

UNIVERSIDAD POLITÉCNICA DE MADRID
Escuela Técnica Superior de Ingeniería Aeronáutica y del Espacio



**Definition of a methodology for the
computation and application of a
variable separation minima between
aircraft in an en-route environment**

DOCTORAL THESIS

Submitted for the degree of Doctor by:

Lidia Serrano Mira
MSc in Air Transport Systems

Madrid, 2024



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A Marina y a nuestros padres,

AMDG

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Abstract

The air transport system is expected to experience a continued increase in the number of movements. The current focus is to address the capacity shortage to handle forecasted demand with enough margin. Although forecasts are long-term, Air Traffic Management (ATM) is adopting strategic solutions to meet future challenges.

This increase in capacity requires research, development and implementation of new concepts and technologies. The Single European Sky ATM Research (SESAR) program proposes research into various solutions in different areas. One of the factors related to airspace capacity is separation minima. Technological advances are opening new horizons, especially in this field. This encourages to explore the evolution of the separation minima, whose values were determined decades ago. In this dissertation a new separation mode, Ad Hoc separation, is proposed and developed.

The Ad Hoc separation concept refers to the application of different separation minima values between aircraft flying in the same volume of airspace. These separation minima depend on certain factors such as the model, mass and speed of the aircraft, the flight level, the encounter geometry, the avoidance manoeuvre, the prevailing wind conditions and the human factor. This concept entails the reduction of current separation values whenever it is safe to do so.

The goal of this dissertation is to develop a methodology for the determination of the Ad Hoc separation and to evaluate its impact on an en-route scenario. Based on the hypothesis that it will be possible to define new separation values, this dissertation aims to answer three questions:

- Under which situations is it possible to define new separation minima values lower than the current ones?
- What would be the mode of operation in a scenario where the Ad Hoc separation minima concept is applied?
- Which benefits does this concept bring to a scenario?

For this purpose, the operational concept of the Ad Hoc separation is defined and a model for its determination is proposed. The new separation minima are

calculated in the horizontal dimension from a collision risk model developed for this purpose and through Montecarlo simulations. The results obtained for the LECMZMU sector (Madrid Area Control Centre, ACC) show that for small encounter geometries (below 56°) it is safe to reduce the separation minima to 4NM (Nautical Miles) or 3NM. Subsequently the concept is applied in the LECMZMU en-route sector in order to obtain the requirements to maintain the current safety levels. The results show that it is necessary to halve the probability of loss of separation per flight hour.

A key element for the implementation of this concept is the Air Traffic Control support tool called Ad Hoc Separation Minima Tool (ASMT) because the Air Traffic Control Officers (ATCO) are unable to mentally calculate the Ad Hoc separation minima to be applied between each aircraft pair. Thus, the ASMT displays to the ATCO these values. In addition, it includes conflict detection and resolution functionalities adapted to this concept. Its architecture and a prototype are presented.

Finally, this dissertation concludes with an analysis of the impact of applying this concept in a scenario in terms of capacity, environment and airspace user cost-efficiency. For this purpose, fast time simulations are performed. This impact is studied in the LECMZMU, LECMTLU and LECMDGU sectors (Madrid ACC). The capacity results show an increase of about one aircraft per flight hour due to the application of this concept alongside the ASMT tool. Regarding the environmental and cost-efficiency outcomes, they are barely significant, but still favour the system. The benefits could be more substantial by applying the concept in larger scenarios (such as ACC) rather than in isolated sectors.

Resumen

En el sistema de transporte aéreo se espera un aumento continuo del número de movimientos. La meta actual es abordar la escasez de capacidad para gestionar la demanda esperada con margen suficiente. Aunque las previsiones son a largo plazo, en la gestión del tránsito aéreo se adoptan soluciones estratégicas para enfrentar desafíos futuros.

Este incremento en capacidad requiere la investigación, desarrollo e implementación de nuevos conceptos y tecnologías. El programa europeo SESAR propone la investigación de varias soluciones. La mínima de separación es un factor relacionado con la capacidad. Avances tecnológicos abren nuevos horizontes, especialmente en este campo. Esto anima a explorar la evolución de la separación mínima, cuyos valores fueron determinados hace décadas. En esta tesis doctoral se propone y desarrolla un nuevo modo de separación, la separación Ad Hoc.

El concepto de la separación Ad Hoc hace referencia a la aplicación de diferentes valores de separación mínima entre aeronaves que vuelan en el mismo volumen de espacio aéreo. Estas mínimas de separación dependen de ciertos factores como son el modelo, masa y velocidad de las aeronaves, el nivel de vuelo, la geometría del encuentro, la maniobra de evasión, las condiciones de viento o el factor humano. Este concepto conlleva la reducción de los valores de separación actuales siempre que ello sea seguro.

El objetivo de esta tesis doctoral es desarrollar una metodología para la determinación de la separación Ad Hoc y evaluar su impacto en un escenario de ruta. Partiendo de la hipótesis de que será posible definir nuevos valores de separación, se pretende dar respuesta a tres preguntas:

- ¿En qué situaciones es posible definir nuevos valores de separación mínima inferiores a los actuales?
- ¿Cómo sería el modo de operación en un escenario en el que la separación Ad Hoc estuviera implementada?
- ¿Qué beneficios aporta este concepto a un escenario?

Para ello, se define el concepto de operación de la separación Ad Hoc y se propone un modelo para su determinación. Las nuevas mínimas de separación son calculadas en la dimensión horizontal a partir de un modelo de riesgo de colisión

desarrollado para este fin y por medio de simulaciones de Montecarlo. Los resultados obtenidos para el sector LECMZMU (ACC Madrid) demuestran que para geometrías de encuentro pequeñas (inferiores a 56°) sí es seguro reducir la mínima de separación a 4NM o 3NM. Posteriormente el concepto es aplicado en el sector de ruta LECMZMU con el fin de obtener los requisitos para mantener los niveles de seguridad actuales. Se obtiene que es necesario reducir a la mitad la probabilidad de pérdida separación por hora de vuelo.

Un elemento clave para la implementación de este concepto es la herramienta de apoyo al Control de Tráfico Aéreo denominada ASMT, como consecuencia de que el ATCO es incapaz de calcular mentalmente la mínima de separación Ad Hoc a aplicar entre cada par de aeronaves. Así, la ASMT muestra al ATCO estos valores. Además, incluye funcionalidades de detección y resolución de conflictos adaptados a este concepto. Su arquitectura y un prototipo de herramienta son expuestos.

Finalmente, esta tesis concluye con un análisis del impacto que tendría la aplicación de este concepto en un escenario de ruta en términos de capacidad, impacto medioambiental y eficiencia de costes para el usuario del espacio aéreo. Para ello, se realizan simulaciones en tiempo acelerado. Este impacto se estudia en los sectores LECMZMU, LECMTLU y LECMDGU (ACC Madrid). Los resultados obtenidos en cuanto a capacidad ponen de manifiesto un aumento aproximado de una aeronave/hora de vuelo, como consecuencia de la aplicación de la separación Ad Hoc junto con la herramienta ASMT. En cuanto a medioambiente y eficiencia de costes los resultados son de menor magnitud, aunque positivos para el sistema. Los beneficios serían mayores si el concepto se implementase en escenarios más grandes (ACC), en lugar de en sectores aislados.

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Nomenclature

ac_{man}	Manoeuvring aircraft
$ac_{non-man}$	Non - manoeuvring aircraft
AC_data	Aircraft data
$angle_{egeom}$	Encounter geometry
ATT	Along Track Navigation error
CPA	Closest Point of Approach
col_dist	Collision distance
$cross\_point$	Cross Point Coordinates
$Ctcr$	Maximum cruise thrust coefficient
$Collision\ Risk_{each\ sit}$	Collision risk calculated for each situation
$Collision\ Risk_{dif\ sit}$	Collision risk calculated for different situations
d	Euclidean distance between aircraft pair
d_h	Critical distance
D	Drag
$DCPA$	Distance at the CPA
FL	Flight level
g_0	Gravity
GS	Ground Speed
h	Altitude
$init\_pos\_acman$	Initial Position Coordinates of the Manoeuvring aircraft
$lim\_distance$	Limit distance
$Mach$	Mach number
Num_sim	Number of simulations
$percentage_{MTOW}$	MTOW percentages
$\bar{r}_{21}$	Relative position of the non-manoevring (2) regarding the manoeuvring aircraft (1)
R	Real gas constant for air

ROC	Rate of climb
sep_{min}	Separation minima
t	Simulation Time
t_0	Initial Time
t_{ATCO}	ATCO Reaction time
t_{com}	Communication time
t_{DCPA}	Time at the CPA
t_{LAT}	Look Ahead Time
t_{LOS}	Time when the LOS takes place
t_{nec}	Necessary time
t_{pilot}	Pilot Reaction time
t_{reqam}	Time required by the aircraft for executing the avoidance manoeuvre
t_{res}	Response time
t_{WPi}	Time required to arrive to the following WP_i
$TCPA$	Available time or time to CPA
Thr	Thrust
TK_{proj}	Track Projection
try_{ac}	Aircraft Trajectory
T	Temperature
T_0	Standard atmospheric temperature at MSL
T_{TROP}	Tropopause Temperature
v	Speed error
$\bar{v}_{21}$	Relative speed of the non-maneuvring (2) regarding the manoeuvring aircraft (1)
V_{TAS}	True Airspeed
V_{UW}	Aircraft speed with uncertainties and wind
Wd	Wind direction
Wi	Wind intensity

WP_i	Waypoint i
XTT	Cross Track Navigation error
$\Delta incr$	Step size
$\ \dot{\bar{r}}_{21}(t)\ $	Closing speed rate

Abbreviations and Acronyms

ACAS	Airborne Collision Avoidance System
ACC	Area Control Centre
ADS	Automatic Dependent Surveillance
ADS-B	Automatic Dependent Surveillance Broadcast
ADS-C	Automatic Dependent Surveillance Contract
ADSM	Ad Hoc Separation Minima
ADS-RAD	ADS in Radar-Controlled Areas
AESA	Spanish Aviation Safety Agency
AIP	Aeronautical Information Publication
AIRAC	Aeronautical Information Regulation and Control
AIRPROX	Air Proximity
AltMoC	Alternative Means of Compliance
AM	Avoidance Manoeuvre
AMAS	Ad Hoc Minimum ATC Separation
AMWS	Ad Hoc Minimum Wake Vortex Separation
ANSP	Air Navigation Service Provider
ASAS	Airborne Separation Assurance Systems
ASMT	Ad Hoc Separation Minima Tool
ATC	Air Traffic Control
ATCO	Air Traffic Control Officers / Air Traffic Controller
ATCS	Automated Air Traffic Control System
ATM	Air Traffic Management
ATM OPS Panel	ATM Operations Panel
ATS	Air Traffic Services
ATT	Along-track Tolerance
AUC	Area Under the ROC Curve
BADA	Base of Aircraft Data
BN	Bayesian Network
CAR-SAM	Caribbean-South American corridor
CAS	Calibrated Airspeed
CAT	Catastrophic
CCO	Continuous Climb Operations
CD	Conflict Detection
CD&R	Conflict Detection and Resolution
CNS	Communication, Navigation and Surveillance
CO ₂	Carbon Dioxide
COM	Communication

CONOPS	Operational Concept
CPA	Closest Point of Approach
CPDLC	Controller Pilot Data Link Communications
CPE	Conflict Probability Estimation
CPT	Conditional Probability Tables
CR	Conflict Resolution
CRM	Collision Risk Model
CS	Certification specification
DAG	Directed Acyclic Graph
DCPA	Distance at the Closest Point of Approach
DDE	Double Exponential Distribution
DME	Distance Measuring Equipment
DOF	Degrees-of-freedom
EASA	European Union Aviation Safety Agency
ECAC	European Civil Aviation Conference
EDA	Exploratory Data Analysis
eFPL	Extended Flight Plan
EKEBN	Expert-based Knowledge Engineering of Bayesian Networks
ENAIRE	Spanish ANSP
ENR	En-route
EPP	Extended Projected Profile
ESARR	EUROCONTROL Safety Regulatory Requirement
EU SES	European Union Single European Sky
EUR NAT	European – North Atlantic Corridor
EUR SAM	European – SouthAmerica Corridor
FAR-Part	Federal Aviation Administration Regulation
FIR	Flight Information Region
FL	Flight Level
FN	False Negative
FOM	Figure of Merit
FP	False Positive
FPL	Flight Plan
FPR	False Positive Rate
ft	feet
FTS	Fast Time Simulations
GA	Go Around
GM	Guidance Material
GNSS	Global Navigation Satellite System
GS	Ground Speed
H	Heavy

HF	Human Factor
HPL	Horizontal Protection Level
IAS	Indicated Airspeed
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IFALPA	International Federation of Air Line Pilots Associations
IFR	Instrumental Flight Rules
IRP	Integrated Risk Picture
ISA	International Standard Atmosphere
kt	knot
KPAs	Key Performance Areas
KPIs	Key Performance Indicators
LIM	Limited to ROD 1500 ft/min
LOS	Loss of Separation
M	Medium
MAC	Mid Air Collision
ML	Machine Learning
MLAT	Multilateration
Mode S	Secondary Radar Mode S
MRS	Minimum Radar Separation
MSSR	Monopulse Secondary Surveillance Radar
MTOW	Maximum Take-off Weight
MWS	Minimum Wake Vortex Separation
N/A	Not Applicable
NAT	North Atlantic Region
NAT-SPG	NAT-Systems Planning Group
NEST	Network Strategic Tool
NM	Nautical Mile
NMAC	Near Mid-Air Collision
NOAA	National Oceanic and Atmospheric Administration
PAC	Conflict Alert: Prediction
PANS-ATM	Procedures for Air Navigation Services-ATM
PBA	Performance Based Approach
PBN	Performance Based Navigation
PIs	Performance Indicators
PSR	Primary Surveillance Radar
PTT	Push to Talk
RA	Resolution Advisory
RBT	Reference Business Trajectory
RECAT	Re-Categorisation

RECAT-EU PWS	European Re-Categorisation Pairwise
RMS	Root Mean Square Error
RNAV	Area Navigation
ROC	Rate of Climb
ROC Curve	Receiver Operating Characteristic Curve
ROD	Rate of Descent
RVSM	Reduced Vertical Separation Minima
s	second
SBT	Shared Business Trajectory
SESAR	Single European Sky ATM Research
SI	Situation of interest
SID	Standard Instrumental Departure
SL	Sensitivity Level
SOAM	Systemic Occurrence Analysis Methodology
SSR	Secondary Surveillance Radar
STCA	Short-Term Conflict Alert
TA	Traffic Advisory
TAS	True Airspeed
TBO	Trajectory Based Operations
TBS	Time Based Separation
TCAS	Traffic Alert and Collision Avoidance System
TCAS RA	TCAS Resolution Advisory
TCAS TA	TCAS Traffic Advisory
TCPA	Time to the Closest Point of Approach
TEM	Total Energy Model
TLS	Target Level of Safety
TMA	Terminal Control Area
TN	True Negatives
TOPAZ	Traffic Organization and Perturbation AnalyZer
TP	True Positive
TPR	True Positive Rate
TSE	Total System Error
T2LOS	Time To LOS
UAS	Unmanned Aircraft System
UIR	Upper Information Region
UNL	Unlimited
UPM	Universidad Politécnica de Madrid
UTC time	Coordinated Universal Time
VAC	Conflict Alert Violation
VFR	Visual Flight Rules

VHF	Very High Frequency
VOR/DME	Very High Frequency Omnidirectional Range co-sited with Distance Measuring Equipment
WL	Workload
WP	Waypoint
XTT	Cross-track Tolerance

1. GENERAL INTRODUCTION

1.1. Motivation

The most reliable traffic forecasts anticipate 16 million Instrumental Flight Rules (IFR) movements by 2050 in the European Civil Aviation Conference (ECAC) region [1], which represents a 44% growth in air traffic compared to 2019 levels. Although this is a long-term forecast of demand growth, in the aviation industry and specifically in the Air Traffic Management (ATM) system, action is needed now to meet future challenges.

Considering this forecast, the ambition is to address this capacity crunch in order to manage the expected demand with a sufficient margin. In the Single European Sky ATM Research (SESAR) context [2], [3], several solutions are being investigated in different areas. These key areas are advanced air traffic services, enabling aviation infrastructure, high performing airport operations and optimised ATM network services. One of the factors in relation to airspace capacity is the separation minima.

The static approach to the allocation of separation minima was introduced in the 1940s, based on expert judgment and the technology available at that time. Separation minima have evolved many times over the past decades. For instance, the Reduced Vertical Separation Minima (RVSM) concept was implemented in the vertical dimension, while in the horizontal one, radar separation minima in en-route (ENR) airspace were reduced from 15NM to the current 5NM (EUROCONTROL in [4] states that horizontal ENR separation minima of 5NM were first implemented in Europe in the 1990s). Despite recent technological advances, these values defined many years ago have remained unchanged and the static approach of conceiving separation minima has persisted. It is worth noting that a reduction in the separation to a fixed value (uniform reduction) may not be a valid solution, as not all aircraft and modes of operation are equal.

New horizons are opening in the ATM system and particularly in the field of separation modes and separation minima, as a result of advances in technology in recent years and the ones expected in the future (European ATM Masterplan,

Level 4 and Level 5 of Automation, [5]). Ad Hoc or Variable separation minima¹ is one of these new topics among others, such as Airborne Separation Assurance Systems (ASAS), Time-Based Separation (TBS) or European Re-Categorisation Pairwise (RECAT-EU PWS). The new stage (2023) of the RECAT-EU PWS [6] is of special interest because it defines different Minimum Wake Vortex Separation (MWS) values based on several aircraft models (considering more than a hundred) according to their individual characteristics. This could be seen, in a way, as a precursor to the Ad Hoc separation.

Ad Hoc separation refers to the application of different separation minima values between aircraft pairs in the same volume of airspace depending on a set of conditions, such as aircraft models, aircraft masses, flight level (FL), etc. These pairwise separation minima (Ad Hoc separation) also imply the reduction of separation values in those situations where it is safe to do so.

The reduction of separation minima not only can contribute to an increase in capacity, but also influences, although not directly, the environmental and cost-efficiency areas. This holds significance, given the escalating emphasis on environmental concerns, particularly in light of the anticipated rise in air traffic demand. The effort to reduce separation minima values aims, between others, to minimize the need for frequent tactical interventions by Air Traffic Control Officers (ATCOs) during in-flight operations. As a result, this reduction in ATCO interventions holds the potential to decrease aircraft deviations from their intended trajectories, leading to savings in fuel, carbon dioxide emissions (CO₂) and mitigating delays.

The latest SESAR call [7] encourages the exploration into the evolution of separation minima. Literally, the scope of the research presented in [7] includes investigating advanced modes of separation (e.g. dynamic separation). This dissertation has identified as a line of research the investigation of the Ad Hoc separation concept, as a way of contributing, in some way, to the increase of airspace capacity.

¹ Ad Hoc separation and Variable separation are used interchangeably throughout the entire text.

1.2. Research proposal

The separation minima values currently applied have remained unchanged for many years. Additionally, a fixed separation value is currently applied to an airspace volume. In the past two decades, significant changes have occurred in the field of ATM. Particularly, Air Traffic Control (ATC) support tools now have functionalities that did not exist in the past, navigation requirements have become more demanding due to the accuracy that the aircraft can achieve using Global Navigation Satellite System (GNSS) as the sole means of navigation (Performance Based Navigation concept, PBN) together with its augmentations. Similarly, with the advent of Automatic Dependent Surveillance (ADS), either ADS-B (broadcast) or ADS-C (contract), or Mode S secondary radar, there has been a more than significant improvement in the amount of information the aircraft transmits to the ground segment, as well as a decrease in position error or a reduction in the position update period.

As a result of the aforementioned advancements, the question arises as to whether it is possible to modify the current separation values. Furthermore, an increasing number of projects, driven by SESAR [7], aim to explore the possibility of defining new separation modes. In this context, separation modes are understood as the set of rules and procedures associated with a minimum separation value [8].

This dissertation explores the feasibility of reducing separation minima values in an ENR environment. Following the trend observed in certain SESAR projects [9], [10] where the reduction of separation minima is proposed as a partial approach depending on specific characteristics (and not as an absolute reduction, e.g. from 5NM to 4NM in all situations), the proposal is to investigate a variable reduction of separation minima. This approach entails reducing separation only in situations where it is deemed safe. This could lead to greater benefits, as an absolute reduction may not be feasible, but a partial reduction may be.

Furthermore, the application of a fixed separation value in a given volume of airspace is, among other reasons, due to Human Factor (HF) limitations. ATCOs are unable to mentally calculate different separation minima values for different situations using traditional methods. However, technological advances have overcome this limitation, allowing the application of variable separation values depending on the conditions.

The application of different separation values within the same volume of airspace is defined as the concept of Ad Hoc or Variable separation. The research proposal of this dissertation is to develop this concept and propose a methodology for the definition of these Ad Hoc separation minima in an ENR environment. This will be based on quantitative modelling of the risk of collision between aircraft for a given target level of safety (TLS) equal to the current one. In addition to quantifying the new separation values, the operational concept (CONOPS) is defined, which includes the mode of operation associated with this concept. A prototype ATC support tool for the implementation of the Ad Hoc separation concept is also defined. Finally, the benefits associated with the application of this concept in ENR airspace are analysed.

1.2.1. Research questions

This dissertation assumes that it is possible to define new separation minima values that are lower than the current ones (hypothesis). As an absolute reduction of the separation minimum may not be safe, new values will only be defined for those situations where it is safe to do so. Therefore, the first research question of this dissertation is:

Research Question 1: *Under which situations is it possible to define new separation minima values lower than the current ones?*

This question refers to the feasibility study of the Ad Hoc separation concept. Therefore, it intrinsically answers the question of whether it is possible to reduce the separation minima or not. Given that it is assumed that this reduction cannot be absolute, the answer to this question would be either accepting or rejecting the hypothesis raised. In addition, the question refers, although indirectly, to the different factors that are involved in the definition of the separation minima and how the combination of these factors could lead to specific situations in which it would be possible to reduce the separation.

Having answered this Research Question 1, the following question arises as how the operation would be with the application of different separation minima values in the same volume of airspace. Thus, the following research question would be:

Research Question 2: *What would be the mode of operation in a scenario where the Ad Hoc separation minima (ADSM) concept is applied?*

The second question refers to the CONOPS. That is, the mode of operation of the Ad Hoc separation in a scenario. This concept implies several changes compared to the current one. For instance, regarding the ATCOs, although they would remain as agents responsible for the separation, with this new concept they take on a more monitoring-based role. Furthermore, it is also necessary to assess the compatibility of this concept with those already implemented (i.e., Free Route) or planned to be implemented in the future (i.e., Trajectory Based Operations (TBO), Extended Projected Profile (EPP)). Similarly, the necessary enablers for its implementation should be considered.

The consideration of the answer to Research Question 2 prompts the question of whether it would be worthwhile to take on the complexity inherent in such a large-scale change to the system. This is formulated in Research Question 3:

Research Question 3: *Which benefits does the Ad Hoc separation concept bring to a scenario?*

This research question focuses on the impact of the Ad Hoc separation concept in a scenario. A CONOPS that does not provide benefits is considered unprofitable, even if it is operationally feasible. Generally, when new concepts are introduced, the complexity of a system increases. Therefore, it is important to perform this analysis, even at a preliminary level, in order to check whether it is beneficial to apply this concept to a scenario or whether, instead, the complexity of the system is being increased in exchange for no benefits. This analysis serves as a Go/No Go test for the next stages of development.

