPO \rightarrow SABER}$	$G_1 = [-0.9, 0.3]$	$G_1 = 7338$	$C_1 = \{G_1\}$	$C_1 =$ 4149 (88.4%)
$\boldsymbol{SABER \rightarrow BRASO}$	$G_1 = [-17, -14]$ $G_2 = [-0.9, 0.3]$	$G_1 = 88$ $G_2 = 9941$	$C_1 = \{G_2\}$ $C_2 = \{G_1\}$	$C_1 =$ 4168 (88.8%) $C_2 =$ 63 (1.3%)
$\boldsymbol{BRASO \rightarrow LAM}$	-	-	-	-

The framework detected an additional low-demand (1.4%) secondary recurrent pattern in the segment S_2^{LAM3A}. The remaining trajectories (~10%) represent low-demand traffic with more distributed cross-track deviation.

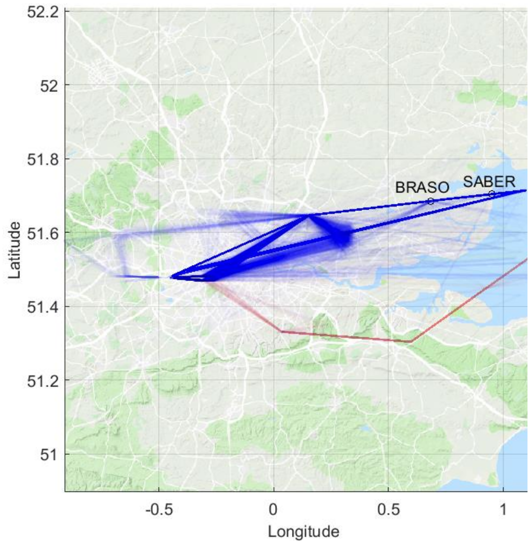

Figure 7-11: Recurrent patterns ($\boldsymbol{S_2^{LAM3A}}$)

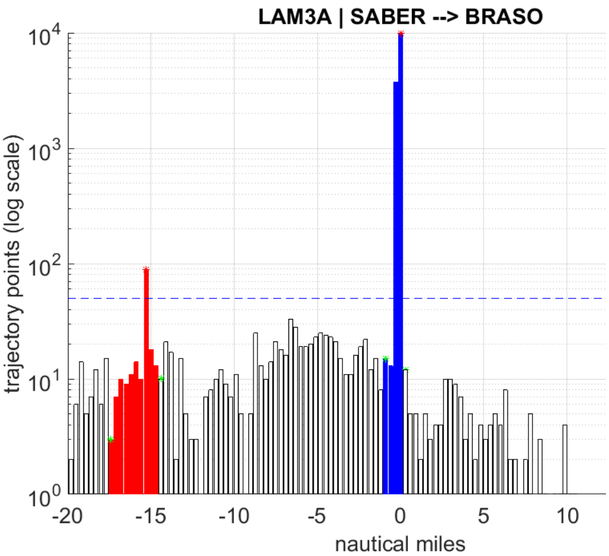

Figure 7-12: Deviation Groups ($\boldsymbol{S_2^{LAM3A}}$)

The Figure 7-12 shows the results obtained by the clustering method for the segment S_2^{LAM3A}. The Figure 7-11 presents two recurrent patterns with different cross-track deviations.

The Table 7-6 shows the results of the clustering process applied to *LORE4Q*. The 15.7% of the traffic associated to the recurrent patterns C_2 and C_3 of the segment $S_2^{LORE4Q} = \{MAY, VATON\}$ are directed to BPK (Figure 7-14). The C_2 trajectories are directed before intercepting *MAY*, while the trajectories associated to C_3 initiates their path to BPK while intercepting MAY (Figure 7-13).

Table 7-6: Results of Clustering process (*LORE4Q*)

Segment	∂_c Sets (NM)	Count (*tp*)	Clusters	Flights
$\boldsymbol{UNDUG \rightarrow MAY}$	$G_1 = [-1.5, 1.5]$	$G_1 = 3484$	$C_1 = \{G_1\}$	$C_1 =$ 836 (95%)
$\boldsymbol{MAY \rightarrow VATON}$	$G_1 = [-3, 1]$ $G_2 = [1, 9]$	$G_1 = 2691$ $G_2 = 111$	$C_1 = \{G_1\}$ $C_2 = \{G_2\}$ $C_3 = \{G_1G_2\}$	$C_1 =$ 690 (78.4%) $C_2 =$ 110 (12.5%) $C_3 =$ 28 (3.2%)
$\boldsymbol{VATON \rightarrow 3OCK}$	$G_1 = [-1.5, 0.5]$	$G_1 = 1480$	$C_1 = \{G_1\}$	$C_1 =$ 701 (79.6%)
$\boldsymbol{3OCK \rightarrow BPK}$	$G_1 = [-5, 9]$	$G_1 = 1607$	$C_1 = \{G_1\}$	$C_1 =$ 827 (93.9%)
$\boldsymbol{BPK \rightarrow BKY}$	$G_1 = [-1.5, 1.5]$	$G_1 = 1975$	$C_1 = \{G_1\}$	$C_1 =$ 783 (88.9%)
$\boldsymbol{BKY \rightarrow BUSTA}$	$G_1 = [-14, -4]$ $G_2 = [-4, 2]$ $G_3 = [4, 9]$	$G_1 = 210$ $G_2 = 1041$ $G_3 = 66$	$C_1 = \{G_2\}$ $C_2 = \{G_3G_1\}$ $C_3 = \{G_2G_3G_1\}$ $C_4 = \{G_1\}$ $C_4 = \{G_2G_1\}$	$C_1 =$ 441 (50.1%) $C_2 =$ 113 (12.8%) $C_3 =$ 42 (4.7%) $C_4 =$ 38 (4.3%) $C_5 =$ 29 (3.3%)
$\boldsymbol{BUSTA \rightarrow LOREL}$	-	-	-	-

The lack of adherence is supported by a reduction of the number of trajectories associated to the high-adherence recurrent pattern (C_1) in the segment $S_3^{LORE4Q} = \{VATON, 3OCK\}$, which represents the 79.6% of the associated trajectories. The Figure 7-15 shows a secondary traffic pattern located below the threshold that represents the remaining 20.4% of trajectories of the segment. It can be observed that these trajectories present a more distributed cross-track deviation that reduces the counts' peaks below the selected threshold ($T_{peak} = 50$). This effect indicates that the method is sensitive to the deviation distribution and the T_{peak} threshold.