1.2.2. Scope and Assumptions

The main goal of this doctoral dissertation is to develop a methodology for the determination of Ad Hoc separation and to evaluate its impact on an ENR airspace. To achieve this aim, the following sub-objectives are tackled:

- Definition of the of the Ad Hoc separation CONOPS.
- Definition of the model for the determination of the Ad Hoc separation.
- Quantification of new Ad Hoc Separation Minima (ADSM) between aircraft.
- Development of the ATC support tool for the implementation of the Ad Hoc separation concept.
- Quantification of the impact on an ENR sector in terms of capacity, environment and airspace user cost-efficiency by the application of the Ad Hoc separation concept.

The following assumptions are considered:

- In this dissertation, wake vortex is not considered for the definition of the ADSM. The definitive values of the ADSM will be determined as the greatest between the Ad Hoc Minimum Wake Vortex Separation (AMWS) and the Ad Hoc Minimum ATC Separation (AMAS) applicable for a specific encounter. The investigation of the AMWS will be conducted in future work. Therefore, when referring to the ADSM in this dissertation, the AMAS is actually being addressed.
- The Ad Hoc separation model developed only applies to horizontal separation minima (2D). Therefore, aircraft flying at constant altitude are the ones considered (which are the majority in the ENR/cruise segment). The separation between aircraft in evolution is maintained at the current value since the model does not consider the vertical dimension (3D).
- A scenario of predefined routes is considered. Nevertheless, the model is prepared to be implemented in a Free Route scenario.
- Collision risk is only calculated between manned aircraft; Unmanned Aircraft Systems (UAS) are not considered.
- Commercial aircraft models are considered for the simulations performed.

1.3. Methodology

To achieve the former goals, this dissertation is constituted by six different modules, which tackle the whole process of the ADSM determination. Each module permits to deepen in a different aspect to finally be in position to constitute the concept of the Ad Hoc separation. Then, this dissertation is divided into three levels: Definition, Development and Assessment (Figure 1).

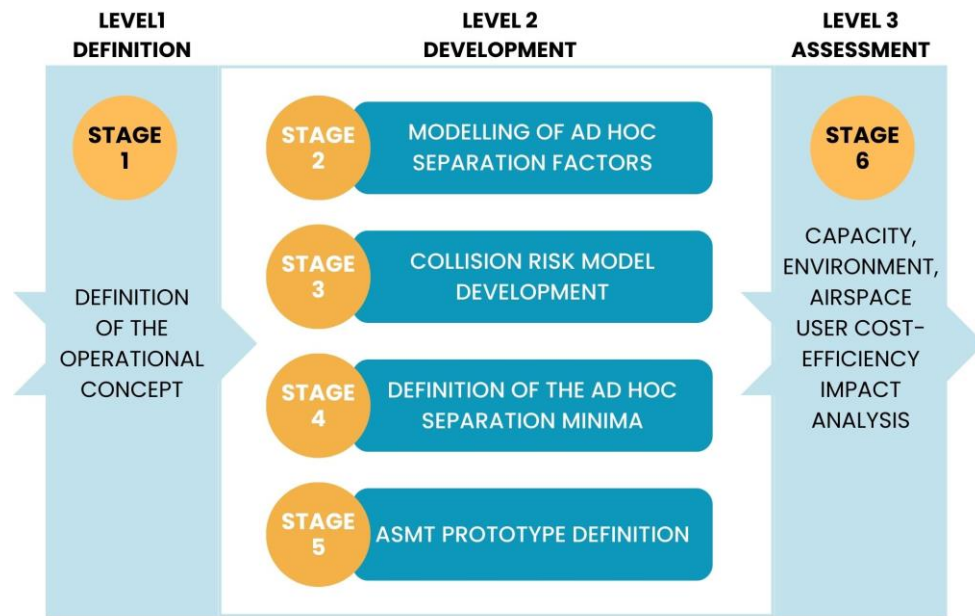


Figure 1. Methodology followed for the development of the Ad Hoc separation.

1. **Level 1** focuses on the definition of the ADSM CONOPS. CONOPS is an overview of how the concept is going to be operated. Stage 1 starts with the concept definition and setting the operational scenario characteristics, Communication, Navigation and Surveillance (CNS) requirements and enablers. Finally, the compatibility with other concepts of the global ATM system is described.

2. **Level 2** is dedicated to developing the necessary processes for determining Ad Hoc separation and applying this concept in a scenario. In Stage 2, the model for determining the ADSM is proposed. The parameters and variables on which Ad Hoc separation depends are analysed and modelled through simulations based on the EUROCONTROL Base of Aircraft Data (BADA) model in a worst-case scenario. Stage 3 involves the development of the collision risk model (CRM). In Stage 4, the ADSM are determined through Montecarlo simulations. Finally, in

Stage 5 is developed a prototype of an ATC support tool for implementing this concept in an ENR scenario. This tool is called Ad Hoc Separation Minima Tool (ASMT).

3. **Level 3** constitutes the final stage of the methodology and aims to determine the impact of the concept within a given scenario, regarding capacity, environmental impact and the airspace users cost-efficiency. To conduct this impact assessment, fast time simulations (FTS) were executed. The LECMZMU sector served as the benchmark scenario for both the application and evaluation of the Ad Hoc separation concept. Additionally, FTS were conducted in alternative scenarios (specifically, the LECMTLU and LECMDGU ENR sectors of Madrid ACC) to verify whether benefits could be realised in contexts distinct from the reference scenario employed.

In addition, each computational code was implemented using MATLAB® software. The simulations were performed on the Margerit-3 computer system at the Madrid Supercomputing and Visualisation Centre of the UPM (Universidad Politécnica de Madrid). The operational data (air traffic flows, trajectories, aircraft mix, ...) were extracted from the Network Strategic Tool software (NEST®). RAMS Plus® software was also used for FTS.

1.4. Document structure

The structure of this doctoral dissertation is as follows:

Chapter 2 describes the state of the art of the separation minima. General concepts related to separation minima, the theoretical factors that influence its determination and the models developed for this purpose are defined. Additionally, a literature review of the historical evolution of these models is presented.

Chapter 3 presents the ADSM CONOPS. This CONOPS includes a description of the mode of operation, the characteristics of the operational scenario, the CNS requirements, the necessary enablers, the compatibility with other concepts in the ATM system, as well as the publication aspects to be considered.

In Chapter 4 the model on which the ADSM are based is presented. The factors that define these ADSM and their relationships are discussed. The model for their determination is described. Simulations with the BADA model are performed to analyse the operational feasibility of the ADSM in a deterministic approach. The results show that the application of this concept is preliminarily feasible.

Chapter 5 presents the determination of the ADSM values, after the collision risk assessment. A new CRM model is developed for this purpose. Montecarlo simulations are performed to determine the ADSM values for each situation. Navigation and speed uncertainties are considered. Once the ADSM values are defined, a case study of the application of the Ad Hoc separation concept in the LECMZMU scenario is conducted to perform a safety analysis and establish the requirements to maintain the current safety level.

In Chapter 6 the prototype of the ASMT is presented. The architecture of the tool is described and its application in LECMZMU sector is shown.

The preliminary impact assessment of the Ad Hoc Separation concept in LECMZMU, LECMTLU and LECMDGU sectors is included in Chapter 7. This impact is analysed in terms of capacity, environment and airspace user cost-efficiency Key Performance Areas (KPA's). ENR throughput, reduced CO₂ emissions, fuel and strategic delay indicators were selected for the impact assessment.

Chapter 8 describes conclusions and further work.

ANNEX A includes a brief summary of the aircraft cross-track deviation study to model the navigation uncertainty. The complete study conducted at the UPM is available in [11].

In ANNEX B a study of the oral communications between ATCO and Pilot in LECMZMU sector is presented. The results obtained from this study are used in the model of the Ad Hoc Separation.

ANNEX C provides the analysis of the contributing factors to the loss of separation (LOS). The goal is to quantify this influence in order to build the ADSM model from these results. For this reason, a data-driven approach was

followed together with expert judgement. Based on the Bayesian Network (BN) model, this influence is studied.

ANNEX D includes the results of the deterministic feasibility study of the Ad Hoc separation presented in Chapter 4.

In ANNEX E the LECMZMU sector is described. This scenario has been used throughout the entire dissertation for the application of the Ad Hoc separation. Moreover, LECMTLU and LECMDGU sectors are described, because the preliminary impact assessment of the concept has also been conducted in these scenarios.

The ATCO and Pilot surveys conducted during this dissertation are included in ANNEX F.

In ANNEX G, the times associated to the different tasks performed by the planning and executive ATCOs for the FTS simulations in RAMS are provided.

1.5. Publications

The following publications were produced as part of the research in this dissertation. The list is given in inverse chronological order:

Journal Papers

- Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, Adrián Casado López, Eduardo S. Ayra, Marta Pérez Maroto. Preliminary Impact Assessment of the Ad Hoc Separation Minima, a new Separation Mode. *Applied Sciences* [Submitted].
- Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, Fedja Netjasov, Eduardo S. Ayra, Irene García Moreno and Juan Sánchez-Cano Mas-Sardá. Risk assessment for the determination of the Ad Hoc Separation Minima for en-route airspace. *Journal of Air Transport Management*. [Submitted].

- Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, Fedja Netjasov, Irene García Moreno, Eduardo S. Ayra. Preliminary Feasibility Study of the Ad Hoc Separation Operational Concept. *Aerospace* 2023, 10, 539. <https://doi.org/10.3390/aerospace10060539>.
- Lidia Serrano-Mira, Marta Pérez Maroto, Eduardo S. Ayra, Javier A. Pérez-Castán, Schon Z. Y., Víctor Gordo Arias, Luis Pérez Sanz. Identification and Quantification of Contributing Factors to the Criticality of Aircraft Loss of Separation. *Aerospace* 2022, 9, 513. <https://doi.org/10.3390/aerospace9090513>.

Conference proceedings

- Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, Juan Sánchez-Cano Mas-Sardá. “Preliminary design of an ATC support tool for the implementation of the Ad Hoc Separation Minima concept in an en-route sector”. <https://doi.org/10.1088/1742-6596/2716/1/012079>. *13th EASN International Conference on Innovation in Aviation and Space for opening New Horizons. Salerno (Italy). 2023*.
- Lidia Serrano-Mira, Fedja Netjasov, Luis Pérez Sanz, Javier A. Pérez-Castán, “Aircraft Encounter Characterization; a scenario-based simulation approach”. *XLIX International Symposium on Operational Research. Vrnjačka Banja (Serbia). 2022*. ISBN: 978-86-403-1750-4.
- Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, “Ad Hoc Minimum Separation: A challenge for Air Traffic Control (ATC)”, <https://doi.org/10.36443/10259/7010>. *Congreso de Ingeniería del Transporte CIT 2021: R-Evolucionando el transporte (14º. 2021. Burgos)*. ISBN: 978-84-18465-12-3

Awards

- European_Academia@EASA Conference Award 2023.

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2. SEPARATION MINIMA STATE OF THE ART

2.1. Introduction

This section provides a general background of the separation minima concept, risk and CRMs. It is intended to provide a general analysis of the separation minima with particular emphasis on the models used for their determination. Thus, it will be possible to decide whether it is necessary to develop a new model for the determination of the Ad Hoc separation. Moreover, from these analyses, it will be easier to grasp the contributions of these doctoral dissertation within its context.

In this chapter, firstly, general concepts associated with separation minima are discussed. The factors defined by the International Civil Aviation Organization (ICAO) that shall be considered for the determination of the separation minima and the influence of the control forms on them are presented. Subsequently, the two main approaches for safety assessment according to the ICAO are described: relative and absolute methods. As the absolute approach has generally been used to determine the separation minima, the historical evolution of the different models is presented, focusing on those that will underpin the definition of the Ad Hoc model. Furthermore, the general limitations of the models discussed are analysed.

The work in this chapter is based on the following Master's project: Serrano Mira, Lidia (2020). Definición preliminar del concepto de operación para la aplicación de la separación mínima "Ad Hoc" entre aeronaves. *Tesis (Master)*, Escuela Técnica Superior de Ingeniería Aeronáutica y del Espacio. Universidad Politécnica de Madrid.

2.2. General concepts related to separation minima

2.2.1. Definition and types of separation

ICAO [8] defines separation as the generic term used to describe the action by Air Traffic Services (ATS) to keep aircraft operating in the same area at such distances from each other that the risk of collision is maintained below an acceptable safety level. The required separation between aircraft is generally expressed as a minimum. Therefore, the separation minima are the minimum distance allowed between two aircraft for each specific airspace to maintain the corresponding safety levels [12].

Separation is applied in the horizontal and vertical dimensions. Two aircraft are separated when, in at least one of the two dimensions, separation is maintained. In the horizontal plane a distinction is made between lateral and longitudinal separation. Lateral separation exists when aircraft are separated from each other by a specified distance (e.g. when approaching to a crossing point), or when spacing between airways is defined. Longitudinal separation is considered to exist when aircraft are separated from each other by a specified distance or time. In the vertical plane, aircraft are established at different levels expressed in altitudes or FLs.

A third type of separation, called composite separation, results from the combination of vertical separation with one of the other forms of horizontal separation (lateral or longitudinal). Lower separation minima than those used when applied separately is defined, but always shall be greater than half the value corresponding to those minima. Composite separation is applied in very specific scenarios: oceanic airspaces where control is procedural, traffic density is not very high, tracks are parallel and aircraft navigation systems are long-range.

2.2.2. Factors influencing the separation minima determination

ICAO [13] outlines the factors to be considered in determining the separation minima. However, this description is merely theoretical. The separation minima depend on the following factors: navigation capability, exposure to risk and intervention capability. Figure 2 should be understood as a graphical equation in which the separation minima are a function of these three distinguishing elements.

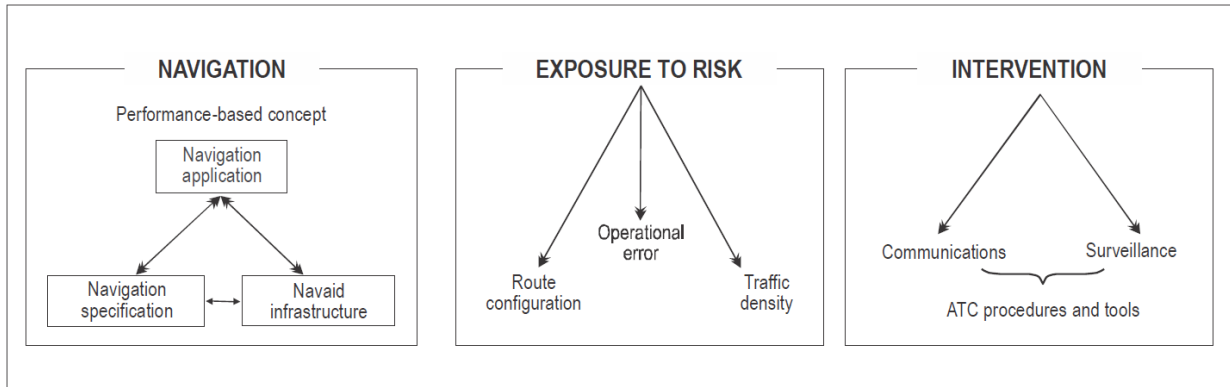


Figure 2. Factors influencing separation minima [13].

- **Navigation:** this concept refers to how an aircraft determines the position it is occupying, compares it to a reference trajectory and determines the guidance manoeuvres required to proceed to the destination. Since the GNSS is used as a sensor for navigation, significant progress has been made in the navigation field. It is noteworthy the relevance of the implementation during the last few years of the PBN concept. Performance is understood in terms of capability to comply specific requirements. The objective is to require a set of minimum performance requirements (in terms of accuracy, integrity, availability and continuity, among others) to be met by the on-board navigation system. The navigation factor is constituted by three elements:
 - **Navigation Specification:** aircraft and flight crew requirements necessary to support a navigation application within a defined airspace concept.
 - **Navaid Infrastructure:** refers to the external technical resources that enable the aircraft to meet the requirements (for instance, GNSS).
 - **Navigation Application:** is the performance required to the aircraft as a result of the specification-infrastructure ensemble in the airspace concept (for instance, RNAV 1 DME/DME).

- Exposure to risk: through this component, the elements and errors that could lead to collision between aircraft are considered. The main factors involved in risk exposure are route configuration, traffic density and operational error.
 - Route configuration: the structure of the route network is a fundamental factor in determining collision risk. Depending on the configuration (intersecting or parallel routes, angles between tracks, routes at a constant altitude, free route airspace, etc.) the risk may change.
 - Traffic density: this element refers to the demand expected to operate in a given volume of airspace, or, in a route network. This parameter is closely related to the term complexity, i.e. the number of simultaneous or near-simultaneous interactions between aircraft trajectories within a given volume of airspace. Thus, generally, a low traffic density scenario will be of low complexity. Generally, higher traffic density means higher risk.
 - Operational error: this factor considers those risks to which the aircraft is exposed as a consequence of human error in the operation (i.e. incorrect entry of waypoint (WP) coordinates into the Flight Management System (FMS) or selection of an incorrect route).
- Intervention capability: this factor refers to the ability of the system to intervene in a conflict situation to avoid a collision. In the current CONOPS, the responsibility for the exercise of separation lies on the ATCO. Surveillance enables the ATCOs to know the relative position between aircraft pairs. The ATCOs issue the clearances/instructions to the flight crew through the communications. Depending on the tools supporting ATC, the detection of conflict situations may be earlier or later, resulting in a greater or lesser ability to intervene.

Figure 3 schematically shows the influence of the above factors on the determination of separation minima and route spacing in scenarios with and without ATC surveillance. Aircraft separation (separation minima) and ATS route spacing (route spacing) are not the same. While the former is the minimum distance allowed between the aircraft (vertical or horizontal), the latter refers to

the minimum distance between route centrelines. Consequently, the degree of complexity of the graphical equation differs depending on whether one is trying to determine separation minima or to establish a route spacing criterion [13].

Each element within the three main factors (navigation, risk exposure and intervention) will take different values depending on the scenario and its specific characteristics. Thus, for instance, the spacing between routes may be different for the same navigation specification, perhaps due to differences in traffic density or ATC intervention capability. For determining separation minima, traffic density is reduced to the consideration of aircraft pairs, whereas for the establishment of route spacing, traffic density is considered (i.e. the flow of aircraft per airway). It is noted that the main element for the determination of the separation minima for tactical use with ATC surveillance is the intervention factor.

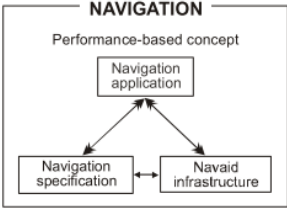
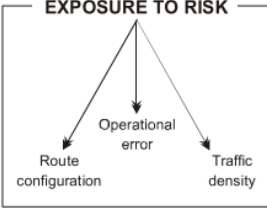
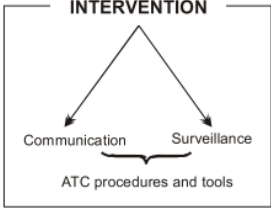
	NAVIGATION Performance-based concept 	EXPOSURE TO RISK 	INTERVENTION 
Determination of separation minima (1) for tactical use <i>without</i> ATC surveillance	✓	✓ (2)	✗
Determination of separation minima (1) for tactical use <i>with</i> ATC surveillance	✗	✗ (2) and (3)	✓
Determination of route spacing <i>without</i> ATC surveillance	✓	✓	✗
Determination of route spacing <i>with</i> ATC surveillance	✓	✓	✓
✓ Relevant; ✗ Largely irrelevant; (1) In context, separation minima based on navaid or navigation sensor or PBN; (2) traffic density = single aircraft pair; (3) separation minima determined as a function of performance of ATC surveillance system.			

Figure 3. Factors affecting separation minima and route spacing [13].

2.2.3. Wake vortex influence on separation minima

Aircraft generate rotating air masses (vortex) behind them during flight because of the pressure difference between the inboard and outboard parts of the wing. The wake vortex intensity is directly proportional to the weight and inversely proportional to the speed. This influence becomes relevant during the approach and take-off phases, as aircraft fly at lower speeds and the distances between

them are smaller. However, it must also be considered in the ENR phase. The vortex effect is dangerous for other aircraft. For this reason, MWS are defined, which are applied when they are more restrictive than Minimum Radar Separation (MRS).

For MWS, ICAO [14] initially classified the different aircraft models according to their maximum take-off weight (MTOW) into three wake vortex categories (heavy (H), medium (M) and light (L), which became four in 2008 with the appearance of the A380-800 model (super heavy). Subsequently, based on the RECAT (re-categorisation) project [15], this classification was extended to six categories (super heavy, upper heavy, lower heavy, upper medium, lower medium and light). Recently, RECAT-EU Pairwise Separation (PWS) [6] has been defined in which the classification is extended to a list of more than 100 categories of aircraft. Among the different categories, different values of longitudinal MWS are defined, which apply in the approach and take-off phases as they are more restrictive than the MRS in these scenarios. These are distance-based or time-based separation minima.

For the ENR phase, the wake vortex separation minima are defined in [14]. Certain values are established for preceding aircraft combinations of higher category than the following aircraft. However, there are projects [16], [17], [18] that have investigated redefining the ENR phase wake separation minima. In [16] this reduction is based on the severity of wake vortex encounters. These separation values are computed for a large number of encounter scenarios, involving different aircraft types, geometries, separations and weather conditions.

2.2.4. Control forms and their effect on separation minima

The separation mode is the approved set of rules, procedures and conditions of application associated with separation minima [8]. As seen before, the most influential factor on determining separation minima in a scenario with ATC surveillance is the intervention capability. In this subsection the influence of control forms on separation minima is analysed.

The separation minima established by ICAO are included in Chapter 5 and Chapter 8 of [14]. The applicable separation minima are determined by each State (ATS authority) based on the available resources and are published in the

Aeronautical Information Publication (AIP) [19]. Consequently, the different separation values (either in distance or time) depend on the technical resources used and therefore on the type of control provided to the aircraft. There are two kinds of control methods.

- **Procedural control:** this was the primary control form prior to the standardisation of the radar system. Currently, it is still applied in scenarios where the radar service is not available, often due to factors such as low traffic density, geographical limitations, or economic infeasibility. The ATCOs perform their collision avoidance task based on the position information they receive from the aircraft. It is the pilot who informs the ATCOs of the aircraft's position via position reports. However, this does not release the ATCOs from their obligation to continuously monitor the traffic situation. Generally, from the flight plan (FPL) and flight strips, which contain the basic information of the aircraft and its positions during the evolution of the flight, ATCOs "visualise", not actually but conceptually, the scenario in which they must provide control service. The position information is subject to a set of (usually large) errors, due to the systems used. Therefore, the separation minima that are determined for procedural control are defined considering these errors.

The separation minima values defined for procedural control are established by ICAO in Chapter 5 of [14]. These values differ depending on several elements (phase of flight, angle between tracks, navigation sensor, etc.). Although these separation minima values were initially defined on the basis of expert judgement (and were relatively large), gradually, to reduce these values, CRMs began to be used. This was intended to demonstrate that the separation minima reduction was safe. Separation minima for procedural control airspaces can be defined as follows:

- Time-based separation: This was the first method used to provide separation between aircraft in the longitudinal dimension. Based on the estimates (estimated time of aircraft crossing a defined point) and the ATCO-Pilot communications, ATCO establishes the approximate time relations between aircraft.
- Separation based on Mach number as a function of time: this technique is used to maintain longitudinal separation between aircraft flying long

distances in scenarios where ATC intervention is reduced (e.g. oceanic regions). If aircraft in similar conditions (i.e. flying the same route at the same FL) maintain the ATC-approved Mach number, longitudinal separation is maintained between them, as they are flying in almost the same conditions.

- Distance-based separation: Longitudinal separation expressed as a distance is normally used when higher quality and more frequently updated aircraft position information is available to the ATCO. Lateral separation is generally specified as a distance.
- Radar control: in this control form, the ATCO continuously visualises on the radar screen the position of aircraft within the system's coverage. This represents a significant change from procedural control as the uncertainty associated with the aircraft position that the ATCO had in a procedural environment almost disappears with radar control. Aircraft can fly outside the established routes, as their position are determined by the radar and displayed on the screen.

Real-time knowledge of aircraft positions provides ATCOs with tools and procedures (e.g. radar vectors), unfeasible in other environments (procedural control scenarios). These tools and procedures allow them to manage traffic more efficiently and ensure safety with more traffic density. Aircraft position is provided by surveillance systems (primary radar, PSR; conventional secondary radar, SSR; and conventional monopulse secondary radar, MSSR). In addition to position, information such as aircraft call sign and flight altitude is available.

Minimum radar separation (MRS) is only applicable in the horizontal plane. They were determined empirically and are not based on CRMs. As more radars were introduced and their performance improved, the separation minima values were reduced. For instance, in the case of Spain, the horizontal separation minima in the ENR airspace have evolved from a value of 15NM (years 1990-1994), 10NM (years 1994-1998), 8NM (years 1998-2008) until the definition of the value of 5NM, which is the value applied today (from September 2011). This value is applicable with multi-radar coverage, remote signal processing and with at least one operational main radar. If one of these specifications is degraded, a higher separation

value (10NM or 15NM) will be applied. Nevertheless, EUROCONTROL in [4] states that horizontal ENR separation minima of 5NM were first implemented in Europe in the 1990s. For the Terminal Control Area (TMA), similar evolution of separation minima occurred, being the current value 3NM. Further information on Spanish separation minima is published in the AIP, ENR 1.6 section [19].

The term “radar control” has been replaced by “enhanced surveillance”, which refers to an improved control concept compared to conventional radar control (PSR and conventional SSR or MSSR). Enhanced surveillance capability is the ability of the aircraft to down-link aircraft derived data via a Mode S transponder [20]. In addition to the advantages of Mode S SSR, the ADS technique is incorporated, which, updated with GNSS, means that the aircraft is able to calculate its position with greater accuracy, overcoming certain limitations inherent to the conventional radar system (overlapping responses) or problems related to their technical nature (such as coverage, update period). These techniques, together with multilateration (MLAT), configure a set of systems that allow the ATCO an improved surveillance performance, knowing with greater accuracy and integrity the position of the aircraft in real time and having other relevant information available, such as accuracy indicators, integrity indicators and operational status. However, despite continuous improvement of these technical resources (Mode S, ADS and MLAT), the separation minima have remained unchanged over the last years (5NM ENR and 3NM in TMA). Nevertheless, for departures and approach phases in which MWS are considered, some improvements such as TBS [21] and RECAT-EU PWS [6], have been implemented or are nearing implementation.

2.3. Safety assessment models

In order to determine the separation minima for an airspace, it is necessary to ensure the air traffic operation maintaining safety levels in that scenario (for which the separation minima are being determined). According to the ICAO [22], there are two methods for evaluating the safety performance of a system: the reference and the absolute methods.

The reference method is a relative method in which it is compared the estimated performance of the proposed system against the performance of a system which has already been judged to be safe [22]. If the performance of the proposed system is equal to or better than that of the reference system in all safety-related aspects, then the proposed system can also be assumed to be safe.

The absolute method is based on estimating the collision risk of the system and then comparing it to a predetermined maximum tolerable collision risk value (denoted as TLS). In general, the absolute method has been used by the ICAO to determine whether a system is safe for specific separation minima.

ICAO defines risk as the assessment, expressed in terms of probability and severity, of the consequences of a hazard based on a worst-case scenario. Whereas safety is defined as a measure of acceptability of risk [23].

The purpose of CRMs in the context of determining separation minima is to model the chain of events leading to the collision of initially separated aircraft pair [24]. Therefore, it is a mathematical tool whose purpose is to predict the risk or probability of collision between aircraft operating in an airspace with certain characteristics. The terms probability of collision or risk of collision are often used interchangeably since in the aviation context it is assumed that any Mid-Air Collision (MAC) is equally fatal for all occupants of the two aircraft involved in the accident [25]. Thus, severity value is constant and equal to 1.

If the estimated risk is lower than the maximum TLS and is expected to remain so throughout the envisaged lifetime of the new system, then the proposed system can be considered to be acceptably safe. TLS is commonly expressed, in the context of MACs, as a function of the expected number of fatal accidents per flight hour, considering a collision as two accidents as defined by ICAO [24].

2.4. Historical evolution of models for determining separation minima

The collision risk metric applied in the context of a MAC has traditionally been used to determine separation minima in different scenarios. This is why, over the last 60 years, several authors have evaluated and proposed different models for estimating and determining collision risk.

Marks [26] and Reich [27], [28], [29] were the pioneers who developed a CRM in the 1960s to assess whether reducing the lateral separation between parallel tracks in the North Atlantic Region (NAT) was safe. This model was developed in response to the controversy between International Air Transport Association (IATA) (airlines' representation) who requested a reduction in the lateral separation (from 120NM to 90NM) to increase capacity in the NAT region and International Federation of Air Line Pilots Associations (IFALPA) who considered this to be unsafe. Marks and Reich developed the first CRM as a support tool for the relevant authority responsible for setting the separation minima in a region.

In the Reich model, aircraft are represented as boxes (parallelepipeds). The collision probability of two aircraft can be determined from the navigation and speed error distributions. The Reich model presented certain limitations. On the one hand, it considered simple collision cases. On the other hand, in the early 1960s, there was not a large amount of data available for an optimal modelling of error distributions and in particular for modelling the tails of the distribution (a key requirement for the calculation of the collision probability which was overcome by statistical approaches). However, this model would become the basis for the CRMs developed in the following decades.

In 1966, to develop the Reich model into a more generic and manageable tool, the ICAO established the NAT Systems Planning Group (NAT/SPG). Mathematicians and researchers participated in this group, with Machol being one of the most prominent. The Reich model was improved by collecting more data (14,000 samples), which allowed more accurate modelling of aircraft navigation errors. The model was renamed as the Machol-Reich model [30], [31], [32]. Furthermore, one of the key contributions was the establishment of the TLS concept, as a threshold level of safety for the comparison of the collision risk. To

calculate this TLS, it was agreed to take the total accident rate of all aircraft and reduce it by a factor of 10, resulting in a TLS of between 0.45 and 1.2 accidents due to collisions per 10 million flight hours for these years.

Considering these TLS values, it was demonstrated that in the NAT region it was safe to reduce the vertical separation from 2000ft to 1000ft (although this would not be implemented until the 1990s) but it was not safe to reduce the lateral separation from 120NM to 90NM. For this reason, the concept of diagonal or composite separation was proposed as the combination of a 1000ft vertical separation and a 60NM lateral separation simultaneously, instead of the previously established 2000ft vertical separation or 120NM lateral separation. This increased capacity levels in the NAT region by almost twofold.

This model was used in the following decades for risk assessment in oceanic scenarios (1970s in the Asia/Pacific oceanic region between California and Hawaii and in the 1980s between Japan and Alaska) and is still used today by several Air Navigation Service Providers (ANSPs) (e.g. by Spanish ANSP (ENAI) for risk assessment in the European – South America Corridor (EUR/SAM) between the Canary Islands and Brazil [33]). Furthermore, the application of the RVSM in 1997 in the NAT region and subsequently in other regions [34], [35], [36] became possible based on the results obtained from the Reich model.

Nevertheless, the application of the Reich and Machol-Reich model is limited to the characteristics of the scenario for which it was developed (NAT region). This CRM is applicable to the strategic determination of separation minima in oceanic airspace, specifically in procedural control scenarios (very low information update rate) for aircraft flying parallel trajectories. Consequently, several researchers worked to extend the application of this CRM to other geometries or scenarios.

Hsu [37] developed the Reich model to be applicable in scenarios with procedural control, but on intersecting trajectories, modelling the aircraft as cylinders. In this CRM, the collision probability is determined at a different time interval than that used by Reich. In the Reich model, the probability of collision is calculated considering the proportion of time in which the overlap occurs in the corresponding direction; whereas in this CRM, the time interval in which the collision is likely to occur is considered. Position errors are modelled with the double exponential distribution function (DDE or Laplace function). In the 1990s,

Anderson [38], [39] generalised and improved the model of Hsu and analysed its sensitivity to crossing angles, required navigation performance and variation in aircraft speed.

In the 2000s, the ICAO introduced its own CRM expressed in the well-known Rice Formula [22], [24] developed from the Reich and Hsu models. Consequently, the ICAO CRM is only applicable to procedural control scenarios. In [40] through the ICAO model, the collision risk is estimated for the reduction of the separation minima in Singapore procedural airspace from the improvement of communication and navigation systems.

However, although these models have been applied to determine the separation minima in scenarios with procedural control [22], they cannot be adapted and applied in scenarios where the risk of collision is not determined by navigation or surveillance errors but by operational errors. These are scenarios with surveillance or radar control in which the ATCO provides tactical instructions to the aircraft.

Over the recent years, new models were developed that envisaged scenarios with radar surveillance or even models for the risk assessment of future concepts such as Free Flight [41]. Bakker and Blom [42], [43], [44], [45] generalised the Reich model to extend its application to more generic scenarios. The separation between two aircraft is considered to follow a stochastic (Markov) process. The model is based on Petri nets and Montecarlo simulations. Nevertheless, the most significant contribution of this model was its integration into the Traffic Organization and Perturbation Analyzer (TOPAZ) methodology [46] for air traffic risk assessment based on the identification of system-internal hazards that are determined analytically. This allows ATC experts to estimate the safety of a system after the implementation of new technologies or the system redesign.

Brooker [47], [48] presented analytical calculations of collision risk because of radar inaccuracies from a new event model methodology. Campos [49] proposed and determined the probability of coincidence, which is an upper bound metric for the probability of collision. Aircraft are considered to fly with constant speed and on arbitrary straight flight trajectories (either in level flight, climbing or descending). In [50] this risk metric was estimated along air corridors scenarios. The same authors in [51] estimated the probability of collision for crossing

trajectories in terms of the Root Mean Square errors (RMS) of the position and encounter geometry.

In [52], [53] the authors developed a three-dimensional CRM based on radar data of aircraft trajectories with the goal of assessing the European ENR risk due to all causes (operational risk) and in all dimensions. HF (Human Factor) was included in the model. The CRM is divided in three parts which are estimated based on the data: frequency of hazards (risk exposure), probability of a potential collision given a LOS (severity of the encounter) and probability of a collision given a potential collision (safety nets part).

However, although CRMs have been developed for radar scenarios, there is no official evidence that mathematical/probabilistic models were developed to assist in the setting of separation standards that would be maintained by radar surveillance [54]. Therefore, it seems that current separation minima values have been determined empirically and not based on a CRM. This is why some authors studied the separation minima from a different perspective.

The concept of a protected zone or buffer was defined and related to separation minima standards between aircraft. In [55], the authors defined the separation minima as a buffer consisting of different factors: surveillance, communications, HF (ATCO and pilot) and aircraft dynamics. Ennis and Zhao in [56], defined the protection zone as a mixture of the vortex or turbulent wake region, the safety region (equivalent to a cylinder of slightly larger dimensions than the aircraft) and the uncertainty region.

Brooker [47] discussed that a particular separation minimum necessarily feeds back into requirements of the radar design criteria. Hence, EUROCONTROL and other researchers [4], [57], [58], [59], [60], [61] adopted a different approach and determined, for a given separation minima value, the requirements of the surveillance factor, to ensure that a separation value was safe from a technical point of view. That is, in these investigations the separation minima were not determined, but a set of technical requirements were defined in order to judge that the system was safe.

Mehadhebi [62] was one of the principal authors of the ICAO CRM and stated that in surveillance environments separation minima should be considered as “time buffers”, in the sense that they provide sufficient time to detect and correct

operational errors. Brooker [63] also shared this view, noting that separation standards were originally required because of inaccuracies in radar and altimetry data, but they were increasingly seen as “buffers” to allow for effective warnings and ATCO/pilot actions. As none of the previous models consider all the parameters necessary for determining the Ad Hoc separation, a new model will be developed for this purpose based on this approach.

2.5. Literature review of conflict probability models

Risk models were also developed for the calculation of conflict probability. The ICAO defines the term conflict as a situation in which separation minima between aircraft could be compromised [8]. Therefore, conflict and LOS are not the same concept, although they have been used in the literature interchangeably by several authors.

Conflict risk models are of special interest for two reasons. First, conflict and more specifically LOS is a precursor to collision. Secondly, many of these models have been the basis for developing automated conflict detection and resolution (CD&R) tools for the ATC support. As this dissertation proposes the prototype of a CD&R tool to support ATC for the implementation of the Ad Hoc separation concept, it is of interest to present a literature review on this topic.

Netjasov and Janic [64] distinguish between intersection and geometric models for conflict risk estimation. Intersection models began to be developed in the 1970s. These are simple models based on estimating the probability of conflict (2D or 3D) at the crossing point of an airway network considering that aircraft fly trajectories with constant speed. Geometric models were developed later (1990s) and although they consider aircraft flying at constant speed, the initial positions of the aircraft are random.

In intersection models the conflict probability is calculated from traffic flows, speeds and aircraft geometry [64]. Siddiquee was one of the pioneers of such models. The model proposed in [65] aims to predict the number of conflicts at airway crossing points per unit time, based on aircraft flows and speeds and assuming that there are no evasive manoeuvres by the aircraft. This information

is relevant in the strategic time horizon. Siddiquee introduced the concept of the "forbidden zone" associated with an aircraft (whose dimensions correspond to the minimum separation) and the "critical section" associated with a crossing point (and, therefore, dependent on the geometry or angle between tracks), so that if two aircraft meet simultaneously in this section, the LOS occurs. In [66] Siddiquee estimated the LOS duration at airway crossing points.

Dunlay [67] estimated the probability of conflict between aircraft in level flight. The probability of conflict is calculated from the number of times that ATCOs perceive two aircraft losing separation (stimulus-response relationship). Dunlay states that the number of lateral and longitudinal conflicts in a given time follows a Poisson process.

Schmidt [68] extended the earlier models and Geisinger [69] generalised Siddiquee's model to 3D, where aircraft are considered to be in evolution or in level flight. Geisinger states that conflict probability is an indicator that can be used to estimate ATC workload (WL) or to measure the relative risk of a system.

Netjasov [70], [71], [72] established a framework for airspace planning and design based on conflict risk assessment in three time horizons: strategic, tactical and operational. The risk assessment models presented in this framework can be applied to ENR and/or TMA airspace. Firstly, the risk of conflict between a pair of aircraft is estimated and then it is extended to a sector with published airways, although it can be extrapolated to free route scenarios.

- The strategic model is based on the Siddiquee [65] and Schmidt [68] models and is developed for strategic airspace planning. The probability of conflict is calculated from the concept of a "critical region" associated with a crossing point. In fact, it is estimated from the probability of occupancy of the critical section by both aircraft. The probability of occupancy is calculated as the quotient of the critical time or conflict exposure time (time spent crossing the critical section) and the flight time. The conflict risk is calculated as the product of the conflict probability and the airway traffic flows and is considered as a deterministic variable.
- The tactical model is developed for programming purposes at the level of tactical airspace planning. Netjasov characterises conflicts with a new metric called elementary risk. The elementary risk depends on the

magnitude of the separation minima violation and the duration of the conflict. The total risk is calculated as the quotient of the elementary risk and the observed time period.

- The model for the operational level aims to support decision-making processes during the airspace sectorisation process, based on the metrics of conflict risk and task load. In this model, risk is considered as a random variable and is calculated from Allen's interval algebra [73]. Task load is calculated according to [74].

In geometric models, the conflict probability is obtained by integrating the probability density function of aircraft positions over the conflict region [64]. Paielli and Erzberger [75] introduced a model to analytically estimate the horizontal conflict probability between aircraft pairs whose trajectories are predicted with some uncertainty in a free flight environment. The trajectory prediction considers a cross-track error of constant value and a longitudinal error that grows linearly with the wind (ellipse). In this model, speed and error prediction are assumed to be constant throughout the conflict. In [76] the Conflict Probability Estimation (CPE) method presented in [75] is developed considering conflicts between aircraft in non-level flight (climb, descent) and an approximate analytical solution is provided, due to the complexity in its computation.

Irvine and EUROCONTROL [77] developed a geometric model in which the conflict probability is calculated in the horizontal plane (2D). The geometric locus of the conflict defines an elliptical region in a rectangular coordinate system in which the axes represent the trajectories flown by both aircraft. This is obtained by applying the cosine theorem to the encounter geometry when the aircraft are separated by the separation minimum value. The probability of conflict corresponds to the overlap of the distribution of the ratio of the average speeds of the two aircraft and the elliptical conflict region. Cross-track errors in the aircraft trajectory are not considered in this model as they are assumed to be negligible compared to along-track errors. These are modelled from the normal distribution and are assumed to increase with flight time.

If the application of the conflict risk models wants to be shown, a comprehensive review of the early Conflict Detection (CD) models is given in [78]. A total of 68 CD&R modelling methods are analysed and categorised according to six key design factors: state propagation, state dimensions, CD, conflict resolution (CR),

resolution manoeuvres and multiple conflicts. Application of CD&R models to novel concepts in the ATM global system can be found, among others, in [79], [80]. In [79], the CD&R model developed is used in the context of TBO for strategic deconfliction (before becoming reference business trajectories). Research in [80] presents conflict resolution algorithms developed for the integration of the continuous climb operations (CCO) in a TMA.

Finally, over the last decade, the emergence of artificial intelligence and particularly the Machine Learning (ML), has triggered a paradigm revolution. One of the main advantages of ML algorithms is that they obtain information and knowledge from historical data. From databases, algorithms learn patterns and rules to predict new situations. Numerous data-driven studies have been conducted for CD based on these techniques such as [81], [82], [83], [84], [85].

2.6. Review of selected CRMs

In this section, some of the previously mentioned models that are relevant to the development of the model for determining Ad Hoc separation are analysed in more detail.

2.6.1. Reich – Marks CRM [27], [28], [29], [86]

The first CRM was introduced by Brian Marks in the context of oceanic navigation [26] and later developed by Reich [27], [28], [29], [86]. This CRM is applicable to the strategic determination of separation minima in oceanic airspace. Specifically for procedural control scenarios (very low information update rate) with aircraft flying on parallel trajectories.

Aircraft are modelled as boxes of dimensions λ_x (length), λ_y (wingspan) and λ_z (height). To simplify the calculations, one of them is assumed to be a box of double dimensions and the other is assumed to be a particle. Thus, the collision is represented by the particle entering the box. Since aircraft are modelled as boxes, there are three types of collisions: lateral, longitudinal and vertical. Additionally, a box of dimensions $2S_x(\text{std})$, $2S_y(\text{std})$ and $2S_z(\text{std})$ is defined around the aircraft, being $S_x(\text{std})$, $S_y(\text{std})$ and $S_z(\text{std})$ the ATC separation minima values. This box is

called the proximity shell and marks the boundary between a negligible collision risk and a relevant collision risk.

The probability of collision between aircraft can be determined from the distributions of velocity and position deviation of the aircraft. The probability density function of the position errors is assumed to be independent of time. This is justified by the fact that this model is applied to oceanic areas where aircraft fly the same route for several hours and the update rate of information is very low. It is also assumed that the cross-track, along-track and vertical position deviations are independent and also the navigation errors of the aircraft pair.

Reich and Marks identified two parts for the calculation of collision risk. The first is called the collision rate and the second is called proximity. The collision rate is defined as the number of collisions per unit of time and is related to the flight errors. Proximity is the amount of flight time in which a pair of aircraft is exposed to a given separation (separation minima), i.e., the exposure to risk in a controlled traffic system during a time interval.

For the estimation of the collision rate, the probability distribution of the magnitude of the errors and the probability distribution of the rate of change of these magnitudes are required. Since the separation minima is associated with very small values of collision risk, the risk will be determined by the tails of the distribution, since they correspond to errors of very low frequency but large magnitudes.

A collision can only occur if there is an overlap between two aircraft in all three dimensions simultaneously. For instance, considering the lateral collision, for a lateral collision to occur, there must be a simultaneous overlap in the longitudinal (x) and vertical (z) dimensions and the separation in the lateral dimension must be less than λ_y . Consequently, the number of collisions per hour in the lateral dimension (y) is obtained as the product of these three factors ($N_{ay} = f_y P_x P_z$). Extrapolated to the three types of collisions (Equation (1)), the number of collisions per flight hour is obtained as:

$$N_a = f_x P_y P_z + f_y P_x P_z + f_z P_x P_y \quad (1)$$

where:

f_n : expected frequency at which the separation on the n-axis is less than λ_n in one hour or number of aircraft passes in the n-direction.

P_n : probability that the aircraft have an overlap in the n-dimension.

All probabilities can be understood as amount of time in which two aircraft are in overlap in each dimension. Thus, the term P_n can be defined as the product of the expected frequency of two aircraft passing in the n-dimension (f_n) multiplied by the total time of all overlap's duration in that dimension in one hour (t_n). Therefore, for the lateral dimension (Equation (2)):

$$P_y = f_y \cdot t_y \rightarrow f_y = \frac{P_y}{t_y} \quad (2)$$

t_n can be expressed as the distance covered in a superposition ($2 \lambda_y$) divided by the relative velocity in that dimension ($|\bar{y}|$). Therefore Equation (3) is obtained:

$$f_y = P_y \frac{|\bar{y}|}{2 \lambda_y} \quad (3)$$

The collision rate is rewritten and Equation (4) is obtained as:

$$N_a = P_x P_y P_z \left(\frac{|\bar{x}|}{2 \lambda_x} + \frac{|\bar{y}|}{2 \lambda_y} + \frac{|\bar{z}|}{2 \lambda_z} \right) \quad (4)$$

Nevertheless, to obtain the collision risk, the proximity factor shall be added. That is, the collision rate of the aircraft pair has been calculated, but the context in which these aircraft pair fly (the amount of traffic) must be considered. Proximity has previously been defined as the amount of flight time in which a pair of aircraft is exposed to a given separation (separation minima). Estimating the proximity is complex as it depends on other elements such as traffic density or route configuration. Figure 4 shows two types of proximity for the lateral dimension between aircraft A and B in the NAT region.

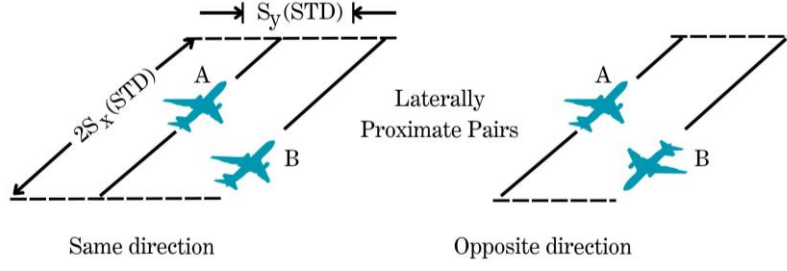


Figure 4. Proximity pairs.