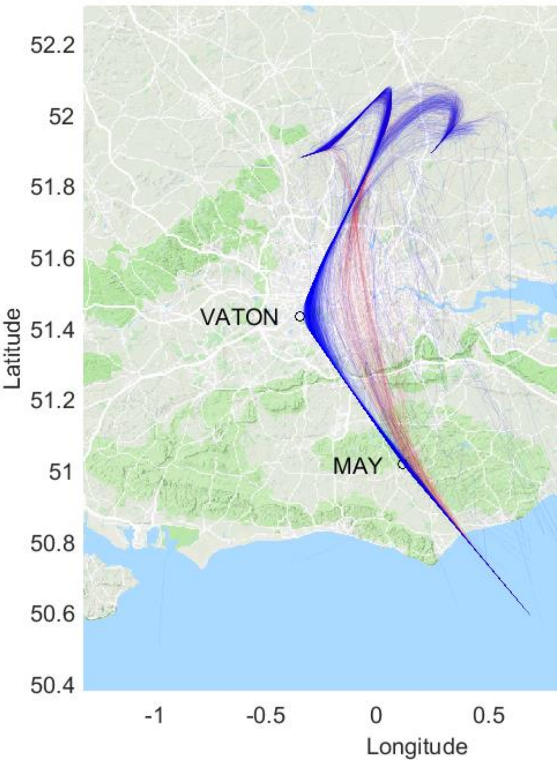

Figure 7-13: Recurrent patterns (S_2^{LORE4Q})

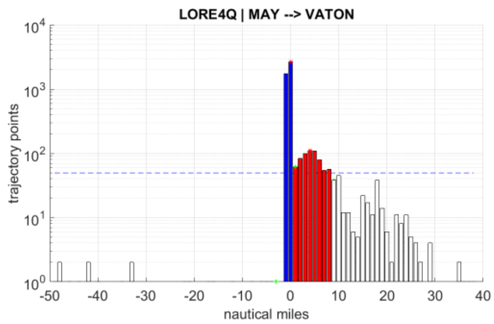

Figure 7-14: Clustering (S_2^{LORE4Q})

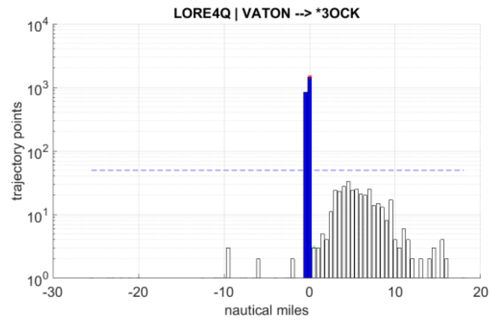

Figure 7-15: Clustering (S_3^{LORE4Q})

The analysis applied to the LTMA determined other low-adherence standard routes with defined secondary traffic patterns. The Table 7-7 presents the low-adherence standard routes of the LTMA with at least one defined recurrent traffic pattern.

Table 7-7: Low-Adherence Standard routes with defined recurrent patterns

Type	Route	Segments	Low-Adherence Segment	Traffic (%)	Recurrent pattern description
STAR	'ASKE3G'	4	$CLIPY \rightarrow BKY$	28.2	Traffic directed from ROBNI to BKY
STAR	'WILO3B'	6	$KIDLI \rightarrow MID$	24.1	Traffic is stretched and directed to MID
SID	‘WOBU3F’	7	$3LOS \rightarrow WOBUN$	17	Traffic diverted in 3LOS
STAR	‘WILO3D’	3	$GWC \rightarrow HOLLY$	11.6	Recurrent pattern parallel to the route, intercepting HOLLY and directed to EGKK
SID	‘BOGN1M’	6	$OCK4 \rightarrow BOGNA$	8.1	Traffic diverted in *OCK4

STAR	'TOMO3E'	2	$BEDEK \rightarrow NIGIT$	4.9	Traffic is diverted before BEDEK to a parallel recurrent pattern
STAR	‘WILO3D’	3	$HOLLY \rightarrow WILLO$	4.8	Traffic is directed from GWC to WILLO
STAR	'LUMB2F'	2	$K063 \rightarrow LARCK$	3.3	Traffic is directed from K063 to EGKK

7.4 Concurrence Events Calculation

The concurrence events searching methodology has been applied to the sampled traffic, determining the number of concurrence events produced in the LTMA. The Figure 7-16 presents the number of concurrence events detected and the traffic demand of one day (grouped by 20-minutes intervals).

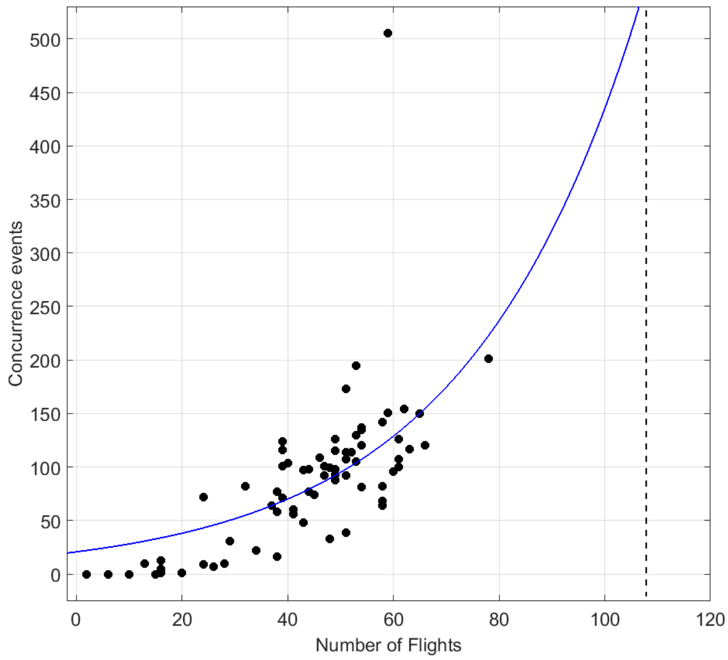

Figure 7-16: Demand vs Concurrence events in the LTMA

The number of flights that the TMA can manage is limited by the ATC taskload. Although it is observed dispersion in some relevant zones, it indicates a fast growth of the number of concurrence events when the demand increases above 110 flights per 20-minute interval.

For the case of *LAM3A*, the Figure 7-17 shows the demand distribution along the time. Except during very low-demand conditions, the trajectories that contain at least one concurrence event associated with the second recurrent pattern are distributed during the day (red). A recurrent pattern is an event that is independent of the demand conditions or the concurrence events calculated. Therefore, the method does not provide enough information to define the causes of the lack of adherence of this 1% of the traffic. However, the structure of the recurrent pattern presented in the previous Figure 7-11 indicates that the flights are directed to the low-adherence pattern *before* accessing to the terminal airspace and intercepting SABER. The recurrent pattern is fully independent of the standard route since the trajectories are intercepting none of the waypoints associated with *LAM3A*. Consequently, the flights are directed to a different standard route minutes before the terminal airspace entry due to an airport/TMA cause that is not related to the demand or traffic complexity.