The simplified method for estimating the lateral proximity (E_y) is according to Equation (5):

$$E_y = \frac{2 T_y}{H} \quad (5)$$

Where:

T_y - represents the total time generated in the system by the aircraft in proximity.

H - represents the total number of flight hours generated in the system during the time period considered.

2 - a collision is represented as two accidents.

Finally, by combining the collision rate and proximity, the Reich model expression (Equation (6)) is obtained for the calculation of the expected number of accidents per flight hour as a consequence of the LOS in the lateral dimension (y):

$$N_{ay} = P_y(S_y)P_z(0)\frac{\lambda_y}{S_x}\left\{E_{y_{same}}\left(\frac{|\bar{x}|}{2\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z}\right) + E_{y_{opposite}}\left(\frac{|\bar{v}|}{\lambda_x} + \frac{|\bar{y}|}{2\lambda_y} + \frac{|\bar{z}|}{2\lambda_z}\right)\right\} \quad (6)$$

2.6.2. Hsu Model [37]

The CRM developed by Hsu determines the probability of collision for a pair of aircraft, during a time interval where the collision is likely to take place. It allows for the calculation of the probability of collision in the horizontal plane and in three dimensions between aircraft pairs in a scenario of non-parallel routes, where radar surveillance is not available.

The Hsu model extends and develops the Reich model [87]. Each aircraft is modelled as a cylinder of diameter λ_{xy} and height λ_z . The collision between two aircraft corresponds to the insertion of a particle (representation of one of the aircraft) into a cylinder of double dimensions (representation of the other aircraft).

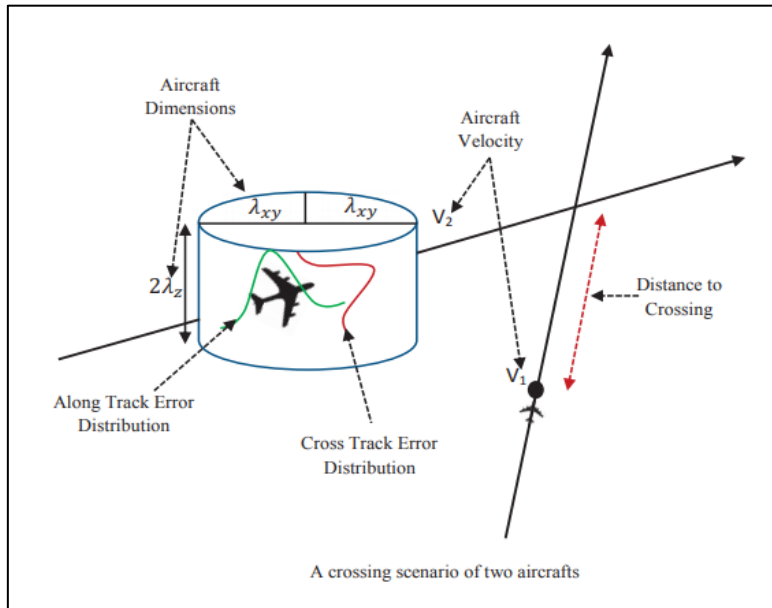


Figure 5. Geometric representation of two aircraft in HSU CRM [87].

Hsu refers [37] that in the Reich CRM the probability of collision is approximated by the expected number of collisions occurring during the flight time. That is, after a first collision, aircraft could collide again, between them or with other aircraft. Hsu proposes a new expression for the calculation of collision risk that overcomes this constraint.

The probability of collision in this model is determined in a different time interval to that used by Reich, who calculates the probability of collision by

taking into account the proportion of time in which the overlap occurs in the corresponding direction. In this CRM the time interval (t_0, t_1) in which the pair of aircraft operates within the route network is considered.

The approach used to estimate the expression for calculating the probability of collision in the horizontal plane is to consider the probability of non-collision in the interval (t_0, t_1) . This is calculated as the sum of non-collision probabilities in all those segments of length Δt between (t_0, t_1) . The horizontal collision probability is obtained by calculating the probability of the complementary event of the probability of non-collision. It depends mainly on the horizontal overlap density function.

From the probability of collision in the horizontal plane, the total probability of collision in three dimensions in the interval (t_0, t_1) is defined as (Equation (7)):

$$CP = P_z(h_z) \left(1 + \frac{|\bar{z}|}{2 \lambda_z} \frac{\pi \lambda_{xy}}{2V} \right) \times HOP \quad (7)$$

where:

$P_z(h_z)$: probability of instantaneous vertical overlapping nominally separated by a distance h_z .

$|\bar{z}|$: average vertical velocity of the aircraft during horizontal overlap.

HOP : horizontal overlap probability.

V : relative speed between aircraft.

A relevant parameter for the calculation of the probability of collision is the horizontal overlap density function. The overlap density function is based on the distribution of position errors and is expressed as a function of the angle of intersection between tracks, aircraft velocities and nominal separation. Unlike Reich, Hsu considers that the distribution of position errors does not remain constant with time.

In this CRM, the Gaussian and DDE (double exponential) probability models are used to model the distribution of position errors and, consequently, the overlapping density functions. Hsu states that this is because position errors

taken under homogeneous conditions obey the Gaussian distribution law; however, large position errors tend to fit better the DDE.

2.6.3. 3D CRM for high density ENR airspaces [88]

This 3D CRM was developed for EUROCONTROL as a method for assessing the European ENR risk due to all causes within the airspace. It is applicable to scenarios with high traffic density and radar surveillance.

It is a data driven model in which the frequency and classification of proximate events are observed from radar data and these are categorised as passing events, conflicts, potential conflicts and potential collisions². The probability of a potential collision is calculated from the radar data and then the 3D CRM estimates the probability that this potential collision will become a collision as a result of the failure of the safety barriers.

The model is based on what Marks stated [26] related to collision risk, which is to divide the model in two parts, the collision rate and the proximity. The model was firstly formulated by Burt in [89] and in this study is developed and improved. The probability of collision is calculated as referred in Equation (8):

$$P(\text{collision}) = FeR * P(\text{pot.coll}/\text{pot.conf}) * P(\text{coll}/\text{pot.coll}) \quad (8)$$

Where,

- *FeR* is the relative frequency of conflict between an aircraft pair. That is, the likelihood that the defined separation standards will be violated. This factor is related to traffic complexity and traffic density.
- $P(\text{pot.coll}/\text{pot.conf})$: is the conditional probability of an aircraft pair to have a potential collision knowing that previously a conflict has taken place. This factor is related to uncertainties and kinematics and represents

² ICAO with the Global Air Traffic Management concept [8], adopted a more strategic conflict management to overcome the limitations of the tactical one. To reflect this movement towards a more strategic conflict management, some terms changed in meaning, such as conflict, potential conflict and LOS.

In the current context, LOS is defined as the situation in which the separation minima between aircraft are lost while conflict is defined as a situation in which separation minima between aircraft could be compromised. The term potential conflict is not used. Nevertheless, in tactical conflict management (that of the past), conflict was defined as the current LOS while the term potential conflict was used to refer to the current meaning of conflict.

This is why some authors still use the old terminology.

the severity of the encounter. It is calculated based on radar data and from the convolution of the bi-dimensional density function of the predicted Closest Point of Approach (CPA) between the involved aircraft and the distribution of aircraft lateral and vertical errors in the projected position.

- $P(coll/pot.coll)$: is the conditional probability of a collision between an aircraft pair if previously a potential collision has taken place. This factor represents the performance/effectiveness of the safety barriers (ATC, Short-Term Conflict Alert (STCA) or Traffic Alert and Collision Avoidance System (TCAS)). It is calculated based on radar data and the accident precursors.

2.6.4. Irvine Conflict Risk Model [77]

Irvine developed a geometric model for the calculation of the conflict probability in the horizontal plane (2D). The geometric locus of a conflict between aircraft pairs defines an elliptical region in a rectangular coordinate system. The axes (x,y) represent the distance of aircraft 1 and aircraft 2, respectively, to the crossing point (Figure 6).

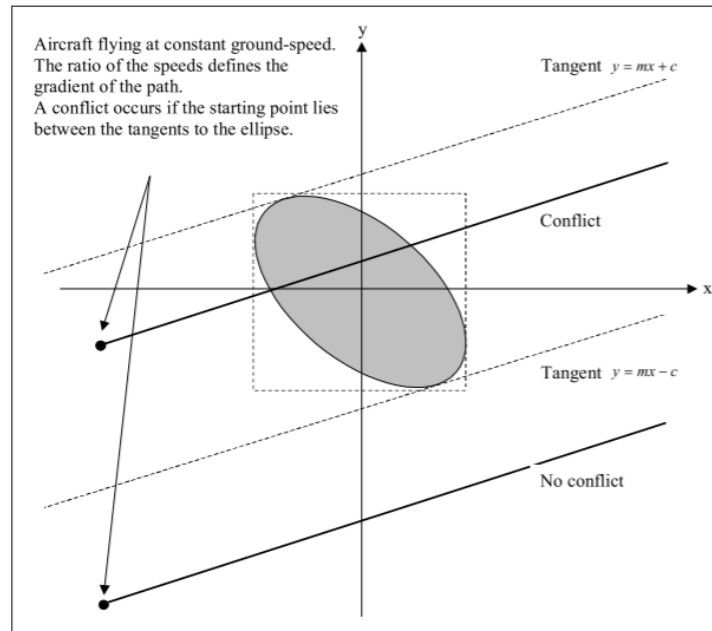


Figure 6. Rectangular coordinate system with elliptical conflict region [77].

Cross-track errors of the aircraft trajectory are not considered in this model as they are assumed to be negligible compared to the along-track errors. Along-track errors are modelled from the normal distribution and are assumed to increase with flight time. This is equivalent to a speed error of 15 knots (kt), which could be rewritten as $k(15) \cdot N(0,1)$. Therefore, the along-track distance flown by an aircraft at a time t is the sum of a planned component ($d(0)$) and an unpredictable error, which taking some considerations, depends on the speed error and could be written as Equation (9):

$$d(t) = d(0) + (v_p + kN_t(0,1)) \quad (9)$$

The along-track distance of both aircraft from the crossing point at any time, define a point in this rectangular coordinate system. The temporal evolution of the point which represents the relative position of the aircraft describe a straight line if the speeds of aircraft are constant. If it is considered that during the encounter (within the region of possible conflict) the aircraft fly with planned constant speed and at time t there are errors ($k N(0,1)$), this temporal evolution could be approximated by a straight line. The gradient of this straight line is given by the ratio of the Ground Speed (GS) of both aircraft referred in Equation (10):

$$\frac{v_y}{v_x} = \frac{v_{py} + kN_y(0,1)}{v_{px} + kN_x(0,1)} \quad (10)$$

Because the elliptical region (centred into the crossing point) defines all the points which represent the geometric locus of a conflict, depending on the position of the line regarding the ellipse, the conflict will take place or not (Figure 7). Important points are those for which the line is tangent to the ellipse. These values are calculated from the system of equations composed by the equation of the ellipse and the equation of the line defined from the initial point and the gradient.

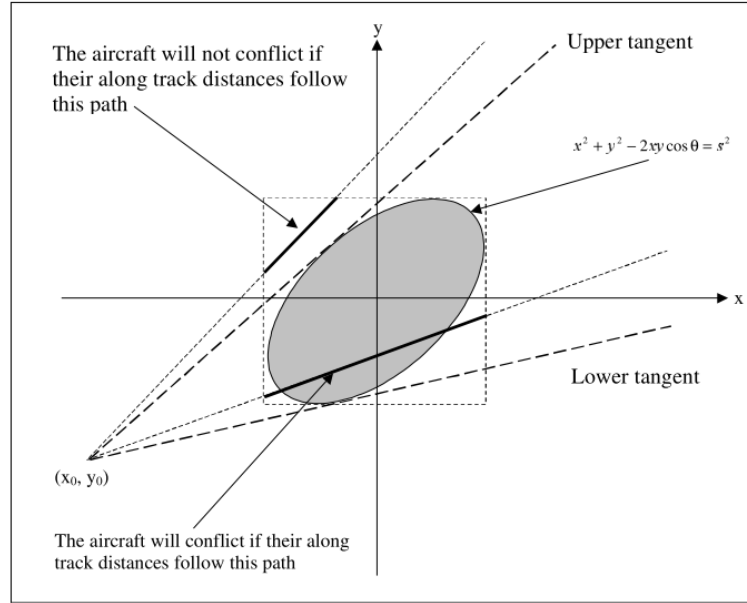


Figure 7. Relative position of the line regarding the ellipse [77].

Considering that GS errors of both aircraft are independent, the distribution of the ratio of the speeds is given by the difference of two normal distributions, which is, in turn a normal distribution. The probability of conflict corresponds to the part of this distribution that lies between both points of tangency.

2.7. Limitations of current models for developing the ADSM

In the previous subsections the historical evolution of CRMs and conflict risk models has been analysed, with a more detailed explanation of some of them. As a conclusion, CRM and conflict models are not the same. While the former have been used to determine the separation minima, the latter have been the foundation of the CD&R algorithms in ATC support tools. As new separation minima values will be defined in this dissertation, a CRM will be used for this purpose. The models presented and analysed have some limitations that make them non-appropriate for the determination of Ad Hoc separation. These limitations are:

1. Application to scenarios with procedural control.

Most CRMs were developed to be applicable to scenarios with procedural control and are based on navigation and speed errors. However, in scenarios with surveillance, errors do not come from inaccurate navigation or surveillance performance, but from operational errors (HF). A novel concept such as Ad Hoc separation must be applied to future scenarios and, therefore, with surveillance control. For this reason, models for scenarios with conventional control are not applicable for Ad Hoc separation.

Moreover, it is not possible to use data-driven CRM, since, although these are applicable to radar scenarios, they require, in general, a considerable amount of data (radar traces or ADS B data). However, since the concept of Ad Hoc separation is new, there is no data to feed into the CRM, so this approach should also be rejected.

2. The HF is not considered in the majority of the models.

Originally, the CRMs developed focus more on technical risk, i.e. risk as a consequence of system errors (navigation, surveillance, etc.), but do not include risk due to human action (operational risk) [90]. Many authors agree that, for scenarios with surveillance, the separation minima have to be considered in terms of "time buffer", meaning that there is time to detect and correct operational errors.

3. Complex mathematical formulation.

Classical CRMs were developed by mathematicians. This means that although they have a solid mathematical foundation and formulation, they are hard for non-mathematician researchers to understand when they want to develop them for application to more complex scenarios, resulting in a lack of confidence in these models by the ANSPs, ATCOs or Pilots.

4. Need for consideration of additional factors.

Although the CRMs analysed consider factors such as navigation errors or encounter geometry, there is none that includes all the factors that determine Ad Hoc separation: aircraft model, aircraft mass, FL, encounter geometry, avoidance manoeuvre (AM), human factor and wind conditions.

Therefore, since none of the studied CRMs is applicable, in this dissertation a CRM will be developed that allows the determination of the ADSM.

2.8. Summary

In this chapter it has been presented a general background of the separation minima concept and CRMs. On the one hand, it is noted that current separation values were determined decades ago. On the other hand, after the analysis of the different models, it has been concluded that it will be necessary to develop a new CRM in order to determine the ADSM. This CRM must include the fundamental parameters that influence this Ad Hoc separation.

In addition, it has been shown that most CRMs have been used to determine the separation minima in procedural control scenarios, whereas this determination has been empirical for radar scenarios. The CRM for Ad Hoc separation will be based on the concept of time buffers, as referred to by experts for the determination of separation in a radar environment.

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3. AD HOC OR VARIABLE SEPARATION CONOPS DEFINITION

3.1. Introduction

CONOPS is a statement of “what” is envisaged [8]. It is a high-level description of the ATM system, an overview and a vision statement that asks and answers what results are expected from the concept, i.e. how this new ATM concept is going to be operated. This chapter describes the Ad Hoc separation CONOPS, introducing the operational scenario, the new mode of operation, the CNS operational and functional requirements and the necessary enablers.

Regarding the time horizon, ADSM concept would be expected to be implemented in the medium term, which means between the years (2030-2035). Therefore, all the requirements and enablers needed for the implementation should be ready for that period.

Some of the work in this chapter is based on the following Conference Proceeding presented in *Congreso de Ingeniería del Transporte CIT 2021: R-Evolucionando el transporte (14°.2021.Burgos)*. Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, “Ad Hoc Minimum Separation: A challenge for Air Traffic Control (ATC)”, <https://doi.org/10.36443/10259/7010>

3.2. Ad Hoc or Variable Separation Minima Concept Definition

The concept of the ADSM refers to the application of a variable separation value for each aircraft pair within the same volume of airspace (Figure 8), depending on a set of factors such as aircraft model, FL or encounter geometry.

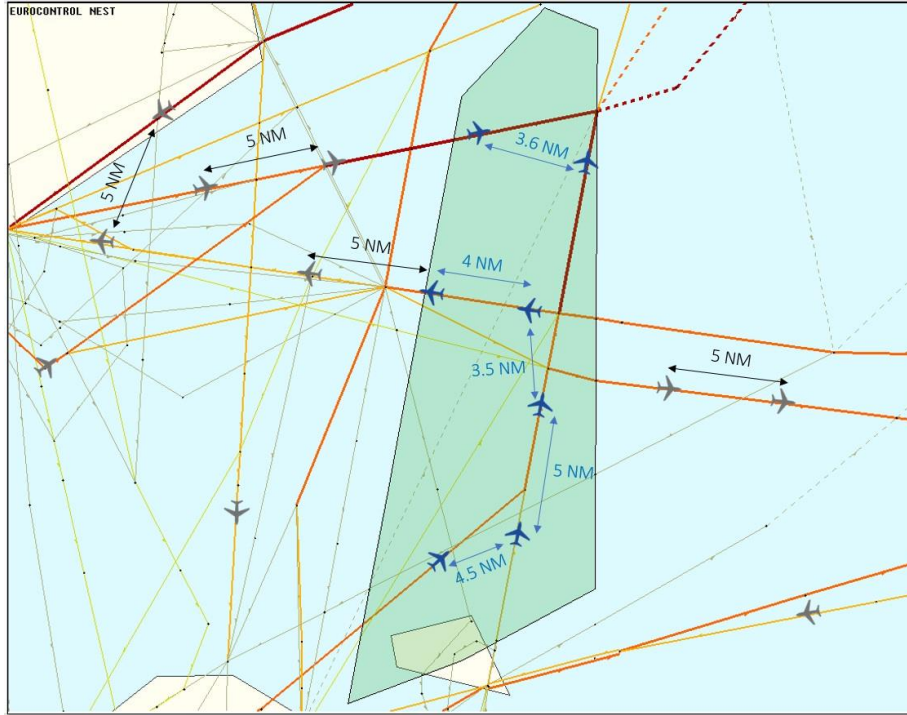


Figure 8. Conceptual representation of ADSM concept.

As noted in subsection 1.2.2, the ADSM shall be the largest between the AMWS and the AMAS applicable to a specific encounter. In this dissertation, the AMAS will be determined, while the AMWS is out of the scope and will be investigated in further work. Therefore, when referring to the ADSM in this dissertation, the AMAS is actually being addressed. Regarding the ENR wake vortex separation minima (MWS), there are projects [16], [17], [18] that have investigated their redefinition. In fact, in the R-WAKE project [16], different MWS are defined in the ENR phase depending on the aircraft categories and the geometry of the encounter (which is a kind of variable separation for the MWS). In light of these results, where the MWS is in some cases less than 5NM, it is expected that AMAS and AMWS can be successfully integrated in future research. AMAS values are determined on the basis of the following elements:

- Aircraft Models
- Aircraft Mass
- Aircraft Speed
- Encounter Geometry (Intersection Angle)
- Avoidance Manoeuvre (AM)
- FL
- Wind Conditions
- Human factor (HF)

The main feature of this new separation mode is that there is a set of possible separation minima values within the range of 3NM–5NM³. This concept therefore implies not only the application of different separation minima values depending on the situation, but also the reduction of the separation minima wherever possible. The possible Ad Hoc separation values within the defined range will be specific (3NM, 4NM, or 5NM)⁴. These extreme values are considered because:

- **Upper limit value (5NM):** currently in ENR scenarios with surveillance the defined horizontal separation minimum is 5NM.
- **Lower limit value (3NM):** in ENR phase when the preceding aircraft belongs to an equal or lower category than the succeeding one the MWS separation may be smaller than 5NM [16]. There are several projects that have studied or are studying the reduction of MWS and are proposing new ENR MWS values [16], [17], [18]. It was therefore decided to use the value of 3NM as the lower limit of the range of variable separation.

3.3. Operational Scenario

For the development of the methodology, the application of this concept in this first stage is limited to:

- ENR airspace, sectors of medium-high complexity and traffic density. Although control sectors are individually referred, for greater benefit, the concept could be implemented in a larger airspace (i.e. ACC).
- Upper FLs are considered (FL 340–FL 660).
- Aircraft flying at the same FL. These are the majority in the cruise segment. This means that it is just considered horizontal separation minima.
- A scenario of predefined routes.

³ As will be mentioned below, the ADSM will only be determined for the horizontal plane in this first stage of the concept development.

⁴ In the first stage of the concept development the Ad Hoc separation values are specific (3NM, 4NM or 5NM). Nevertheless, in further stages, other separation values could be applied with higher resolution (i.e. 3.5NM).

Nevertheless, because this is a novel concept, once its feasibility is demonstrated, its application will be extended to 3D (aircraft in evolution) and to FRA (Free Route Airspace), which are the future scenarios towards which the ATM system is evolving. Therefore, in this first stage, the separation between aircraft pairs in which unless one is in evolution, is maintained at the current values of the separation minima.

3.4. Mode of operation

3.4.1. ATCO – ASMT interaction

Applying different separation minima values in the same volume of airspace means that the ATCO is unable to mentally calculate the ADSM, as opposed to the current fixed value (5NM). Therefore, ATCOs need a new tool which presents this separation value for each aircraft pair in the airspace under their responsibility. In this separation mode the monitoring role of the ATCOs become more important and even more complex. Hence, a new tool is necessary when this concept is implemented in an airspace, the ASMT (Ad Hoc Separation Minima Tool).

ASMT shows ADSM values for each aircraft pair to the ATCO. In other words, the ATCO remains the agent of separation, but the concept of operation in the control exercise changes somewhat. ADSM values are not calculated in real time by the ASMT but are calculated strategically for a specific sector and specific aircraft pair situation (FL, encounter geometry, aircraft models, etc.) and saved in a database. This is because Ad Hoc separation values must be subjected to a collision risk assessment to determine, prior to implementation, whether they are safe or not.

The ASMT, not only provides ATCOs with Ad Hoc separation values for aircraft pairs but also informs ATCOs with preventive information in a two-step process: by identifying conflicting situations and suggesting manoeuvres to resolve them. The main difference from a typical CD&R tool is that ASMT calculates specific Ad Hoc separation values for each aircraft pair and CD&R tasks are performed according to that Ad Hoc separation value. Therefore, the ASMT includes CD&R functionalities.

The ASMT is developed for the tactical ATCO, who continuously monitors the state of the aircraft throughout the airspace. It is composed of different modules (Figure 9): trajectory prediction module, situation of interest (SI) detection and characterisation module, Ad Hoc separation determination module, CD module and CR module. Therefore, this tool is intended to mitigate the increased complexity in the system as a result of the different separation minima values to be applied. In this way, the ATCOs are expected to perform their tasks without an increase in their workload (WL).

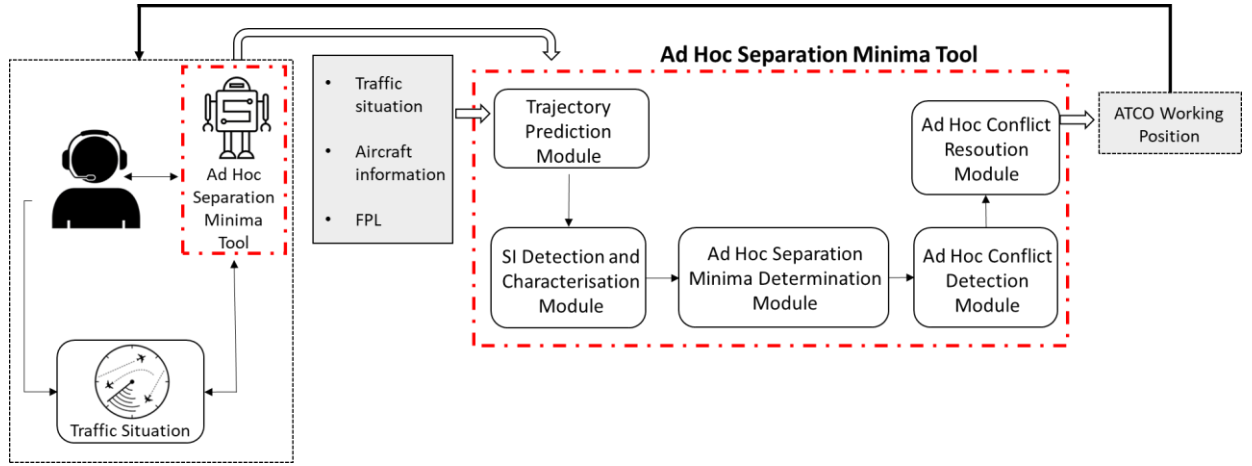


Figure 9. ASMT architecture and relation to the working position of the ATCO.

3.4.2. ASMT mode of operation

In this subsection the ASMT mode of operation is explain briefly. A deeper explanation is included in Chapter 6 of this dissertation.

The ASMT (through the trajectory prediction module, Figure 9) predicts the trajectory of those aircraft that are close to entering the sector in a short time horizon (e.g. 30 minutes before entering, although this is a customisable value) and the trajectory of those aircraft that are already in the sector. This prediction is based on real-time information of the aircraft speed, FL, aircraft mass, wind conditions (this information is provided by the aircraft) and the FPL. Furthermore, it will calculate the distance between predicted aircraft trajectories (Figure 10). The trajectory prediction module is considered to be included in the ASMT. However, a current trajectory predictor external to the ASMT could be used and the predicted trajectories could be an input to the ASMT.

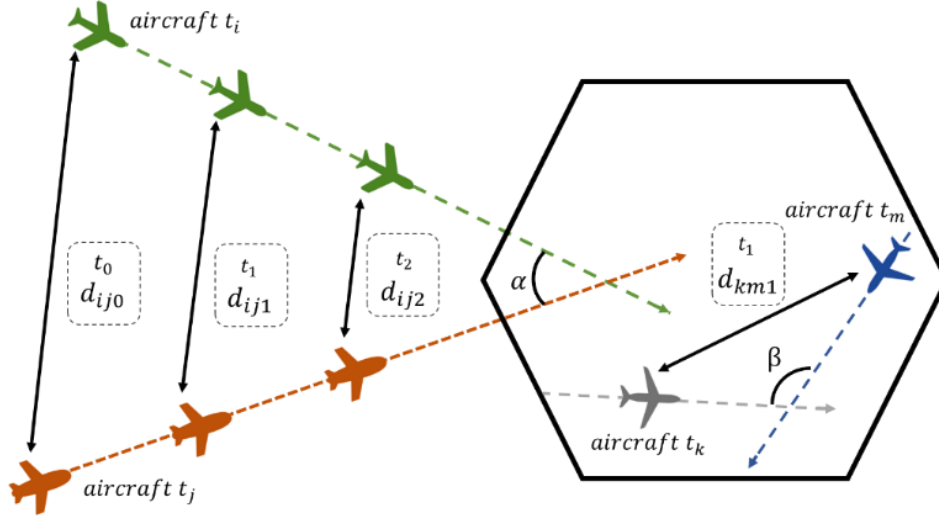


Figure 10. Trajectory prediction by ASMT.

From the aircraft trajectories prediction, situations of interest (SI) are analysed. A SI is a situation in which an aircraft pair is expected to intersect with a horizontal separation smaller than a predefined distance [81]. Typically, this predefined separation is specified by the ANSP and is larger than the separation minima. In this work 10NM was defined. Therefore, if the Euclidean distance between two predicted aircraft trajectories (positions) is going to be lower than 10NM and both aircraft are in the same FL, a SI is detected and is characterised according to the following features: aircraft models, aircraft masses, speeds of the aircraft, FL, crossing angle and wind conditions.

After the characterisation of the SI, the ASMT searches for the ADSM applicable value in a database. This database contains the ADSM values for different situations and for a specific ENR sector. In addition to determining the ADSM to be applied for a SI, the ASMT tool calculates the distance value between the aircraft pair at the Closest Point of Approach (*DCPA*), the Time to the Closest Point of Approach (*TCPA*) and the Time to LOS (*t2LOS*) once the SI has been detected and characterised. These data (ADSM, *DCPA*, *t2LOS* and *TCPA*, among others) are displayed on the ATCO screen by the ASMT.

Apart from showing Ad Hoc separation values, the ASMT is a CD&R tool. Once an aircraft pair has been classified as SI and its ADSM determined, the conflict probability is calculated for that specific ADSM (by the CD module). If conflict probability reaches a threshold, an alert (graphical and audible) is presented to

the ATCO and a set of horizontal resolution manoeuvres to avoid the LOS are proposed (it is considered that just one aircraft of the aircraft pair performs the conflict resolution manoeuvre). It is up to the ATCOs to decide when to apply the conflict resolution manoeuvre and to which aircraft.

This CR module calculates real-time manoeuvres in the horizontal plane to avoid LOS occurrences. It should not be confused with the AM (avoidance manoeuvre), which, as will be seen later in Chapters 4 and Chapter 5, is a manoeuvre in the vertical plane to avoid the collision and is associated with the ADSM. The ASMT will also inform the ATCO about the AM associated with the ADSM in the specified time interval.

In the future, fully developed versions of ASMT are expected to replace the Short-Term Conflict Alert tool (STCA) in scenarios where the Ad Hoc concept is implemented. As a CD&R tool, ASMT will encompass all the functionalities of STCA.

Regarding data provision, it is assumed that the aircraft is sending data (wind data, aircraft mass, speed, etc.) to the ASMT. In the situation where the aircraft ceases to send its trajectory to the ASMT or the data sent does not meet the required quality indicator, a separation value of 5NM would be re-established between that aircraft and all other aircraft in the sector.

3.5. CNS Requirements

One of the main issues of the CONOPS is the definition of the technical requirements in terms of CNS. The implementation of this concept and the consequent reduction of separation minima requires aircraft and ground system to be capable of ensuring minimum performances from the improved technical systems available. Failure to comply with any of the CNS requirements would reinstate a reference separation value of 5NM which corresponds to the current applicable standard and the maximum value of the ADSM.

3.5.1. Navigation

Aircraft operating in these scenarios are required to have PBN capability, in particular RNAV certification and approval. PBN requires that for 95% of the flight time, performance related to lateral and longitudinal accuracy, continuity, availability and integrity are guaranteed. RNAV 5 is the ENR specification required for aircraft which fly in scenarios with Ad Hoc separation concept implemented.

The Total System Error (TSE), which is the lateral and longitudinal accuracy required for aircraft during 95% of flight time, for RNAV 5 is 2.51NM [91]. This TSE value was defined as a function of GNSS. However, for VOR/DME nav aids, the corresponding TSE is higher and depends on the distance from the point to the VOR/DME nav aid. Nowadays, aircraft mostly fly with GNSS.

A study performed in the UPM [11] modelled the actual deviation value of aircraft position flying RNAV 5 specification with GNSS. For different segments of SID and ENR, actual radar trajectories were recorded (months of June, July and August 2019) and analysed to determine the cross-track error. Results shown that a conservative upper bound of cross-track deviation was 0.4NM for aircraft flying RNAV 5 specification with GNSS. Some results of this study are included in ANNEX A of this dissertation.

Therefore, the navigation specification required for the Ad Hoc separation concept is RNAV5 but flown with GNSS sensor. Currently, almost all commercial aircraft are certified and approved to this specification. Actual measured navigation deviation values (0.4NM) are used to model navigation uncertainty in the simulations performed in this dissertation.

In the situation of GNSS signal loss (because of signal interference, receiver system failure, loss of coverage, etc.) the pilot shall notify the ATC service (as the aircraft will revert the navigation to other sensors) and the current separation minimum value of 5NM shall be applied for the separation of this aircraft from the rest in the scenario. Furthermore, in those continental areas where GNSS service problems may exist, Ad Hoc separation concept will not be implemented.

3.5.2. Communication

Communications service is available throughout the volume of airspace. Non-urgent communications would be via data link (Controller Pilot Data Link Communications (CPDLC)) while urgent communications would be oral in the Very High Frequency (VHF) band. However, some improvement in communications will be necessary so that, in the case of urgent communications (those situations in which separation minima is lost), the ATCO-Pilot instruction with the corresponding readback could be completed in the shortest time possible. For this purpose, specific phraseology will be defined for these urgent communications. This phraseology is included in Chapter 4 (section 4.2.2).

A study with real communications has been performed to demonstrate the temporal duration of current communication when ATCO issues an instruction related to a manoeuvre, such as velocity modification, heading modification, direct to clearance or level modification and the pilot provides a readback of the communication. This study is included in ANNEX B of the present dissertation.

3.5.3. Surveillance

In scenarios where this concept is implemented the ATC surveillance service shall meet with the following requirements defined by EUROCONTROL [59] for a horizontal separation minimum of 3NM (Table 1). This is because ADSM values will be between 3NM and 5NM.

To fully meet all these requirements (Table 1), surveillance based on ADS in radar controlled areas (ADS RAD) is required. ADS is a surveillance technology designed to allow aircraft to report information via data link to the ground segment. Automatic means that non-intervention of the pilot is needed. Because is dependent, means that other onboard systems (such as navigation systems) shall it provide information. Surveillance control is only possible with ADS if the aircraft positioning is based on GNSS. Two different techniques of sending the information to the ground segment exist, ADS-B and ADS-C. With ADS-C, a contract is established between the aircraft and the ground segment to transmit the agreed data at the agreed frequency. Communication is point-to-point. The ground segment establishes a contract specifying the characteristics of the reports, the frequency at which the report is issued and the conditions. Whereas

with ADS-B, data is transmitted via a broadcast data link at regular intervals so that it can be used by any user on the ground or in the air.

For the Ad Hoc separation concept, ADS-C will be the required technique, since not only surveillance service shall be provided, but also it is needed some extra information essential for the Ad Hoc separation, such as wind or aircraft mass information. Because mass information is sensible to the users, point-to-point communications are preferable.

In the ADS-C, the transmission of information is by ADS-C reports. The update frequency of the information provided by the aircraft (reports) shall be high, less than or equal to 4s. These reports, if agreed in the contract, may include any of the following groups [92]: basic group, flight identification group, earth reference group, air reference group, airframe identification group, meteorological group, predicted route group, fixed projected intent group and intermediate projected intent group. In controlled airspace in which Ad Hoc separation concept is implemented, meteorological group shall be included in the contract between the ATS Units and the airspace users in order to know wind information (direction and intensity)⁵.

The on-board GNSS receiver provides the ADS-C transmitter with a position accuracy indicator (figure of merit, FOM) and a position integrity indicator (horizontal protection level, HPL) together with other data [93]. It is a prerequisite that the figure of merit corresponds to the satellite navigation system (FOM 6) and not to other systems (FOM 5 - DME/DME, FOM 3 - Inertial, etc.), otherwise the default separation value (5NM) would be applied among those aircraft not complying with this requirement.

In the event of a regional loss of GNSS positioning capability and consequently, the inability to comply with any of the requirements (Table 1), radar surveillance would be used as a contingency system and separation management would be provided under current conditions (5NM fixed separation value).

⁵ It should be noted that one of the factors influencing ADSM is the wind (direction and intensity), therefore this information is considered relevant.

Table 1. Mandatory and recommended performance requirements for 3NM horizontal separation provided by ATCO [59].

Req. #	Quality of service	Mandatory performance	Recommended performance	Justif.	Assessment
3N_C-R1	Measurement interval for probability of update assessments (R2, R7 and R14)	Less than or equal to 5 seconds	Less than or equal to 4 seconds	2.2.1 2.2.2	4.2.1
3N_C-R2	Probability of update of horizontal position	Greater than or equal to 97% for 100% of the flights, any flight below 97% shall be investigated as defined in R22 and Greater than or equal to 97% global, counting only target reports based on a horizontal position measurement with a data age lower than or equal to 7 sec	Greater than or equal to 97% for 100% of the flights, any flight below 97% shall be investigated as defined in R22 and Greater than or equal to 99 % global	2.2.3 2.2.4	4.2.2.1
3N_C-R3	Ratio of missed 3D position involved in long gaps (larger than 3 x MIs + 10%)	Less than or equal to 0.5%	--	2.2.5	4.2.3
3N_C-R4	Horizontal position RMS error	Less than or equal to 300 m global and less than 330 m for 100% of the flights, any flight above 330 m shall be investigated as defined in R22	Less than or equal to 210 m global and less than 230 m per flight	2.2.6 2.2.7	4.2.4
3N_C-R5	Ratio of target reports involved in series of at least 3 consecutive correlated horizontal position errors larger than 555m – 0.3NM	--	Less than or equal to 0.03 %	2.2.9	4.2.5
3N_C-R6	Relative time of applicability of horizontal position for aircraft in close proximity (less than 11110m – 6NM)	--	Less than or equal to 0.3 second RMS	2.2.10	4.2.6
3N_C-R7	Probability of update of pressure altitude with correct value	Greater than or equal to 96 % global	--	2.2.11	4.2.2.2
3N_C-R8	Forwarded pressure altitude average data age (see Note 9 in §3.4.6)	Less than or equal to 4s	--	2.2.12	4.2.7
3N_C-R9	Forwarded pressure altitude maximum data age	Any forwarded pressure altitude data item with an age greater than or equal to 16s shall be considered as not available when assessing R3, R7, R8 and R10	--	2.2.13	4.2.7
3N_C-R10	Ratio of incorrect forwarded pressure altitude (see Note 9 in §3.4.6)	Less than or equal to 0.1 %	--	2.2.14	4.2.8

Req. #	Quality of service	Mandatory performance	Recommended performance	Justif.	Assessment
3N_C-R11	Pressure altitude unsigned error (see Note 9 in §3.4.6)	Less than or equal to 200/300 ft in 99.9% of the cases for stable flights and less than or equal to 300 ft in 98.5% of the cases for climbing/descending flights	--	2.2.15	4.2.9
3N_C-R12	Delay of change in emergency indicator/SPI report	Less than or equal to 7.5s for 100% of the cases, case above 7.5s shall be investigated as defined in R22	--	2.2.16	4.2.10
3N_C-R13	Delay of change in aircraft identity	Less than or equal to 15 s for 100% of the cases, case above 15s shall be investigated as defined in R22	--	2.2.17	4.2.11
3N_C-R14	Probability of update of aircraft identity with correct value (see Note 9 in §3.4.6)	Greater than or equal to 98% global	Greater than 98% per flight	2.2.18 2.2.19	4.2.2.2
3N_C-R15	Ratio of incorrect aircraft identity	Less than or equal to 0.1%	--	2.2.20	4.2.12
3N_C-R16	Rate of climb/descent RMS error	--	Less than or equal to 250 ft/mn for stable flights and less than or equal to 500 ft/mn for climbing/descending flights	2.2.21	4.2.13
3N_C-R17	Track velocity RMS error	--	Less than or equal to 4 m/s for straight line and less than or equal to 8 m/s for turn	2.2.22	4.2.14
3N_C-R18	Track velocity angle RMS error	--	Less than or equal to 10° for straight line and less than or equal to 25° for turn	2.2.22	4.2.14
3N_C-R19	Density of uncorrelated false target reports	--	Less than or equal to 2 false target reports per area of 100NM ² and over a duration of 720 applicable measurement intervals	2.2.23	4.2.15
3N_C-R20	Number per hour of falsely confirmed track close to true tracks	--	Less than or equal to 1 falsely confirmed track per hour that are closer than 16700m – 9NM from true tracks	2.2.24	4.2.16
3N_C-R21	Continuity (probability of critical failure)	--	Less than or equal to 2.5 10 ⁻⁵ per hour of operation	2.2.25	4.2.17
3N_C-R21	Investigations	Flights/cases for which requirements R2, R4, R12 or R13 are not achieved shall be investigated and an impact assessment conducted and appropriate risk mitigation/reduction measures introduced if necessary.	--	NA	--

3.6. Enablers

An enabler is a new or modified technical system/infrastructure, HF element, procedures, standard or regulation necessary to make (or enhance) an operational improvement [94]. According to the requirements for the Ad Hoc separation CONOPS, the following enablers shall be considered:

- **Extended Projected Profile (EPP)**

One of the main factors for determining the ADSM is the aircraft mass. This information is predicted by the airline FPL in each point of the route and calculated in real time by the FMS.

The EPP is a technological solution for the transmission to the ground segment key information obtained from the FMS. This information, such as speed profiles, mass, aircraft intention, etc. are downlinked in real time to the ground systems via ADS-C. The downlink of the EPP data from the aircraft and the processing of these data by the ATC systems is expected to be covered by the end of the year 2027 in all the European Union Single European Sky States (EU SES) [95].

- **Extended FPL (eFPL)**

In the event that real-time aircraft mass information could not be transmitted to the ground segment, mass predictions along the aircraft route (airline FPL or via eFPL) would be required.

Extended Flight Plan is a FPL, which, in addition to the ICAO FPL data, also includes flight trajectory information in the form of 4D trajectory (filed trajectory), as calculated by the operator of flight, as well as Performance Data specific to the flight [96]. Through eFPL predicted aircraft mass information along the route of the aircraft could be transferred to the ground segment. This enabler is expected to be ready in the ECAC by the year 2026 [97].

- **ASMT**

A new ATC support tool shall be developed for the implementation of the Ad Hoc separation concept in an airspace. This tool will present to the ATCO the ADSM because he/she is unable to mentally calculate which value of separation minima applies to each aircraft pair. Moreover, it will include CD&R functionalities, according to each ADSM.

- **Specific communication procedures to ensure reduced time communication**

The communication procedure in an emergency (a LOS situation) should incorporate specific phraseology.

- **Change in the ATCO mode of operation**

The ATCO remains the agent responsible for maintaining separation between aircraft, although it will assume a greater monitoring role in this concept. This entails certain changes in its mode of operation for which the ATCO will need to be trained. In particular, these changes affect the ATCO-ASMT interaction.

The ATCO should follow the ASMT indications regarding the separation minima to be applied and the CD&R tasks. Therefore, it should rely on the ASMT and trust that the separation minima value presented as well as the conflict situations alarms are correct.

Regarding the resolution tasks to avoid the occurrence of a LOS, to obtain the greatest benefits, the ATCO should issue the instruction to the pilot after the ASMT alert and accept one of the resolution manoeuvre suggestions proposed by the tool. These manoeuvres are determined with a sufficient temporal buffer and the criterion of optimising the resolution, aiming for minimal distortion or deviation of the aircraft trajectory from the estimated one.

- **Necessary standards or regulation**

Regarding the regulatory aspects⁶, two types of procedures exist in order to implement the Ad Hoc separation concept: long-term process and short-term process. In both cases the publication or amendment of official documents is necessary. Spanish example is used to illustrate the process.

The long-term process (Figure 11) may last between 5 and 10 years. The Member State wishing to implement this concept (i.e. the Spanish Aviation Safety Agency (AESA)) submits the request to its ICAO Region (i.e. the European – North Atlantic (EUR/NAT Region)). If it is considered relevant to global operations, ICAO discusses the issue in the ATM Operations Panel (ATM OPS Panel). The ICAO ANC Committee approves or rejects it.

- If approved, the concept would be included in the PANS ATM document (Doc. 4444). Subsequently, European Union Aviation Safety Agency (EASA) would publish it as an Acceptable Means of Compliance (AMC) or Guidance Material (GM), in case it is wanted to be followed by the Member States.
- In the event of rejection by the ICAO ANC Committee, the concept would be returned to the ICAO ATM OPS Panel for further development.

⁶ This PhD was awarded last year by the EASA for an exchange. Regulatory aspects regarding this new concept were discussed with their experts.

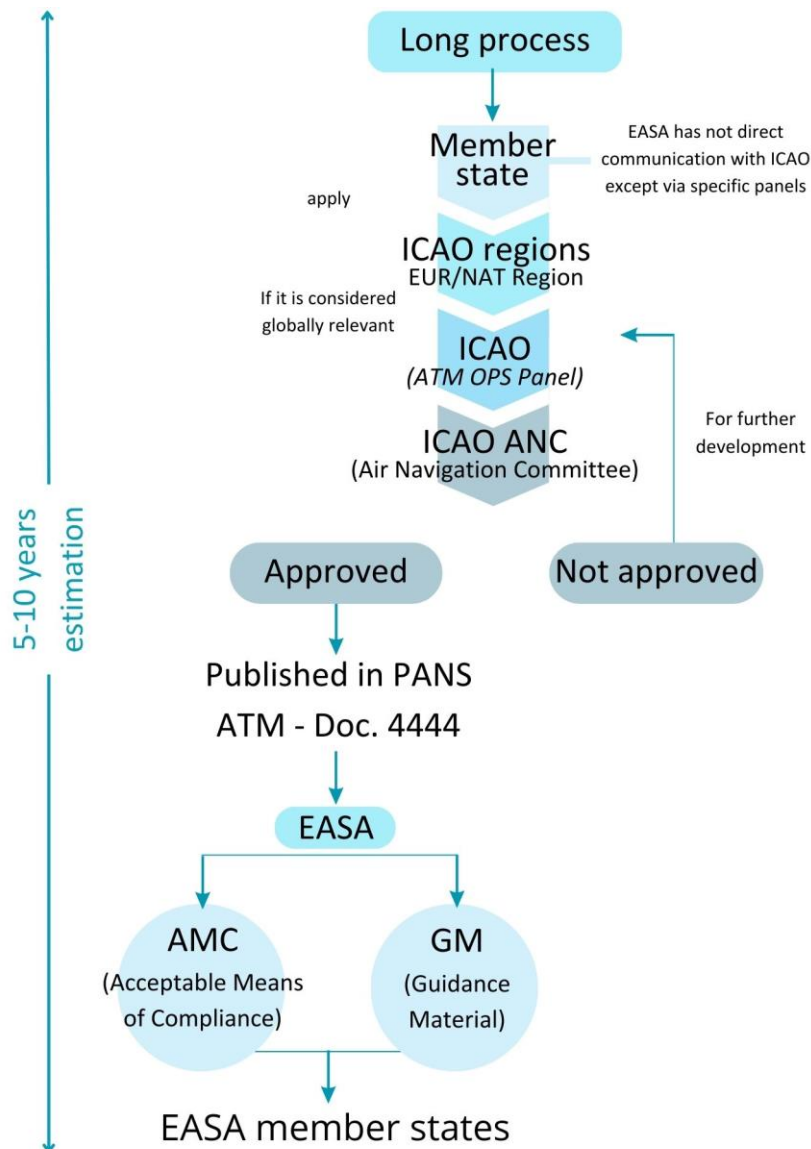


Figure 11. Flow chart diagram for long term process of regulatory issues (EASA experts).