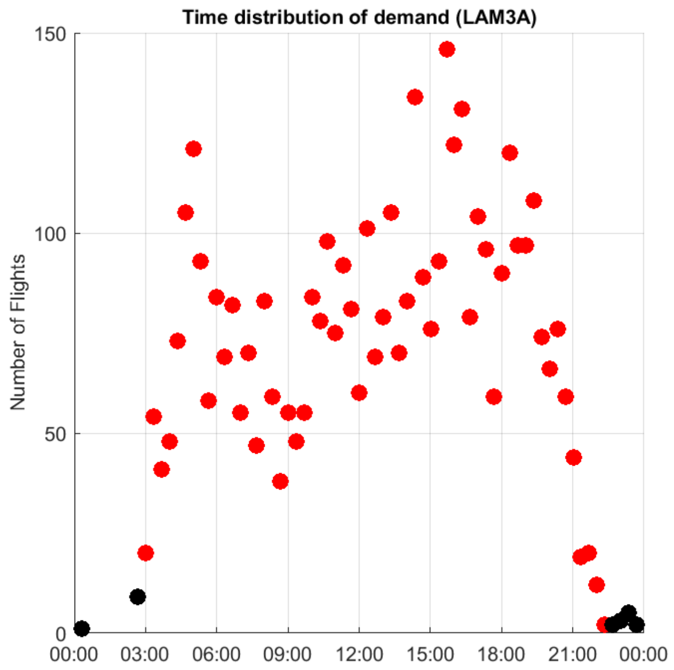

Figure 7-17: Demand distribution (*LAM3A*)

For the case of *LORE4Q*, the algorithm detected 1184 concurrence events in the segment S_2^{LORE4Q}. Figure 7-18 presents the relationship between the demand and the number of concurrence events. During low-demand conditions, the primary pattern/secondary pattern ratio is greater than in high-demand conditions.

Specifically, in the segment S_2^{LORE4Q}, that is the source of the low-adherence recurrent pattern, an important percentage of flights have deviated to the secondary pattern during low-demand conditions, which indicates that in most of the cases, ATCOs are directing the traffic to BYK *to improve the efficiency of the traffic flow*. However, the number of flights deviated increased during high-demand conditions on very specific days, which indicates that the secondary pattern is used *to release the system pressure* in some hotspots during high-demand peaks.

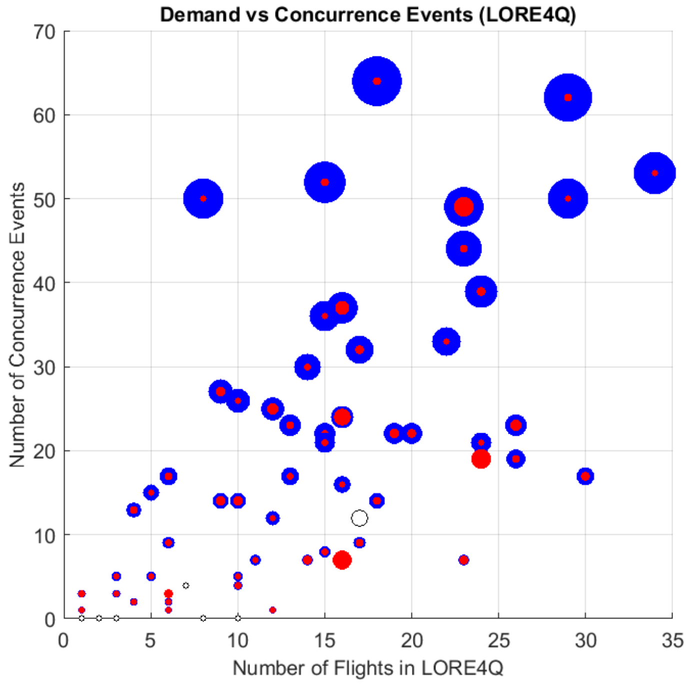

Figure 7-18: Demands vs Concurrence Events (*LORE4Q*)

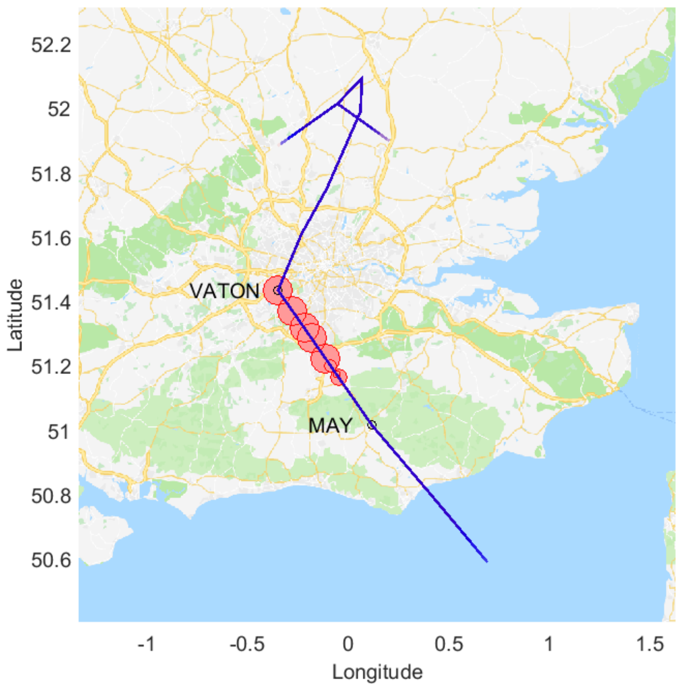

Figure 7-19: Concurrence Events Location (*LORE4Q*)

7.5 Conclusions

The directions provided by the ATC determine an important part of the predictability associated to the terminal airspace operations. Determining the high-adherence standard routes and low-adherence recurrent patterns reduces the amount of uncertainties that experienced during the strategic/pre-tactical phases of the air traffic management.

The previous chapter 6 presented a data-driven generic methodology that contributes to characterize and evaluate the terminal airspace operations of multi-airports systems. The procedure determines the standard routes interdependences, associates a set of traffic sample data and determines the trajectory deviation. Subsequently, the method determines recurrent patterns and concurrence events that are used to understand the real operations of a terminal manoeuvring area.