The short process duration can be estimated at two years (Figure 12). The ATS service provider (i.e. in Spain, ENAIRE) must apply to the civil aviation authority (i.e. AESA) to implement the concept. The civil aviation authority will, if deemed appropriate, approve an Alternative Means of Compliance (AltMoC) and communicate it to EASA for evaluation.

- If the EASA assessment is positive, the civil aviation authority will implement the concept. If other states approve such an AltMoc, EASA will consider publishing it as an AMC or GM. And, if deemed relevant to global operations, it would be considered by ICAO through ICAO panels.

- If the EASA assessment is negative, the civil aviation authority will not implement the concept.

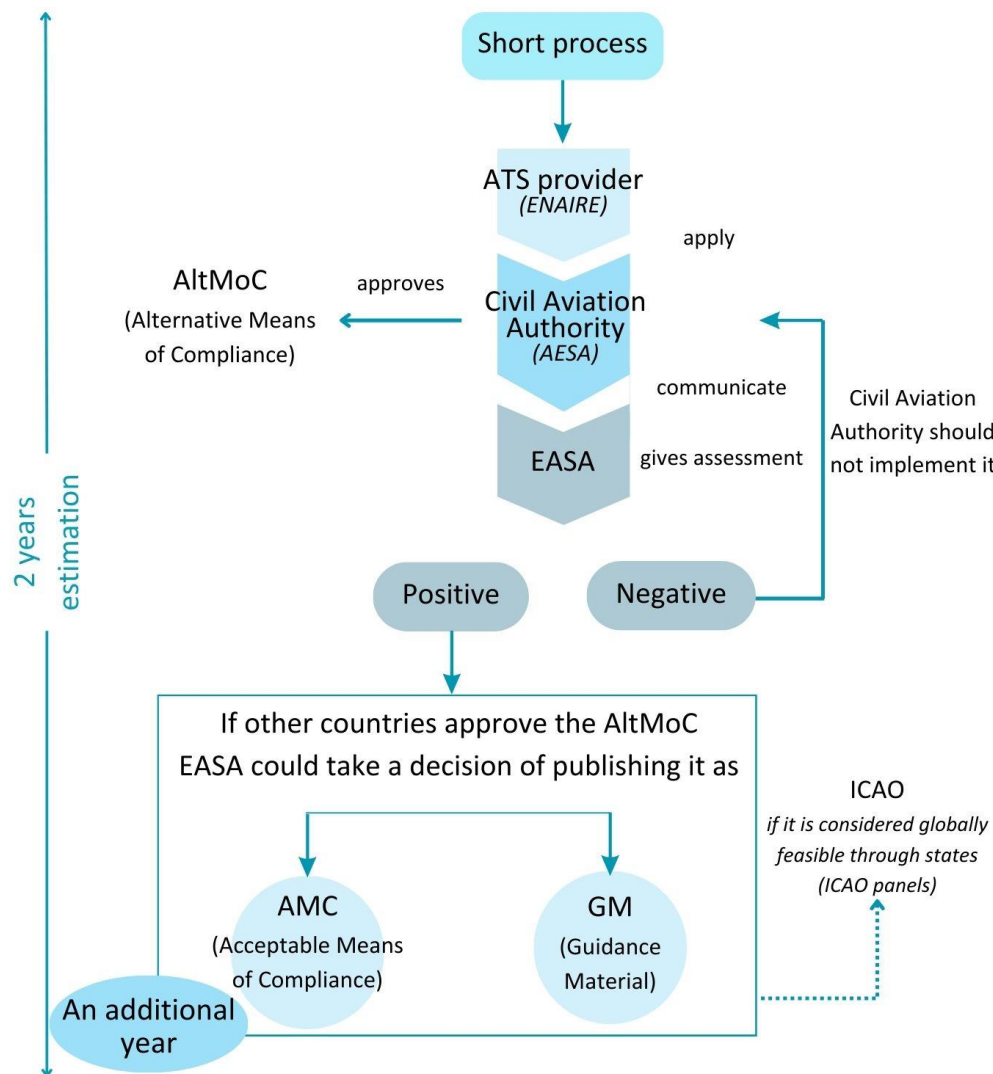


Figure 12. Flow chart diagram for short term process of regulatory issues (EASA experts).

3.7. Compatibility with other concepts and systems

- Future ATM scenario – new concepts

The future CONOPS according to the ATM Master Plan [5] relies on the Trajectory Based Operations (TBO). TBO is a comprehensive SESAR concept, based on a wide range of solutions that, when combined, help achieve the envisaged paradigm change.

In this concept, the trajectory, which represents the airspace users' business/mission intentions and integrates ATM and airport constraints, is developed and agreed for each flight resulting in a reference trajectory that the airspace user agrees to fly and ANSPs and airports agree to facilitate. The integration of trajectory management processes in the planning and execution phases concerns the management, negotiation and sharing of the shared business trajectory (SBT), as well as the management, update, revision and sharing of the reference business trajectory (RBT) and finally the transition from SBT to RBT.

The TBO concept is closely linked to others such as Free Route or eFPL and it is necessary that the concept of Ad Hoc separation is compatible with them. While the TBO concept is strategic, the concept of the Ad Hoc separation is tactical. Initially, it is believed to be compatible. However, this needs to be further analysed in future work.

- Systems compatibility

The CONOPS of the Ad Hoc separation needs to be compatible with safety nets. Particularly, with the Airborne Collision Avoidance System (ACAS) system and the STCA system.

- ACAS/TCAS system

ACAS is designed to act as a last resort safety net to prevent MAC. ACAS interrogates the ICAO standard compliant transponders of aircraft in the vicinity. Based upon the replies received, the system tracks, the slant range and altitude (when it is included in the reply message), ACAS II can issue two types of alerts:

- Traffic Advisories (TAs), which aim to help the pilots in the visual acquisition of the intruder aircraft and to alert them to be ready for a potential resolution advisory.
- Resolution Advisories (RAs), which are avoidance collision manoeuvres recommended to the pilot. An RA will tell the pilot the range of vertical rates within which the aircraft should be flown to avoid the intruder aircraft. An RA can be generated against all aircraft equipped with an altitude reporting transponder (Mode S or

Mode A/C); the intruder does not need to be fitted with ACAS II. When the intruder aircraft is also fitted with an ACAS II system, both systems coordinate their RAs through the Mode S data link, to select complementary resolution senses. ACAS II does not detect non-transponder equipped aircraft or aircraft with a non-operational transponder.

Depending on the altitude of the aircraft, the sensitivity level (SL) of the TCAS system differs, which means that the horizontal time horizons in which the TA or RA triggers varies. For ENR airspace SL 7 applies, which means that aircraft fly above FL200. These times are: 48s for TA and 35s for RA. ADSM values are defined to be compatible with the ACAS system. That is, the defined separation minima shall be high enough so that, in the temporal dimension, they are not below the RA resolution alarm (35s). Nevertheless, this compatibility needs to be studied in detail in future work.

- STCA system

STCA is a system that alerts the ATCO of any situation where defined separation minima values between any aircraft pair is predicted to be violated within a short look ahead time (typically 2 minutes). This is achieved by means of a visual alert on the radar display, although some systems also provide an audible alert.

The ASMT contains two modules (CD&R) which make it itself an STCA. This means that the ASMT must not only show the ATCO the applicable ADSM between a pair of aircraft, but it must also predict if the Ad Hoc separation between the pair of aircraft will be violated and propose a resolution manoeuvre to the ATCO.

3.8. ADSM Publication Aspects

Nowadays, MRS values defined are published in the AIP, in ENR 1.6 section. These separation minima values are classified depending on the control dependencies and surveillance features.

Regarding the Ad Hoc separation, a section in the AIP shall be included explaining the concept and presenting some separation minima values to allow the users the understanding of the concept. Since the ADSM values are different for each encounter and for each control sector, there are many separation values, so it is not meaningful to publish them completely in the AIP.

3.9. Summary

In this Chapter, the Ad Hoc separation CONOPS is presented. Essentially, CONOPS refers to how a new ATM concept is going to be operated.

Firstly, the Ad Hoc separation concept and the factors that characterise it are discussed. It is emphasised that the ADSM determined in this doctoral thesis correspond to the AMAS, while the definition of the AMWS is out of scope and will be investigated in future work. However, results from the R-Wake project are positive (reduction of MWS in ENR phase depending on the situation) and it is expected that AMAS and AMWS could be successfully integrated. The ADSM shall be the greatest between the AMWS and the AMAS.

Subsequently, the features of the operational scenario and the mode of operation are defined. Particularly, in this first stage of the concept development, an ENR airspace with predefined routes is considered, with the ADSM just defined for the horizontal dimension. Regarding the mode of operation, the ATCO remains as the agent responsible for aircraft separation but acquires a greater monitoring role.

In addition, the CNS requirements and enablers necessary for the implementation of the concept are defined. The compatibility with other concepts or systems is discussed. Finally, a consideration of the publication aspects of the concept is included.

4. ADSM MODEL

4.1. Introduction

Once the Ad Hoc separation CONOPS have been defined, the model for the development of the Ad Hoc separation is presented.

For this purpose, firstly, the framework of the ADSM model is addressed. The variables used to define these separation minima are discussed and their behaviour with the parameters that define them is analysed. These variables are calculated for specific cases in simulations with the BADA model in a worst-case scenario. Secondly, from the analysis of the simulation results, it is possible to state that the concept of the Ad Hoc separation is preliminarily feasible.

The work presented in this chapter is based on the following paper:

Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, Fedja Netjasov, Irene García Moreno, Eduardo S. Ayra. Preliminary Feasibility Study of the Ad Hoc Separation Operational Concept. *Aerospace* 2023, 10, 539. <https://doi.org/10.3390/aerospace10060539>

4.2. Model for the ADSM definition

In order to establish the ADSM model and its fundamental variables, it is first necessary to know quantitatively the different parameters that influence the separation minima (ICAO defined this influence theoretically [13]). For this reason, an analysis of the factors contributing to the separation minima is presented in ANNEX C. However, since the objective is to quantify this influence, a data-driven approach is followed together with expert judgement. Based on the Bayesian Network (BN) model this influence is studied.

The ADSM model is defined as a layer-based model in which the manoeuvrability of the aircraft and the HF are considered. In particular, it focuses on the set of activities that must be performed in order to prevent a LOS from turning into a collision in the temporal dimension (time buffer). There are two main reasons for following this approach, which are:

- According to the analysis of the contributing factors to LOS criticality (ANNEX C), the probability that a LOS occurs due to technical systems (CNS) failure is practically negligible compared to the probability that a LOS occurs as a result of HF error.
- Mehadhebi [90] and Brooker [63] state that in scenarios with surveillance the risk should not be modelled from navigation errors or radar inaccuracies but from operational error. Moreover, they refer that separation minima are seen as “time buffers”.

4.2.1. Framework of the ADSM Model

The model for the development of the Ad Hoc separation is based on the approach of conceiving the separation minima as a barrier to collision. That is, they are a buffer to ensure that in case of a LOS, the situation does not develop into a collision. Therefore, the barrier to collision is the separation minima while the precursor to collision is the LOS.

This notation of precursors and barriers is adopted from the EUROCONTROL Integrated Risk Picture (IRP) model [98]. This model states that the MAC occurs due to the combination of barrier failures and the occurrence of precursors due to these failures. Figure 13 illustrates this relationship; it is the equivalent of a ‘Swiss cheese’ diagram (or Reason’s layered model). The IRP model is shown alongside the ICAO conflict management layers (strategic, tactical and immediate)[8].

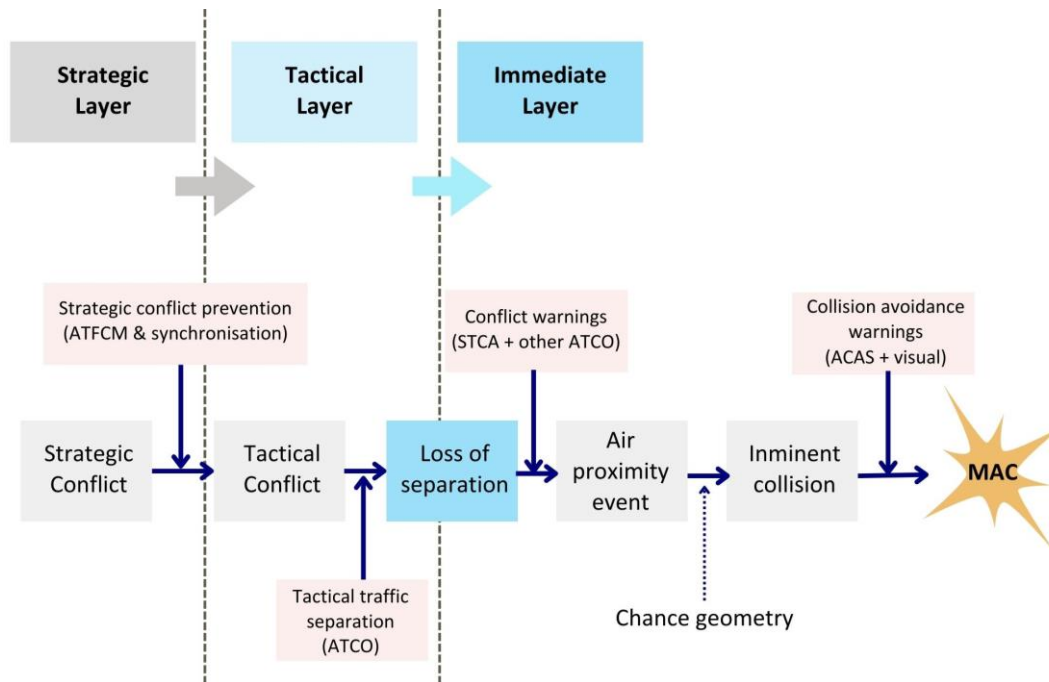


Figure 13. Barrier diagram for MAC, IRP model and ICAO conflict management layers. Barriers are indicated in pink, while precursors are indicated in grey.

ICAO [8] defines the separation minima as the minimum displacements between an aircraft and a hazard (which could be another aircraft) that ensure the risk of collision remains at an acceptable level of safety. A key concept associated with the separation minima is the separation mode [8], which is an approved set of rules, procedures and conditions of application associated with separation minima. The relation between separation minima and separation mode is clearly seen in the EUROCONTROL IRP model. This model analyses the precursor–barrier relationship from the strategic time horizon. The values of separation minima are associated, on the one hand, with the separation mode (a way of working, mode of operation). That is, from the strategic layer, barriers are working to avoid the collision. And, on the other hand, with a risk of collision that must be lower than a TLS.

For this reason, the Ad Hoc separation model is based on the IRP/Reason’s models and the Encounter Timeline concept (which refers to the set of actions that must be taken to avoid a LOS becoming a collision, in the temporal dimension). Two fundamental variables of this model, which will be described in depth in the following sections, are the Necessary Time and the Available Time.

The Necessary Time (t_{nec}) is the time required to perform the collision avoidance actions, without considering the safety nets (as established by ICAO in [22]). Therefore, t_{nec} is made up of the time allocated to different actions: the time required by the ATCO to detect the LOS, the time to communicate the AM to the pilot, the reaction time of the pilot, the response time of the aircraft and the time required by the aircraft to complete the AM. The latter time (time required by the aircraft to complete the AM) depends on the following factors: the aircraft model, the mass⁷ of the aircraft, the kind of AM performed (climb or descent) and the FL at which the aircraft is flying. Therefore, also the t_{nec} depends on these parameters.

The Available Time to avoid the collision ($TCPA$) is defined as the time since the separation minimum is lost until the CPA. $TCPA$ depends primarily on the geometry of the encounter, the aircraft velocities (closing speed rate), the separation minima, the wind conditions and also the FL.

Thus, it can be stated that t_{nec} will be different for each aircraft and for different FL. That is, each aircraft has its own MTOW and its own performance, which varies with FL. For example, climbing 500 feet (ft) to FL380 with an aircraft mass of 0.6 MTOW is not the same as climbing 500ft to FL340 with 0.8 MTOW. The $TCPA$ will be different for each encounter geometry, for the speeds of the aircraft and the applicable separation minima. It is noteworthy that equal $TCPA$ values result from different situations (Figure 14). In other words, a $TCPA$ of 40s could be the result of an encounter geometry of 60° between tracks, aircraft speeds of 480 kt and separation minima of 5NM, but it could also be the result of an encounter of 25°, aircraft speeds of 460 kt and 480 kt (aircraft 1 and aircraft 2's speeds, respectively) and separation minima of 3NM.

⁷ In this study aircraft mass is referred as a percentage of the MTOW. MTOW is the data provided by BADA model. The difference between mass and weight is assumed.

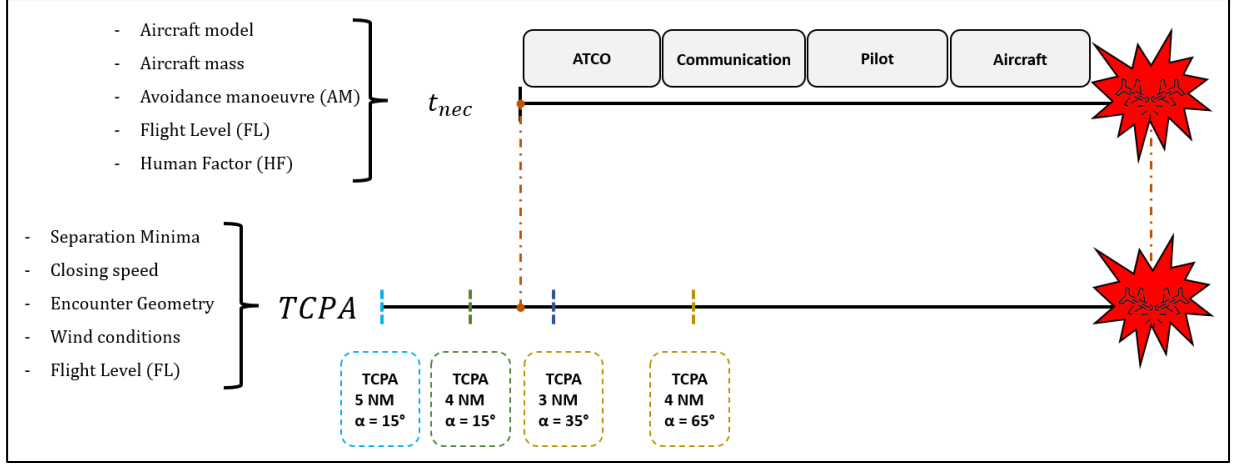


Figure 14. Diagram of t_{nec} and $TCPA$ in the short time horizon to collision.

A collision is defined as a situation wherein the $DCPA$ between two aircraft, which have already lost the separation minima, is equal to or less than 500ft (NMAC distance, according to [99]), with the t_{nec} to perform the AM being greater than the $TCPA$ (Equation (11)).

$$Collision = (DCPA < 500 \text{ ft}) \cap (t_{nec} > TCPA) \quad (11)$$

Those situations in which t_{nec} is lower than $TCPA$ are potential situations in which the separation minima corresponding to this $TCPA$ could be applied. This would imply that for the separation minimum applied to a particular situation for which the values of t_{nec} and $TCPA$ have been calculated, the collision would not occur, as the AM could be executed. Therefore, the determination of the variables t_{nec} and $TCPA$ is paramount. It is important to note that safety nets (such as TCAS) are not considered. This last requirement is in line with the ICAO [22] when examining separation minima. Nevertheless, as stated in [100], [101], ground safety nets such as STCA can be considered for the TLS assessment.

4.2.2. Necessary Time (t_{nec})

t_{nec} is defined as the time required to perform a set of actions to prevent that a LOS becomes a collision without considering the safety nets. Therefore, the LOS has taken place. This is in line with the Encounter Timeline concept [102], [103], [104]. t_{nec} is made up of the time allocated to three different actions (Figure 15):

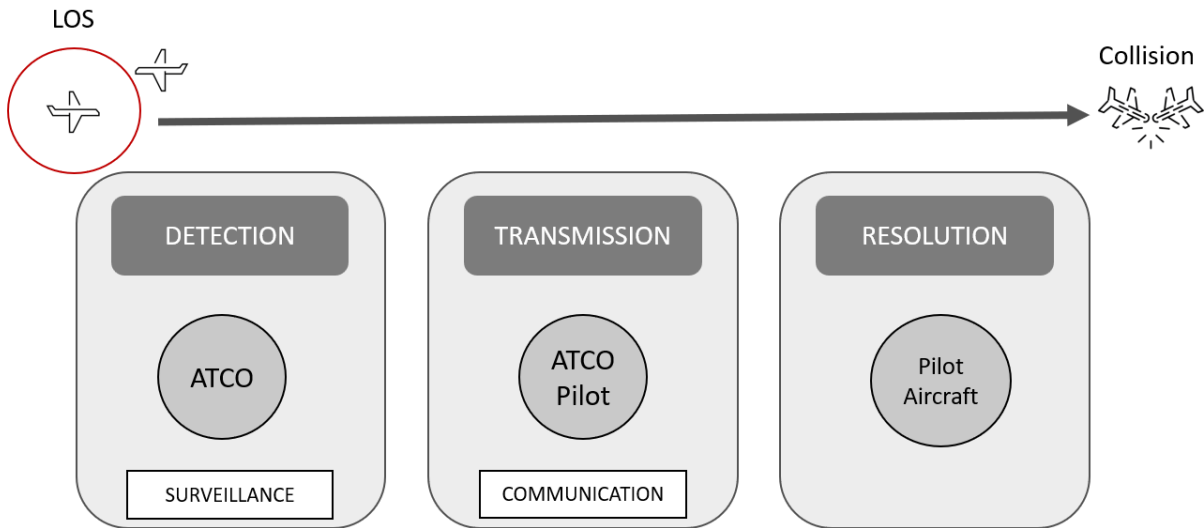


Figure 15. t_{nec} based on Encounter Timeline concept.

- Detection of the LOS by the ATCO once it has taken place (worst-case scenario).
- Transmission of the instruction for the avoidance manoeuvre (AM) from the ATCO to the pilot (communication ATCO - pilot).
- Collision avoidance when the aircraft performs the AM. The AM is the manoeuvre, executed by the aircraft after being instructed by the ATCO, to avoid the collision with the other aircraft. It is a vertical manoeuvre (Figure 16) consisting of a climb or descent (either with the Rate of Descent (ROD) limited to 1500 ft/min or unlimited) of the manoeuvring aircraft to cross the other aircraft (non-manoeuving) at least 500ft away, which is the NMAC distance [99]. Only one of the two aircraft performs the AM, which is the manoeuvring one.