In this chapter, the methodology has been packed in a generic methodological framework divided into two components. The first one is a method to calculate the 4D adherence of the high-demand standard routes. The second one is a method to estimate the causes of lack of adherence by analyzing the concurrence events that could have been produced before the ATC interventions.

The framework has been applied to a representative multi-airport system such as the London Terminal Manoeuvring Area to test and demonstrate its effectiveness.

The point-to-point association and the identification of the standard routes interdependences revealed the most used inbound and outbound standard routes and effective classification of its interdependences.

The 4D adherence method determined a set of high-adherence standard routes that directs more than 95% of their traffic with a very low cross-track deviation.

For the particular case of *LAM3A*, the framework determined the existence of a low-demand recurrent pattern that directs the 1% of the traffic ~15 NM off the standard route. However, this pattern could not be directly associated with specific demand or traffic complexity conditions, which emphasizes the importance of other elements of the TMA (e.g. airport runway configurations) in the analysis tasks.

The results presented the low-adherence routes that contain at least one secondary recurrent traffic pattern. For the particular case of *LORE4Q*, the framework determined the existence of a secondary recurrent pattern that directs the 15.7% of the traffic during low-demand conditions, which is caused by ATC directions issued to improve the TMA efficiency. Although the pattern is mostly present during low-demand conditions, it could be also used during high-demand peaks on rare occasions to reduce the system pressure.

The proposed method identifies key elements that define the TMA-MAS performance and could contribute to creating more useful indicative views of the TMA performance.

8 Conclusions and Future Work

This research has explored the key elements for the application of STAM solutions in a terminal airspace, specifically, those that perform temporal displacements on selected flights on the ground.

This chapter concludes the PhD thesis by revisiting the initial objectives. Subsequently, it discusses the impact of the research and provides directions and recommendations for future work. The section 8.1 revisits the research objectives. The section 8.2 and 8.3 provide consideration for the proposed OpsCon and for the implementation and fine-tuning of the developed framework for MAS-TMA diagnosis.

The section 8.4 summarizes the main outcome and contribution of this thesis that is a set of key elements for the application of a STAM methodology in a MAS-TMA. Subsequently, the section 8.5 provides directions and recommendations about future work.

Lastly, the section 8.6 lists the publications and awards that resulted from this work.

8.1 Revisiting research objectives

This section reviews the aim and objectives described in the chapter 1 in order to provide a context for the achievements of this thesis.

The main objective of this thesis was to understand "How *the short-term ATFCM measures can be applied to improve the dynamic Demand Capacity-Balancing and reduce the complexity of the traffic flows in a Multi-Airport Systems?*"

A novel contribution of this research aims at finding answers to the proposed research question, which has been achieved by performing a study of the application of STAM to determine how these could be applied in a terminal manoeuvring area of a multi-airport system. Firstly, by proposing an OpsCon for STAM application (focused on temporal displacements on the ground) and aligned with the SESAR TBO/dDCB concept (chapter 4).

Secondly, by developing a real-time simulation of the temporal displacements proposed in the OpsCon in order to explore the uncertainties that could be produced during ground operations and to assess the effects of this methodology in the human performance (chapter 5).

Thirdly, by developing a data-driven methodology for diagnosis of a MAS-TMA in order to explore the uncertainties that might affect the STAM application in a terminal airspace (chapter 6).

To achieve the main objective of this thesis, the specific objectives were elaborated:

- The first objective was to *"Develop a novel framework that support the analysis and evaluation of the terminal manoeuvring area"*. This was achieved by the development of a data-driven 4D adherence calculation method and a concurrence events localization method that was implemented in a generic framework for diagnosis of a MAS-TMA.
- Having developed the framework proposed in the first objective, the research focused on tasks to *"Characterize and evaluate the performance of the terminal manoeuvring area of a multi-airport system".* The characterization of the MAS-TMA was achieved by implementing the framework proposed in the first objective and performing a study case of the London TMA in which key elements for STAM application have been obtained.
- A key objective of the thesis was to *"Identify the key elements and precursors for the application of STAM in a terminal manoeuvring area"*. The STAM application was focused on an OpsCon that was designed to apply temporal displacements on the ground. This objective was achieved by developing an OpsCon, identifying the uncertainties associated and determining the elements that could affect the proposed concept. Then, the key elements for the STAM application have been obtained by proposing solutions that contribute to the robustness of the concept.
- Lastly and in order to achieve the main goal, it was proposed to *"Test and evaluate the models developed and analyze the effects of STAM in the de-*

confliction of aircraft trajectories". This was achieved by implementing and testing the framework for diagnosis of the MAS-TMA, (presented in the chapter 6) and by implementing a real-time simulation exercise, including a specific technical solution (PARTAKE tools). The tests were performed to analyze the capabilities of the ATCOs to reduce the uncertainties before take-off while evaluating the effects of the solution in the human performance (chapter 5).

The main achievements of this thesis are analyzed in this section and grouped by chapters.

Chapter 1 provides a background of the problem to be solved. STAM is a novel concept introduced. Apart from the works developed by SESAR, few research activities have been performed in this specific context. The chapter outlined the research aim and proposed a set of specific objectives to achieve the main goal.

Having provided a background of the problem in chapter 1, chapter 2 focused on providing a review of the current ATM system and focused on providing a general context of this thesis.

The chapter 3 focused on providing the specific fundamentals to understand this thesis. It began with a review of the Dynamic Demand and Capacity concept, which represents the basics of STAM. Having introduced the STAM concept, the chapter reviews the past and current research about STAM developed by SESAR and other authors. Subsequently, it identified the different STAM methodologies and focused on those that are applied during ground operations including temporal or spatial displacements of selected flights before take-off. Lastly, it is provided particular interest to the PARTAKE-STAM methodology, which has been used as a technical enabler to test and validate the concepts proposed in this thesis.

Having reviewed the STAM methodologies, the chapter 4 introduced the OpsCon for STAM application. A novel concept aligned with the current ATMS operations and the dDCB/TBO concept that proposes the use of a STAM system and describes the roles of different agents. Additionally, the OpsCon is the base for the analysis of the different uncertainties that could affect the temporal displacement on the ground. This analysis gave rise to the development of the concepts and contributions proposed in the following chapters 5 and 6.

The chapter 5 describes a real-time simulation of the ground operations proposed in the OpsCon. The concept is validated by a combination of quantitative and qualitative methods that provide insights about the application of time displacement on the ground and human performance.

The use of high-adherence routes or low-adherence with secondary recurrent patterns is proposed in order to tackle the uncertainties produced in the terminal airspace. The chapter 6 proposed the use of a methodology designed to produce a diagnosis of a MAS-TMA. This methodology has been implemented to create a generic methodological framework that is composed firstly, by a data-driven 4D adherence calculation method that makes use of real-traffic data to determine the adherence of the traffic to the standard routes and to identify the existence of recurrent patterns. Secondly, by a process used to explore the possible causes of the non-conformance patterns of some routes, by analyzing the concurrence events that could have been produced in the standard routes of the MAS-TMA.

The next step included the implementation and testing of the developed methodology. Chapter 7 tests and validates the generic methodological framework specially created to characterize, analyze and improve the operations of a terminal airspace of a multi-airport system. The framework has been specially designed to analyze aircraft trajectories at segment level (high level of granularity). In this context, a study case of the London TMA is presented, which provides indicative views of two representative routes of the LTMA but also its potential could be extended to help guide future planning and investment the structure of the airspace.

Finally, the chapter 8 proposes considerations about the OpsCon proposed, the benefits of the methodologies presented and different ways in which the work presented in thesis could be continued and extended.

8.2 OpsCon considerations

In previous chapters, this thesis has presented an OpsCon that aims at describing the application of short temporal displacements of selected flights on the ground, in order to reduce terminal airspace complexity and ATC interventions on air. The concept, aligned to SESAR's dDCB/TBO and the current ATMS operations, requires a transition in the ATC system and to include additional tasks in the ATCOs operations. This section discusses some of the potential implementation issues of the OpsCon in real-life operations.

For the proposed ConOps to become operational feasible, there are some considerations to take into account.

Regarding the system enablers, the PARTAKE-STAM methodology, requires to maintain acceptable levels of fairness and transparency between the affected airspace users, to perform changes in the departure sequence. In this direction, a collaborative constraint management process such as the one offered by User Driven Prioritization Process (UDPP) (Eurocontrol, 2017b) to include margins of manoeuvre for each stakeholder could be taken into account.

The OpsCon requirements in terms of inputs is the access and transmission to all the interested parties of consistent real-time 4D trajectories that describe the airspace user intentions. Currently, this can be achieved by TBO, which represents a key element for other ATM strategies and concepts included in the SESAR Master Plan (Eurocontrol, 2015b) and ICAO Global Air Navigation Plan (GANP) (ICAO, 2016b).

The OpsCon has a direct impact in the ATC operations on the ground, a new departure sequence requires to be transmitted to the ground and local ATCOs. Consequently, the ATC system requires a technological transition that allows the ATCOs to access further information about the modified ETOTs. This can be accommodated as a complementary function of an existent ATC system (e.g. DMAN/SMAN) or a stand-alone system with exclusive data-link capabilities. Additionally, the STAM system requires to transmit the ETOTs to the ATC, which can be achieved by making use of data-link capabilities of the current ATMS.

In terms of air navigation requirements by the airspace user, the use of RNAV (and RPN) contributes to conserving flight distance with the standard route, improving the confidence of the predicted information used by the systems.

8.3 Considerations for implementation of the framework for MAS-TMA diagnosis

The framework for MAS-TMA diagnosis has been developed to analyze the trajectories of the terminal airspace.

The developed framework, is a generic methodological approach capable to determine 2D routes interdependencies, calculate traffic deviations from the standard route (at segment level), determine recurrent patterns based on the 3D adherence and identify concurrence events intended to support a causal analysis that responds about "*why*" and "*when*" are these recurrent patterns produced. In this context, the following considerations are suggested to implement and use the developed framework.

The statistical approach followed to calculate the 4D deviation, is sensible to the amount of traffic data (number of actual trajectories). Consequently, the input used for the population of standard routes with real traffic data should contain enough information to complete a successful analysis. Considerations to select the input data depends on the characteristics and purpose of the intended analysis. When the traffic data is obtained as a general package that includes the full TMA (like the case of DDR2), particular importance should be provided to the characteristics of inbound/outbound traffic of selected airports (to be analyzed). The distribution of traffic is different depending on the particular traffic of the airport and the standard procedures. An example of this is observed in the traffic sample used in the study case presented in the chapter 7. The 20% of the outbound traffic sample is concentrated in a few routes (DET2F and BPK7F). This makes the traffic sample suitable to analyze in detail those routes from EGLL, while for some northern airports (EGSS/EGGW) might not be enough data to obtain acceptable results.

The structure of the traffic data required by the framework is described in the section 6.2.2. The use of DDR2, which is provided by (Eurocontrol, 2018b), represents a complete source of information for traffic that has been widely used by other authors. The data is represented by trajectory points that are recorded based on "*events*" produced by the aircraft (e.g. it is recorded a trajectory point when the airspeed changes more than a specific value or when a significant change of heading is detected). Given the dynamics of aircraft in real operations, these events are not recurrent in time. Therefore, the separation of these trajectory points is not homogeneous (there is not a unique time/separation distance between points). To overcome this, a discretization process is required to perform a point-to-point association, which is described in the section 6.2.2. The methodology was designed so that each original segment of the standard route is divided in k-1 equally distanced sub-segments. The main consideration to adjust the k value is to provide acceptable levels of accuracy in the point-to-point association while maintaining a good performance of the algorithm implementation. The framework validation case presented in the chapter 7, used a parameter $k = 300$, which was empirically adjusted to maintain this hardware/performance balance. However, this balance might change depending on the hardware used for the analysis.

The recurrent patterns are computed based on a clustering method described in the section 6.2.4. A particular characteristic of the developed methodology is the reduced number of parameters that intervene in the clustering process. The number of *bins* are associated to operational conditions, representing minimum deviation values. The T_{peak} threshold represents the minimum number of trajectory points that produce a subset of trajectories. It should be considered that the variation of these parameters impacts in the number of subsets (and clusters) founds. These parameters were adjusted empirically in the chapter 7.

Lastly, the concurrence events identification presented in the section 6.3.1 is based on the parameters Q_z, Q_d and Q_t. Considerations to select these parameters should be linked to realistic separation minima requirements for terminal airspace (e.g. 3NM/500ft). For the time separation minima condition (C_t), it could be associated to the time required by the ATCOs to detect a conflict and issuing an ATC intervention, which could be quite subjective and variable depending on each ATCO. It should be considered that the Q_t parameter is proportional to the number of concurrence events detected. However, a more detailed sensitivity analysis to adjust this parameter might be required.

8.4 Key elements for STAM application

The main goal of this thesis aims at understanding the key elements for the application of STAM solutions, specifically those that produce temporal displacements on flights ready to depart.

The outcomes of this thesis are based on the development of an OpsCon, the assessment of the uncertainties that impact the effectiveness of the concept and finally a set of proposed solutions to improve the robustness of the solutions.