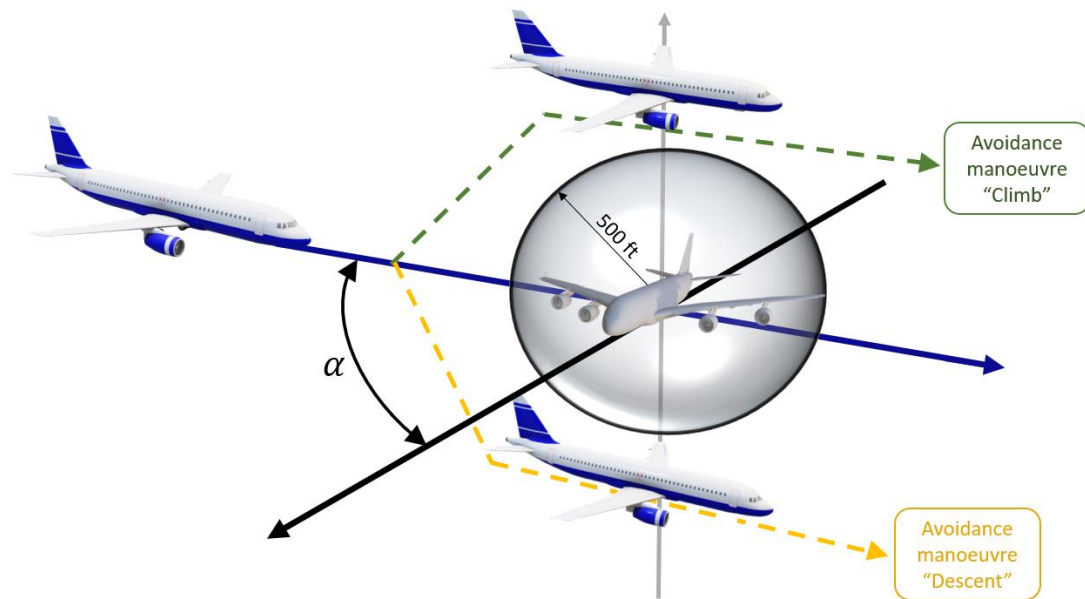


Figure 16. Climb and descent AMs.

4.2.2.1. Detection Layer

The first component of the Encounter Timeline refers to the state information acquisition cycle and the evaluation step. This is the time required for the LOS detection by the ATCO (t_{ATCO}).

It is considered that the ATCO controls an ENR sector. The ATCO receives information from surveillance sources (ADS-C in a RAD environment) with an update rate of equal to or less than 4s (requirement). Therefore, the majority of LOS would be detected before they occur. Furthermore, the ATCOs are assisted by the STCA system, or other tools or functionalities that help them in the task of detecting conflict situations before they occur. The model is based on the worst-case scenario, i.e. the ATCO realises about the LOS once the separation minimum between aircraft has already been lost.

As soon as the ATCO detects the LOS, he/she shall communicate to the pilot the AM to be performed (either a climb or a descent) as an instruction. This AM will be provided automatically by the ASMT (because the AM is associated with the ADSM defined between that aircraft pair). This information, provided automatically by the ASMT, avoids the need for the ATCO to spend extra time thinking about the best manoeuvre to be executed by the aircraft.

4.2.2.2. Transmission Layer

The transmission layer refers to the time required by the ATCO to communicate the ATC instruction of the AM to the crew (t_{com}). This time is the addition of the time allocated to the following actions:

1. Duration of the first ATCO transmission;
2. Delay between the end of the ATCO's initial transmission and the beginning of the pilot's response;
3. Duration of the pilot's initial response to the ATCO's first transmission.

A specific study has been performed with real communications in the LECMZMU sector, presented in ANNEX B.

Moreover, for the urgent communication of the AM instruction from the ATCO to the pilot, a specific phraseology is defined.

1. For the climb manoeuvre:
 - *ATCO: "CALLSIGN, AVOIDANCE MANOEUVRE, CLIMB WITH MAXIMUM RATE OF CLIMB IMMEDIATELY"*
 - *PILOT: "CLIMBING, CALLSING"*
2. For the descent manoeuvre with unlimited ROD (UNL ROD):
 - *ATCO: "CALLSIGN, AVOIDANCE MANOEUVRE, DESCEND WITH MAXIMUM RATE OF DESCENT IMMEDIATELY"*
 - *PILOT: "DESCENDING, CALLSING"*
3. For the descent manoeuvre with limited ROD (LIM ROD to 1500 ft/min):
 - *ATCO: "CALLSING, AVOIDANCE MANOEUVRE, DESCEND WITH A RATE OF AT LEAST 1500 ft/min IMMEDIATELY"*
 - *PILOT: "DESCENDING 1500, CALLSING"*

4.2.2.3. Resolution Layer

In the resolution layer, the pilot performs the collision AM. Depending on how this AM is executed by the aircraft, the approach is different, although the detection and transmission layers are equal for both approaches. Two different procedures exist: the first is the execution of the manoeuvre by the autopilot, the second by the pilot manually. As it can be seen in Figure 17, different assumptions shall be considered depending on the procedure.

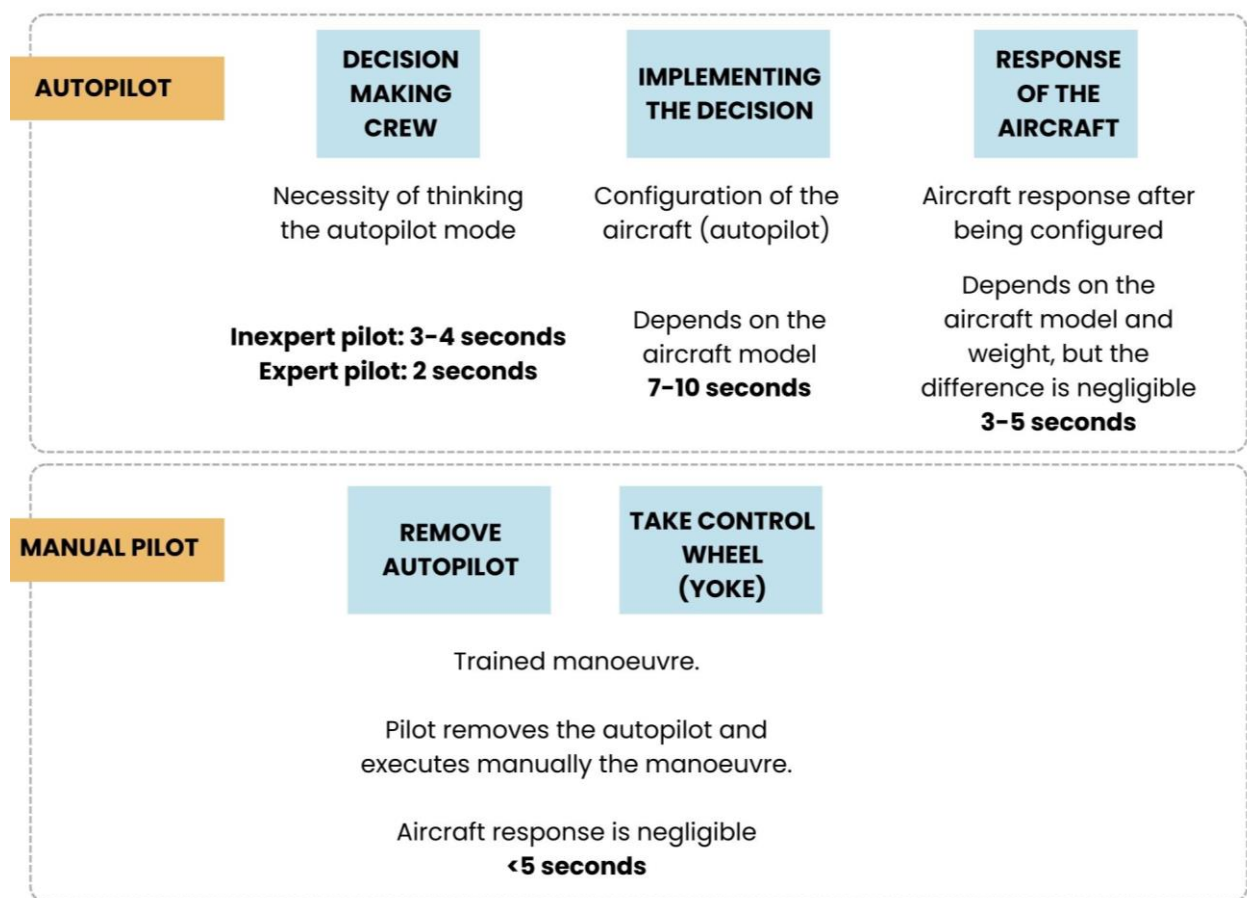


Figure 17. Manoeuvring options by the pilot (EASA experts).

1. The manoeuvre executed by the autopilot is not an AM. It is practically divided into three stages: the crew's decision phase (necessity of thinking the autopilot mode), the implementation of this decision (configuration of the autopilot) and the aircraft's response. According to EASA experts⁸, this action is spread over a period of 12 to 20s.
2. The manoeuvre executed manually by the pilot is typically an AM. In this case, the pilot must disengage the autopilot and take the control wheel. This action is trained by the pilots and must be executed in a time equal to or less than 5s (according to EASA experts and [105]). This is an immediate manoeuvre. Therefore, this procedure is the one followed for an AM.

As a result, in the resolution layer, it is necessary to consider the pilot reaction time to the ATC instruction (t_{pilot}) and the time required by the aircraft to execute the manoeuvre (t_{reqAM}). A response time of the aircraft (t_{res}) is considered, in order to adopt a conservative approach.

1. The t_{pilot} is the time needed by the pilot to process the instruction given by the ATCO and execute the necessary actions to perform, manually, the AM. These actions are:
 - disengage the autopilot
 - take the joystick
2. Regarding the response time of the aircraft (t_{res}), it is defined as the temporal delay from the time the pilot triggers the manoeuvre until the aircraft begins to perform it. The time needed by the aircraft for a change from 60–70% thrust (cruise thrust) to maximum thrust (climb AM) is not zero; there is a response time on the part of the aircraft which is relevant for the determination of the t_{nec} parameter. Two factors need to be considered: the vehicle's inertia and the aerodynamic response (aerodynamic stability).

⁸ This PhD was awarded last year by the EASA for an exchange. EASA experts reviewed documents that are part from this thesis. Additionally, for 15 days, meetings were held in Cologne with experts in which some aspects of the dissertation were subjected to expert judgment.

3. The t_{reqAM} is calculated based on the BADA 3 model [106]. It is the time needed by the manoeuvring aircraft to climb or descend from the altitude at which both aircraft are flying, until a margin of 500ft above or below the non-maneuvring aircraft is reached.

Once all factors have been explained in depth, the t_{nec} is determined according to Equation (12):

$$t_{nec} = t_{ATCo} + t_{com} + t_{pilot} + t_{res} + t_{reqAM} \quad (12)$$

4.2.3. TCPA or Available Time

Another important variable in the model is the Available Time needed to avoid the collision or *TCPA*. This is defined as the time since the separation minima is lost until the CPA (note that it is considered that the CPA is always below the separation minima). In the worst-case scenario, CPA represents the collision between aircraft. *TCPA* depends primarily on the geometry of the encounter, the aircraft velocities, the wind conditions and the separation minima.

4.2.4. Worst-case simulations for the t_{nec} and *TCPA* determination

In this section, an overview of the simulations performed in MATLAB® for the determination of the t_{nec} and *TCPA* variables is given. Simulations are deterministic and based on the BADA model.

BADA is an accurate performance model developed by EUROCONTROL which provides theoretical specifications to simulate the behaviour of any aircraft. It is based on the ‘Total Energy Model (TEM)’, a three-degrees-of-freedom (3DOF) model that relates (Equation (13)) the rate of work done by forces acting on the aircraft (Thrust and Drag) to the rate of the increase in potential and kinetic energy [106].

$$(Thr - D) \cdot V_{TAS} = mg_0 \frac{dh}{dt} + mV_{TAS} \left(\frac{dV_{TAS}}{dh} \right) \left(\frac{dh}{dt} \right) \quad (13)$$

Where,

Thr — thrust acting parallel to the speed vector [Newtons]

D — aerodynamic drag [Newtons]

V_{TAS} — true velocity [m/s]

m — aircraft mass [kilograms]

h — geodetic altitude [m]

g_0 — gravitational acceleration [9.80665 m/s²]

$\frac{d}{dt}$ — time derivative [s⁻¹]

A scenario-based model of geometric/intersection type was developed (Figure 18). A worst-case scenario is designed, because the aim of these simulations is to provoke a collision and to obtain actual values of t_{nec} and $TCPA$.

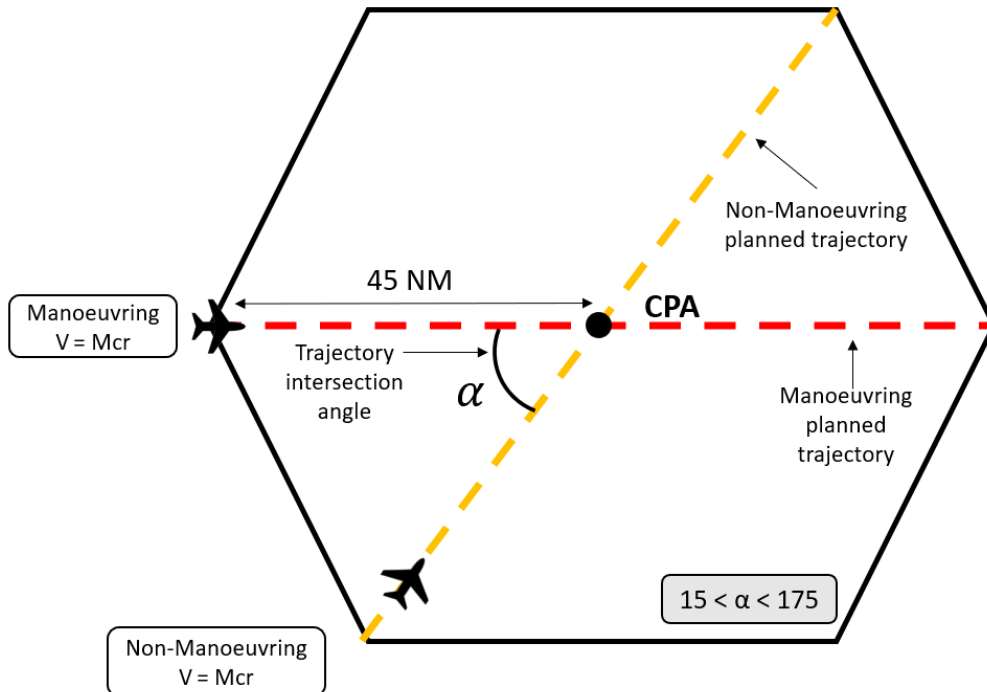


Figure 18. Conceptual representation of the scenario simulated for determining t_{nec} .

The initial position of the manoeuvring aircraft in the horizontal plane and the initial velocities (or specific cruise Mach number for each aircraft model) of both the manoeuvring and non-manoevring aircraft are provided as inputs to the simulation.

The simulation model is based on the following assumptions:

- Aircraft trajectories intersect at a specific angle.
- Simulations are calculated for different encounter geometries (from 15° to 175° in 10° steps) in order to simulate a wide range of cases.
- The starting point of the non-manoevring aircraft is calculated based on the angle between airways, given the initial position of the manoeuvring aircraft, which is fixed. This is because the collision is being provoked (both aircraft reach the intersection point at the same time) to consider the worst-case scenario.
- Aircraft velocities are constant during the simulation of encounters.
- Aircraft fly at the same FL. This is because the model is applied to 2D. Simulations are performed separately for FL350, 360, 370, 380, 390 and 400.
- The model is deterministic. With these simulations, the collision is searched for the worst-case scenario. Therefore, uncertainties are not considered to facilitate the collision calculation.
- Four different aircraft models (AC1, AC2, AC3, AC4)⁹ are considered to simplify the study. Three of them are M type (wake turbulence classification) while one is H type. This criterion is followed because in the LECMZMU reference scenario and in an ENR upper airspace, the aircraft mix is generally 90% M and 10% H.

Table 2 summarizes control and target variables for simulations with BADA model and their nomenclature in the pseudo-code, which is presented below:

⁹ Due to confidentiality issues with BADA licence it is not possible to mention the specific aircraft models, as comparisons between them could be made based on results obtained.

Table 2. Control and target variables of the worst-case simulations with the BADA model.

Target Variables		
Nomenclature	Explanation	Values in the simulation
t_{nec} (scalar value)	Necessary Time	> 0
$TCPA$ (scalar value)	Available Time	> 0
Control Variables		
Nomenclature	Explanation	Values in the simulation
$ac_{manoeuvring}$ (vector)	Aircraft that executes the AM	AC1(M), AC2(M), AC3(M), AC4(H)
$ac_{non-manoeuvring}$ (vector)	Aircraft that does not execute the AM	AC1(M), AC2(M), AC3(M), AC4(H)
AC1_data, AC2_data, AC3_data, AC4_data (array)	Aircraft data	MTOW, Mach, surface wing, FL Maximum Aerodynamics (drag coefficients) Engine thrust (climb/descent thrust coefficients...) Fuel flow (fuel consumption coefficients)
$percentage_{MTOW}$ (vector)	Aircraft mass considered	0.9 MTOW, 0.85 MTOW, 0.8MTOW 0.75 MTOW, 0.7 MTOW
FL (vector)	FLs considered	FL350, FL360, FL370, FL380, FL390, FL400
$angle_{egeom}$ (vector)	Encounter geometries considered	15°, 25°, 35°, 45°, 55°, 65°, 75°, 85°, 95°, 105°, 115°, 125°, 135°, 145°, 155°, 165°, 175°
sep_{min} (scalar value)	Separation minima	5 NM, 4 NM, 3NM
col_{dist} (scalar value)	NMAC Distance	500ft
$cross_{point}$ (vector)	Crossing point coordinates	(45, 45) NM
$init_{pos}_{acman}$ (vector)	Initial position manoeuvring aircraft coordinates	(45, 0) NM
$t_{ATCO}, t_{pilot}, t_{COM}$ (scalar value)	HF time (ATCO and pilot reaction times and time for ATCO – Pilot communication)	40, 30 or 20 seconds
t_{DCPA}	Time at the CPA	> 0
Other variables		
d	Distance between aircraft pair	> 0
t_{LOS}	First moment when the distance between aircraft is below the separation minima	> 0
t_{res} (scalar value)	Aircraft response time	3 seconds
Simulation parameters		
t (scalar value)	Simulation time	0 : 1 : 1000 seconds
t_0 (scalar value)	Initial time	0 seconds

Algorithm 1 summarises the pseudo-code used for computing t_{nec} and TCPA variables for a climb AM.

Algorithm 1. Algorithm for computing t_{nec} and TCPA variables for a climb AM.

1.	Input: $sep\_min, col\_dist, AC1\_data, AC2\_data, AC3\_data, AC4\_data, Ctr, FL, percentage_{MTOW}, angle_{egeom}, cross\_point, init\_pos\_acman$
2.	For every aircraft pair (ac pair) combination (i.e. $AC1_{manoeuvring} - AC1_{non-manoeuvring}, AC1_{manoeuvring} - AC2_{non-manoeuvring}, \dots, AC2_{manoeuvring} - AC1_{non-manoeuvring}, \dots$) do
3.	For $FL = 1 : FL_{max}$ do
4.	Calculate the temperature from altitude (ISA model)
5.	Calculate the V_{TAS} of both aircraft from Mach (AC_data) and Temperature (calculated in the previous step)
6.	Calculate: 1) time to the crossing point of manoeuvring aircraft 2) Force both aircraft to arrive at the crossing point at the same time to trigger the collision 3) Determine initial position of non-manoeuvring aircraft to meet the previous condition 2)
7.	For $percentage_{MTOW} = 1 : (percentage_{MTOW})_{max}$ do
8.	For $angle_{egeom} = 1 : (angle_{egeom})_{max}$ do
9.	Calculate the aircraft trajectories at the same FL (horizontal flight) based on rectilinear uniform motion (MRU) as a function of the angle projection (TK_{proj}) $\overline{try}_{ac}(t) = \overline{try}_{ac}(t-1) + V_{TAS} \cdot t \cdot TK_{proj}$
10.	Calculate the Euclidean distance (d) between both trajectories every second $d(t) = \text{norm}(\overline{try}_{ac-manoeuvring}(t) - \overline{try}_{ac-nonmanoeuvring}(t))$
11.	Calculate $t_{DCPA}, t_{LOS}, TCPA$ $t_{DCPA} = t(d = col\_dist) - t_0$ $t_{LOS} = t(d = sep\_min) - t_0$ $TCPA = t_{LOS} - t_{DCPA}$
12.	Calculate ROC as $ROC = \frac{dh}{dt} = \frac{(Ctr \cdot Thr - D) V_{TAS}}{percentage_{MTOW} g_0} \left[1 + \left(\frac{V_{TAS}}{g_0} \right) \left(\frac{dV_{TAS}}{dh} \right) \right]^{-1}$
13.	Calculate t_{reqam} as the time needed to perform the avoidance manoeuvre
14.	Calculate t_{nec} as $t_{nec} = t_{ATCo} + t_{com} + t_{pilot} + t_{res} + t_{reqAM}$
15.	if $ROC < 0$, then AM NOT POSSIBLE else
16.	if $t_{nec} \geq TCPA$, then COLLISION TAKES PLACE else
17.	save t_{nec} and TCPA
18.	end if
19.	end if
20.	end for
21.	end for
22.	end for
23.	end for
24.	Output: t_{nec} and TCPA for a specific encounter (ac pair, FL, $percentage_{MTOW}$, $angle_{egeom}$, HF) and climb AM

4.2.4.1. Determination of t_{nec}

- $t_{ATCo}, t_{com}, t_{pilot}$

t_{nec} variable is calculated from $t_{ATCo}, t_{com}, t_{pilot}, t_{res}, t_{reqAM}$ (Equation (12)). The times related to HF ($t_{ATCo}, t_{com}, t_{pilot}$) are probabilistic, due to the fact that not all humans perform in the same way. Two approaches exist when considering the time corresponding to the HF. The first approach corresponds to the research of these time in the state of the art. The second approach is based on expert judgement and measurement of current data.

1. If data from the state of the art are considered, a value of HF corresponding to 40s shall be considered (2σ). t_{ATCo}, t_{com} and t_{pilot} are modeled with a normal distribution.
 - According to [107], the ATCO mean reaction time (t_{ATCo}) is 6.9s and the standard deviation 4.9s, $N(6.9;4.9)s$.
 - According to a 1991 study [108], the time required to communicate ATC instructions in a critical situation (t_{com}) in the ENR phase can be estimated with a mean of 10.8s and a standard deviation of 5.9s, $N(10.8;5.9)s$. These values include a second communication ATCO-Pilot.
 - According to [109] the pilot reaction time (t_{pilot}) could be estimated with a mean value of 5.7s and a standard deviation of 2.3s, $N(5.7;2.3)s$.

The normal distribution verifies the addition theorem. That is, given a set of independent normal random variables of different means and different variances, the sum variable of all will be distributed according to a normal distribution with the mean, the sum of the means and with the variance, the sum of the variances [110]. Therefore, the sum of the t_{ATCo}, t_{com} and t_{pilot} distributions is a normal distribution, called the HF distribution. As it is known, for the standard normal distribution, 95% of the values are within 2 standard deviations of the mean ($\mu \pm 2\sigma$). For the HF distribution, this value is 40s. Therefore, if 40s is set, it could be said that 95% of situations are considered.