The prediction capabilities provided by the TBO concept is a key element that improves the accuracy and level of granularity required to calculate air traffic flow complexity in the dDCB process. Having a good prediction of the demand and airspace user intentions leads to detect and localize concurrence events, which is the first step to apply STAM.

Determining the demand with acceptable levels of accuracy in a MAS-TMA airspace is a complex task. The main source of uncertainties are produced by ATC interventions on air, which are dependent of many factors. However, the terminal airspace is composed of structures and standard routes that help to reduce the ATC taskload. In this context, a key element is to determine the adherence of the actual traffic to the standard routes to identify those high-adherence routes that are characterized by more predictable traffic and ATC interventions.

Although the high-adherence routes represent a more suitable choice to determine the complexity, another key element that could enhance trajectory predictability is the determination of secondary low-adherence recurrent patterns. In this case, it is required to anticipate *when* these patterns are likely to occur by carrying out a temporal analysis of the concurrence events and route demand that could intervene in the formation of these patterns. This thesis contributes to determining these elements by proposing a framework to detect a lack of adherence, high/low adherence recurrent patterns and concurrence events in a MAS-TMA.

Additionally to the benefits provided by the identification of high-adherence routes or low-adherence recurrent traffic patterns to enhance the trajectory predictability, the effectiveness of the OpsCon relies in the capabilities of the ATCOs on the ground to absorb the uncertainties produced before take-off. Reducing the take-off time error ensures that the effect of the time displacement is propagated downstream with the objective to mitigate the complexity. A key element to reduce those uncertainties is the synchronization of the different ATC roles on the ground. Push-back & taxi operations are managed by the ground/delivery ATC, while the stand-by and take-off operations are managed by the local ATC. This synchronization requires a change in the ATC operations on the ground. The first requirement is that applying temporal displacements on the ground changes the "*first in, first out"* paradigm used by the classical ATC operations. A change in this paradigm requires acceptable levels of fairness and transparency in the way the new ETOTs are calculated by the STAM system. This is key to obtain the support of airspace users in this methodology.

The performance of the ground operations is determined by another key aspect that is the airports' taxiways layouts. More distributed and redundant taxiways enhances the flexibility to manage the taxi operations and reduces the take-off time errors of the selected flights. Nevertheless, this key element and the change of the departure sequence could have an impact in the runway throughput, which means that heavily congested airports might not be suitable for this solution.

Additionally to the synchronization required between the ground/delivery and local ATCOs, a properly management of the take-off time errors is affected by the time distribution of the landing events. Consequently, a key element to reduce the take-off time error is to extend the local ATCOs synchronization to the TMA ATC, which is responsible for the landing sequence.

8.5 Future work and limitations

This thesis presented an OpsCon for STAM application and explored the uncertainties that could impact the proposed concept. This section discusses the limitations of the proposed OpsCon and the proposed methodologies.

From a technical point of view, it discusses the limits of the real-time simulation of STAM operations on the ground and the framework and algorithms developed to carry out the LTMA study case presented in the chapter 7. Finally, this section suggests possible ways to extend this research by providing directions for future work.

8.5.1 Operational Concept

The operational concept proposed describes the use of a technical enabler for STAM application in the current ATMS. The OpsCon main function was to create a context about how to implement this methodology. The proposed concept was designed to be aligned with the TBO strategy, and the technical enabler is aligned with the operational procedures proposed by the dDCB process. Although the concept was designed to support a *generic* STAM methodology that applies temporal displacements on selected flights on the ground, the test and validation of this concept were adjusted to endorse the PARTAKE-STAM methodology, which added some limitations in the analysis of uncertainties.

The process to calculate the sector complexity proposed by the PARTAKE-STAM methodology is based on a detection functionality that discretizes the S-T distribution of the reference trajectories and maps them to a grid of cells (or 3D blocks) that are defined by a cell-size and a vertical separation minimum. Consequently, the analysis of uncertainties in the terminal airspace is limited to determine only *important deviations* of the actual traffic. Consequently, the analysis of the uncertainties is neglecting minor deviations produced by wind, since it is assumed that these do not impact on the determination of concurrence events that are reduced to determine if more than one aircraft is inside of a cell/block.

Alternative methodologies to calculate temporal displacements on selected flights that do not use a similar method to compute the complexity (cell-based) might require further analysis of the uncertainties produced by the wind and minor deviations in the actual trajectories.

The OpsCon is a process that assumes that the different agents share *packages* of relevant data (e.g. trajectories information, suggested ETOTs, EBOTs…). In this context, the OpsCon definition is limited to assume that there exists a data-link connection between all the interested parties (FMPs, ATCOs). PARTAKE suggests the use of a SWIM-like network, where the information is centralized and distributed among all the interested stakeholders.

8.5.2 Real-time simulation of ground operations

The main goal of the real-time simulation was to understand if the uncertainties produced during ground operations could be absorbed by the ATCOs and to determine the effects of the new departure sequence in the ATCOs taskload.

From a technical perspective, it has been developed a conceptual Decision Support Tool that shared and shown the new departure sequence to the ATCOs. The concept was designed to match the simulation requirements for the exercises while limiting its performance for simulation purposes and without considering other systems used by ATCOs (e.g. DMAN or SMAN).

The roles of the local and ground/delivery ATCOs was performed by Cranfield Airport ATCOs. During the briefing sessions, they were provided with limited information of the Stansted airport in order to understand the taxi layout, runways and approach/departure procedures. However, the ATCOs were not familiar with all the Stansted airport operations. Therefore, the simulation was limited to carry out simplified and generic procedures for push-back, taxi, and take-off operations. The real-time simulation was additionally limited to two ATCOs on the ground, being the delivery and ground roles performed by a unique person. Further research is required to determine *how* the new departure sequence affects the ATC ground and delivery tasks individually.

The assessment of uncertainties on the ground could be improved by increasing the complexity of the procedures or improving the realism of the simulation. However, a key element to continue this research might focus in the synchronization of the ground ATCOs with the TMA ATCOs by extending the simulation to include TMA operations.

8.5.3 Methodology and framework for MAS-TMA diagnosis

The developed methodology has been designed to be applied to any MAS with proper adjustment and calibration. The study case was limited to evaluate the performance of the LTMA, which is the most complex and representative MAS in Europe. The application of the framework to other MAS has been limited by data availability and resources.

The analysis of the MAS-TMA is dependent on the actual historical traffic samples used for the population of the standard routes. Having developed a statistical approach, the amount of required data determines the accuracy and consistency of the results. However, the performance of the algorithms is dependent on the amount of data and the hardware resources. When used traffic samples distributed in many standard routes (which is a common use of the DDR2 data), the developed framework is limited to evaluate the most used standard routes of a TMA, which are filtered according to the number of actual trajectories provided in the traffic sample. This is because the framework requires to maintain a balance between the number of used data and the available hardware resources. The ratio of this balance was determined empirically during the test and validation process.

In addition, the selection of the parameters that define the clusterization method (threshold T_{peak} and the number of bins) have been adjusted empirically, after performing several tests. Further work is required to determine the sensitivity and optimal values for these parameters.

8.6 Publications and Awards

8.6.1 Journal Papers

- Amaro Manuel, Francisco Saez, Verdonk Christian. "*A Data-Driven Methodology for Characterization of a Terminal Manoeuvring Area in Multi-Airport Systems*". Transportation Research Part C: Emerging Technologies (Q1). (Peer-reviewed full paper submitted).
- Amaro Manuel, Schefers Nina, Francisco Saez, Ramos Juan, Verdonk Christian. "*An Operational Concept to Apply Short-Term ATFCM Measures in Multi-Airport Systems*". Transportation Research Part C: Emerging Technologies (Q1). (Peer-reviewed full paper submitted).
- Schefers Nina, Amaro Manuel, Ramos Juan, Saez Francisco. "*STAM-based methodology to prevent concurrence events in a Multi-Airport System (MAS)*". Transportation Research Part C: Emerging Technologies (Q1). (Peer-reviewed full paper submitted).

8.6.2 Conferences Presentations & Posters

- "*Pre-tactical Concurrence Event Detection Tailored for STAM Application: A Study Case of London TMA*" (Poster Presentation). 7th SESAR Innovation Days Conference. Nov 28-30, 2017. Belgrade, Serbia.
- "*Cooperative Departures for a Competitive ATM Network Service*". 2nd Annual Cranfield Aerospace Research Student Conference. Jun 21-22, 2018. Cranfield, United Kingdom.

8.6.3 Awards

- Award of Best Presentation (First Prize) by Cranfield University. "*Cooperative Departures for a Competitive ATM Network Service*". Annual Cranfield Aerospace Research Student Conference. Jun 21-22, 2018. Cranfield, United Kingdom

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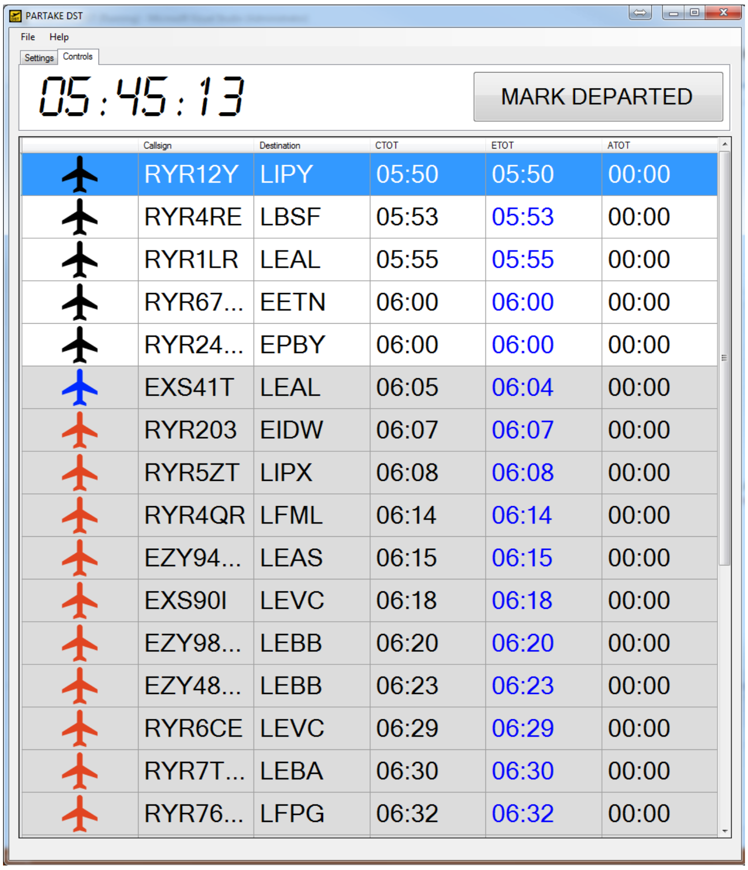
APPENDICES

Appendix A : Software, Hardware and Equipment

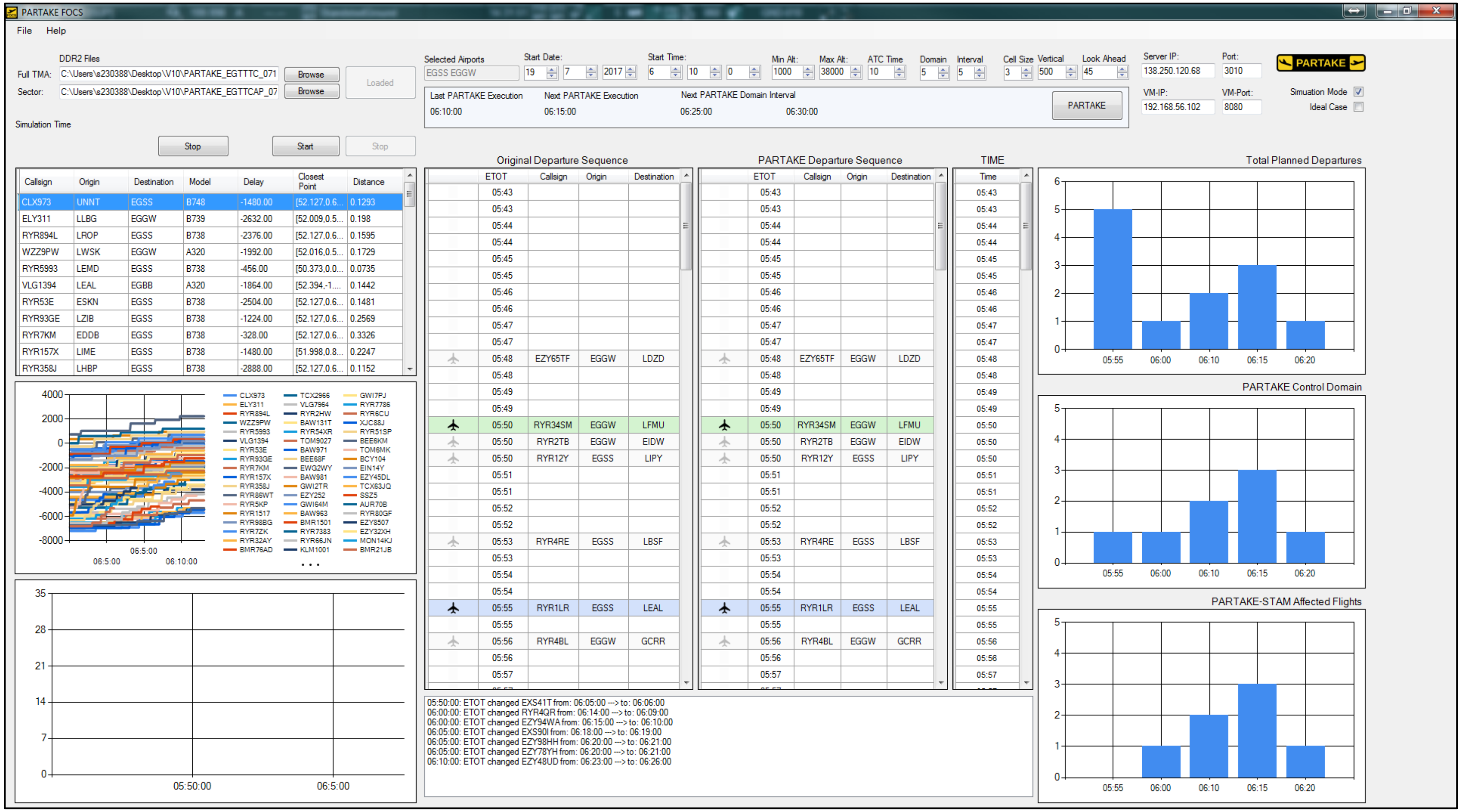
A.1 Decision Support Tool (DST) ATC Module

The DST ATC/PP Module is a software that provides the TWR/GND ATCOs with a user-friendly guide to manage the departure sequencing tasks based on optimized ETOT proposed by the PARTAKE software. The software has been designed considering the requirements of the real-time simulation exercise and the inputs provided by the ATCOs during the briefing sessions. The departure sequence is shown in the main screen and highlights those flights that have been selected for a change in the ETOT. Additionally it shows relevant information such as the simulation time and the CTOT. ATCOs were instructed to click on the “*Mark*

Departed” button once a take-off clearance was issued in order to record the ATOT.



A.1.1 Decision Support Tool (DST) Control System (FOCS)

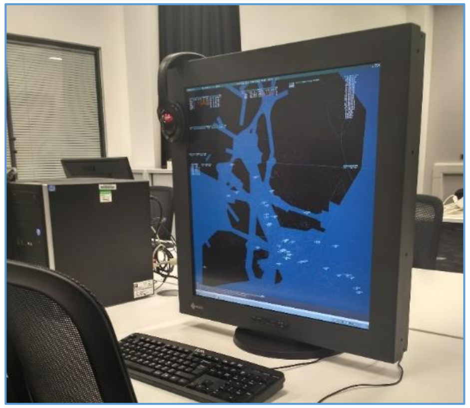


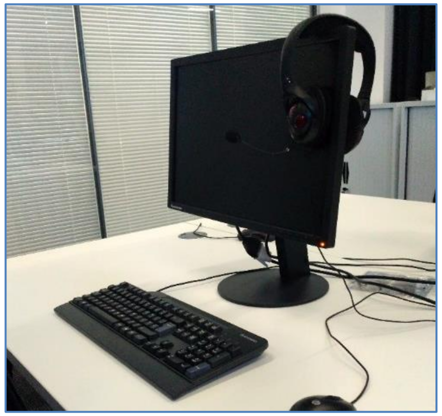
A.2 Software used and technical details

Software/Data	Description
Microsoft© FSX	The Microsoft Flight Simulator X (FSX) is a software developed by Microsoft Corporation and it is supported by an important community that provides the application with an important amount of additional resources (realistic sceneries, aircraft, cockpits, textures, plugins and tools). FSX is the main software used by VATSIM worldwide virtual community.
EuroScope© v3.7	EuroScope is the most popular ATC simulator and client in the VATSIM network. The software is a set of tools that simulate real-life radar software. The software features a built-in simulation system including a pseudo-pilot module.
vPilot© v2.1.3	vPilot is a VATSIM client used by the VATSIM network. It provides a communication interface between tower and aircraft simulators.
TeamSpeak© v3.1.4	TeamSpeak is a voice communication software that provides directly integration with Microsoft Flight Simulator.
PARTAKE integrated software	PARTAKE algorithms, logic and model are packed in an integrated software capable to receive predicted trajectories and output a new set of ETOTs (PARTAKE, 2016). PARTAKE software has been executed in a virtual machine linked to the monitoring DST ATC/PP Module, FOCS and Dashboard.

PARTAKE Monitoring Dashboard	The PARTAKE Monitoring Dashboard is a web-based software developed in order to represent graphically the concurrence events detected by the PARTAKE Detection Tool.
DST ATC/PP Module	The DST ATC/PP Module is a software that provides the TWR/GND ATCOs with a user-friendly guide to assess the departure sequencing tasks based on optimized ETOT proposed by PARTAKE software.
Flight Object Creator Software (FOCS)	ETOT timestamp values and flight time values are inputs of the next PARTAKE execution. A trajectory prediction software is required to produce an updated RBT based on data obtained from the flight/pseudo-flight simulators. Additionally, the FOCS controls and supervises the real-time simulation and broadcast the information obtained from PARTAKE to all the DST ATC/PP modules

A.3 Facilities and hardware equipment used

Facility	Description	
Control Tower Simulator	The control tower simulator is composed by hardware and software elements that emulate the operations of a control tower. The system is equipped with a large-scale curved screen powered by projectors to emulate the tower view of any airport. The position is provided with all the relevant communication assets and equipments for ATC operations.	
ATC Simulator	The ATC simulator is equipped with high definition screen, communication equipment and software to emulate the operations of a en-route, approach/departure or tower controller. Additionally, these positions could be used to monitor, supervise or record simulation data.	

Virtual/Pseudo Pilot Position	The Virtual/Pseudo Pilot position is composed by low-fidelity flight simulator software and pseudo-pilot software in order to simulate aircraft operations. The position is also provided with hardware to simulate ATC/pilot operations.	
Data Recorder Position	The system has been used to record the tower/view and tower audio channels during the real-time simulation.	

IDEAS Area (Aerospace Integration Research Centre)	The IDEAS area, located in the Airspace Integration Research Centre (AIRC) at Cranfield University is a facility that includes a large scale visualization system integrated with the ATM Laboratory. This area served for the briefing/de-briefing sessions and open discussion about the real-time sumulation.