However, these data are from studies conducted more than one or two decades ago and do not correspond exactly to the emergency situation modelled in this dissertation (for instance, previous t_{ATCO} value correspond to ground ATCO controlling taxi routing). Furthermore, these data have been modelled using the normal distribution as the most common distribution, but no reference is made in the state of the art regarding the distribution from which they are derived.

2. From expert judgement and considering the advances in technology, reduced HF time could be considered. Nevertheless, if this HF reduced wants to be considered, this would be set as a requirement. That is, no probabilistic time is considered because a requirement is defined, which means that in 100% of the situations it will have to be fulfilled.
 - According to surveys conducted on ATCO of ENAIRE and EASA (Table 3), the t_{ATCO} estimated could be defined as 5s as maximum. The survey model completed by the ATCOs is included in ANNEX F.
 - According to data measurements and defining specific phraseology for the situation of a collision avoidance, for the 99.7% of the situations within 10s the communication between ATCO and pilot (t_{com}) would be done. No second communication ATCO-Pilot is considered. Thus, this is the time considered. This study is included in ANNEX B¹⁰ of this dissertation.
 - According to surveys conducted on commercial pilots (Table 4), the t_{pilot} reaction time is expected within 5s and is set as a requirement. Moreover, according to the state of the art [105], [111] relative to TCAS, the pilot maximum reaction time shall be within 5s after the TCAS RA (which is a similar manoeuvre). The survey model completed by the pilots is included in ANNEX F.

Therefore, if 20s is considered as HF time, 99.7% of communication situations are considered and the requirement of the t_{ATCO} and t_{pilot} within 5s respectively would be stated. Nevertheless, in the simulations, three different HF times (40, 30 and 20s) are considered to contemplate all the situations.

¹⁰ Although the ATCO and pilot surveys included questions on ATCO-pilot communication times, due to the disparity of responses, data measurement was used to obtain a more objective value.

Table 3. Answers of ATCOs to PhD survey. The blue row contains the data analysed to determine t_{ATCo} .

		ATCO 1	ATCO 2	ATCO 3	ATCO 4	ATCO 5	ATCO 6	ATCO 7
ANSP		ENAIRE	ENAIRE	ENAIRE	ENAIRE	ENAIRE	ENAIRE	ENAIRE
AIRSPACE		ACC	ACC	ACC	TMA	ACC	ACC	ACC
PREDEFINED ROUTE	Detection (s)	2	3	-	1	3	1	3
	Communication (s)	12	13	-	9	15	15	5
	Resolution implementation (s)	8	7	5	3	15	7	2
FRA SCENARIO	Detection (s)	3	3	-	1	3	1	2
	Communication (s)	7	13	-	9	15	15	2
	Resolution implementation (s)	10	7	-	3	15	7	4
TRAINING VAC RESPONSE		2 times a year training on the simulator	2 per YEAR	YES	YES	YES	-	YES

		ATCO 8 (EASA)	ATCO 9 (EASA)	ATCO 10 (EASA)	ATCO 11 (EASA)
ANSP		FINLAND	Air Nav Ireland	Italian Air Force ENAV DANS	NATS
AIRSPACE		TMA/TWR	ACC	ACC, TMA, TWR	TMA TWR
PREDEFINED ROUTE	Detection (s)	5	5	-	4
	Communication (s)	20	30	20	10
	Resolution implementation (s)	10	10	20	20
FRA SCENARIO	Detection (s)	5	5	-	-
	Communication (s)	20	30	20	-
	Resolution implementation (s)	10	10	40	-
TRAINING VAC RESPONSE		Theoretically, since have not worked with STCA tool	YES	YES	YES

Table 4. Answers of pilots to PhD survey. The blue row contains the data analysed to determine t_{pilot} .

		PILOT 1	PILOT 2	PILOT 3	PILOT 4	PILOT 5	PILOT 6	PILOT 7	PILOT 8
AIRLINE(s)		AIRDOLOMITI NEW LIVINGSTON SW ITALIA	ALITALIA	CARGOLUX NEOS Others	ALITALIA ERNEST AVIONEXPRESS	ALITALIA EXPRESS ATHENS AIRWAYS PRIVATE OPERATORS	QATAR AIRWAYS	ALITALIA	IBERIA
AIRCRAFT MODELS PILOTED		Cessna 500 ATR 42/72 AIRBUS A320 B747-400	MD80 B777	B747 B737NG B767ER	MD80, A320, A330, A350 B737, B767, B787	EMB-135/145	A319 A320 A321	FO A320 B777	MD-87, DC-10-300, B-747-300, A319, A320, A321, A330-300, A340-600 A350-900
AM COM	Time to communicate the instruction ATCO - Pilot (s)	10-15	7	10-20	3-6	10	10	8-12	3 - 5
	Time considered if needed to be repeated (s)	45	-	-	-	30	-	-	5 - 8
PILOT REACTION TIME	Does the pilot need a reaction time?	YES	YES	NO	YES	YES	YES	YES	YES
	For an urgent climb manoeuvre/ descent manoeuvre of 500 ft of the manoeuvre is performed by the autopilot. How much time is needed by the pilot to configure the autopilot? (s)	20	6	10	2	5	-	3-5	3 - 4
	For an urgent climb manoeuvre/ descent manoeuvre of 500 ft, if the manoeuvre is performed manually. How much time is needed by the pilot to start the manoeuvre? (s)	3	4	2-5	1	5	5	2-3	2 - 3
AIRCRAFT RESPONSE TIME		3	3 sec with autopilot 2 sec without autopilot	Negligible	Negligible	1-2	Negligible	2-3	It is more relevant aircraft technology than aircraft model, but the difference should not be relevant

- t_{res}

Regarding the t_{res} , generally is included in the literature with the value corresponding to t_{pilot} . However, to adopt a conservative approach, this time is considered apart from the t_{pilot} . Thus, an analogy is made using data published by Airbus [112]. In particular, data are taken for aircraft that in the final approach segment (idle thrust) must perform a Go Around (GA) manoeuvre, in which the thrust is 100%. According to FAR–Part 33 certification, it must be ensured that no more than 5s are taken to accelerate from 15% thrust to 95% thrust. Moreover, FAR–Part 25 and CS 25 [113] set a maximum of 8s from idle to GA power. Assuming that in the ENR phase, the aircraft is flying with 60–70% thrust, according to Figure 19, the aircraft needs 3s to reach 100% of thrust (AM) from 60% of thrust.

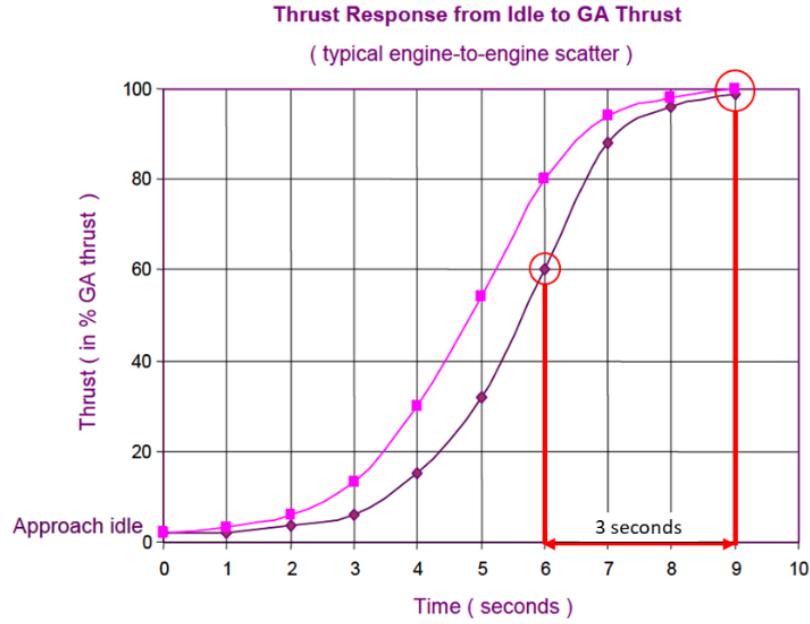


Figure 19. Engine response [112].

- t_{reqAM}

Since the time relative to HF is fixed (i.e., 20, 30 or 40s), what really makes the t_{nec} Ad Hoc for each aircraft model, FL and mass is the t_{reqAM} variable, which is calculated with simulations based on the BADA model, referred above. This t_{reqAM} has been calculated for each aircraft model with different FL and different masses in the simulations. Regarding the mass, five different values, calculated as a percentage of the MTOW, are considered. The most conservative situation is for 0.9 MTOW, which means

that the AM needs to be performed when the manoeuvring aircraft has almost begun the cruising stage. When the concept is implemented in an airspace, the aircraft shall be required to communicate its mass value to be used as input by the ASMT.

- Climb AM

For the determination of the t_{reqAM} to execute the climb AM, the thrust and speed are set and the Rate of Climb (ROC) is calculated according to the BADA Model. Therefore, the TEM equation is integrated in the following form (Equation (14)). The thrust considered in the simulation of the climb AM is the maximum (due to the fact that is an AM). Regarding the speed, it is considered that in the ENR phase, aircraft fly with their Mach cruise (provided by BADA), which is transformed into TAS from the speed of sound, using the ISA atmospheric model.

$$ROC = \frac{dh}{dt} = \frac{(Thr - D)V_{TAS}}{mg_0} \left[1 + \left(\frac{V_{TAS}}{g_0} \right) \left(\frac{dV_{TAS}}{dh} \right) \right]^{-1} \quad (14)$$

Table 5 shows the parameters used to simulate the climb AM for different aircraft models and the mean value of the ROC calculated in the simulations. It is observed that AC2 is the one with the best performance.

Table 5. Climb AM parameters for different aircraft.

Manoeuvring Aircraft	FL [-]	Mach Cruise [-]	Mass (0.75 MTOW) [kg]	Thrust [N]	Drag [N]	ROC [ft/min]	Wake Turbulence Category
AC 1	360	0.78	57750	53107	41851	915	M
AC 2	360	0.78	52560	52902	36693	1447	M
AC 3	360	0.78	52500	51168	36283	1331	M
AC 4	360	0.82	172500	136920	97121	1140	H

In Figure 20a, the ROC variation with FL for the four simulated aircraft is shown. The ROC decreases as the altitude increases. In Figure 20b, for a specific aircraft and FL, the change in ROC with MTOW is simulated. The

effect is the same as with the altitude; the ROC decreases when the mass increases.

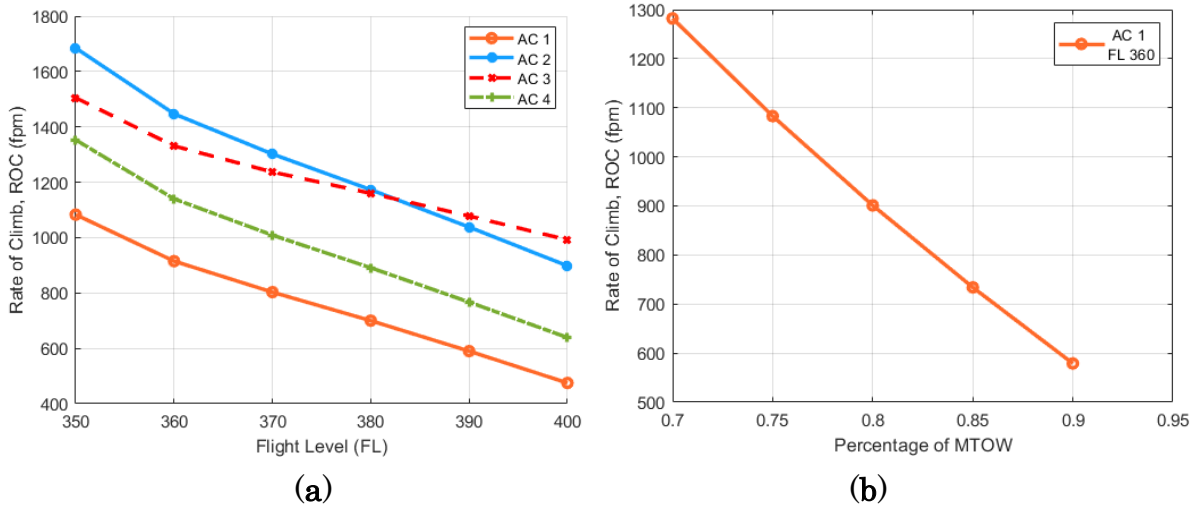


Figure 20. (a) Change in ROC with FL for different aircraft. (b) Change in ROC with aircraft mass for a specific FL.

Figure 21 shows the climb AM performed by the manoeuvring aircraft (blue line), while the non-manoevring aircraft flies at a constant altitude (red line). These simulations have been performed for different aircraft pair models (that is, AC1–AC2, AC1–AC3, AC2–AC4), FL and aircraft masses. Here, only one pair is shown (AC1–AC2).

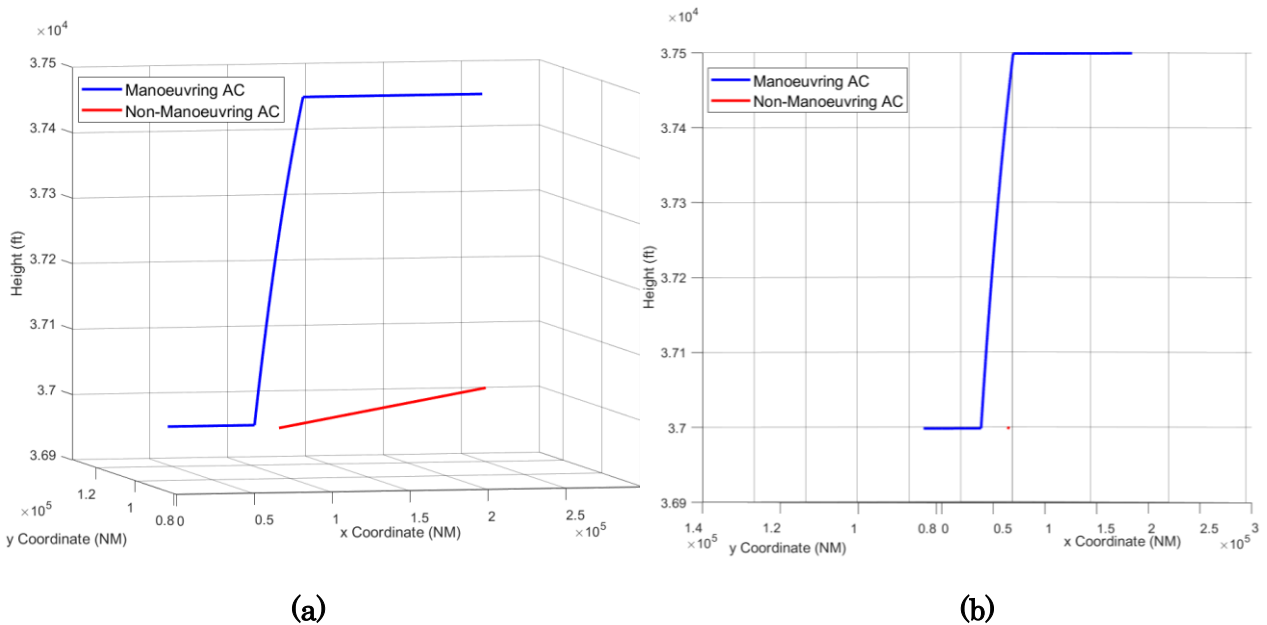


Figure 21. (a) Climb AM performed by the manoeuvring AC. (b) Overview and profile view.

- Descent AM

For the determination of the ROD, the procedure is similar to that followed for the climb AM. Nevertheless, the descent thrust is calculated as a ratio of the maximum thrust with different correction factors used for high and low altitudes. The results obtained from BADA for this manoeuvre showed a ROD in the order of 2000 to 2900ft/min (Table 6).

Table 6. Descent AM parameters for different aircraft.

Manoeuvring Aircraft	FL [-]	Mach Descent [-]	Mass (0.8 MTOW) [kg]	Thrust [N]	Drag [N]	ROD [ft/min]	Wake Turbulence Category
AC 1	380	0.79	61600	6785	42040	2644	M
AC 2	380	0.78	56064	1797	36598	2868	M
AC 3	380	0.79	56000	4007	35472	2596	M
AC 4	380	0.82	184000	9038	97588	2337	H

ROD values of 2000–2900 ft/min are considered high. For this reason, the t_{reqAM} for the descent manoeuvre is calculated in two ways. The first is based on the BADA results, assuming the ROD values obtained in the simulations. In the second way, the ROD value is set at 1500ft/min for determining t_{reqAM} , based on the TCAS RA alert [105], which uses this value (1500ft/min) in a first filtering. Thus, when the ROD considered is 1500ft/min, the t_{reqAM} to perform the AM is 20s and all aircraft perform it in the same way. For the descent manoeuvre (Table 6), it is observed that AC2 is the one with the best performance, followed by AC1.

Figure 22 shows the descent AM performed by the manoeuvring aircraft (blue line), while the non-manoevring aircraft flies with constant altitude (red line). These simulations have been performed for different aircraft pair models (that is, AC1–AC2, AC1–AC3, AC2–AC4), FL and aircraft masses in MATLAB®. Here, just one pair is shown (AC1–AC2).

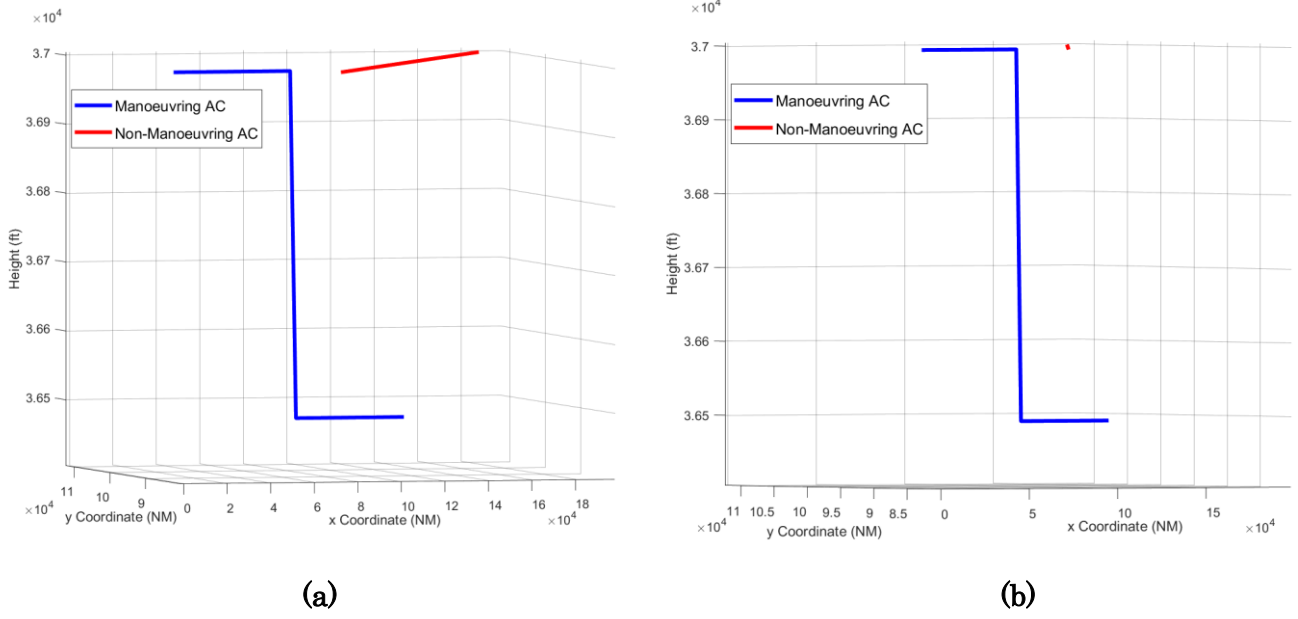


Figure 22. (a) Descent AM performed by the manoeuvring AC. (b) Overview and profile view.

4.2.4.2. t_{nec} results

Figure 23 shows the results of t_{nec} variable from simulations with BADA model. The variation t_{nec} with FL and mass for different aircraft models performing a climb AM are represented. As expected, aircraft require more time to perform a climb AM at higher FL (always below their operational ceiling). The same is true for the mass. The greater the mass, the longer the t_{nec} .

Among the four aircraft models in the study, AC1 (M) is the one with the highest values for the t_{nec} for a climb AM. It is noteworthy that AC4 (H) requires less time than AC1. In turn, AC2 (M) and AC3 (M) present similar values of Necessary Time, although AC3 has better performance for higher FL.

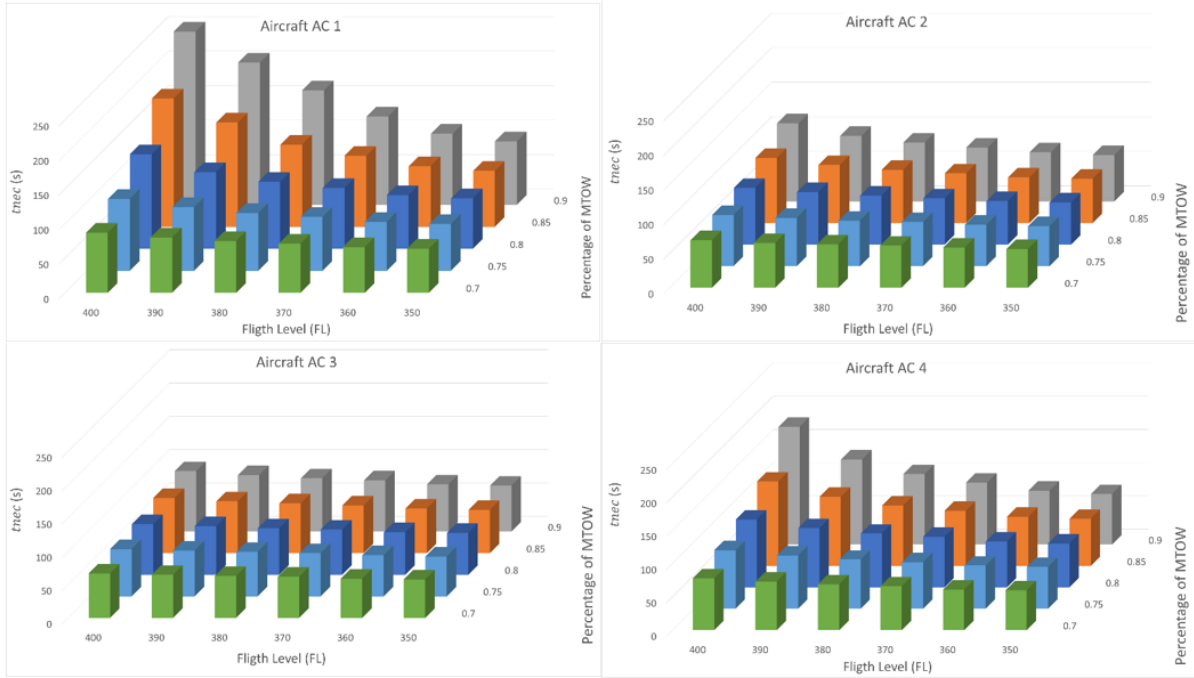


Figure 23. AC1, AC2, AC3, AC4 t_{nec} for a Climb AM at different FLs and masses.

The t_{nec} for the descent manoeuvre is presented in Figure 24. It is observed that the values are practically of the same order of magnitude for all the aircraft models analysed, being shorter than those required for the execution of the climb AM.

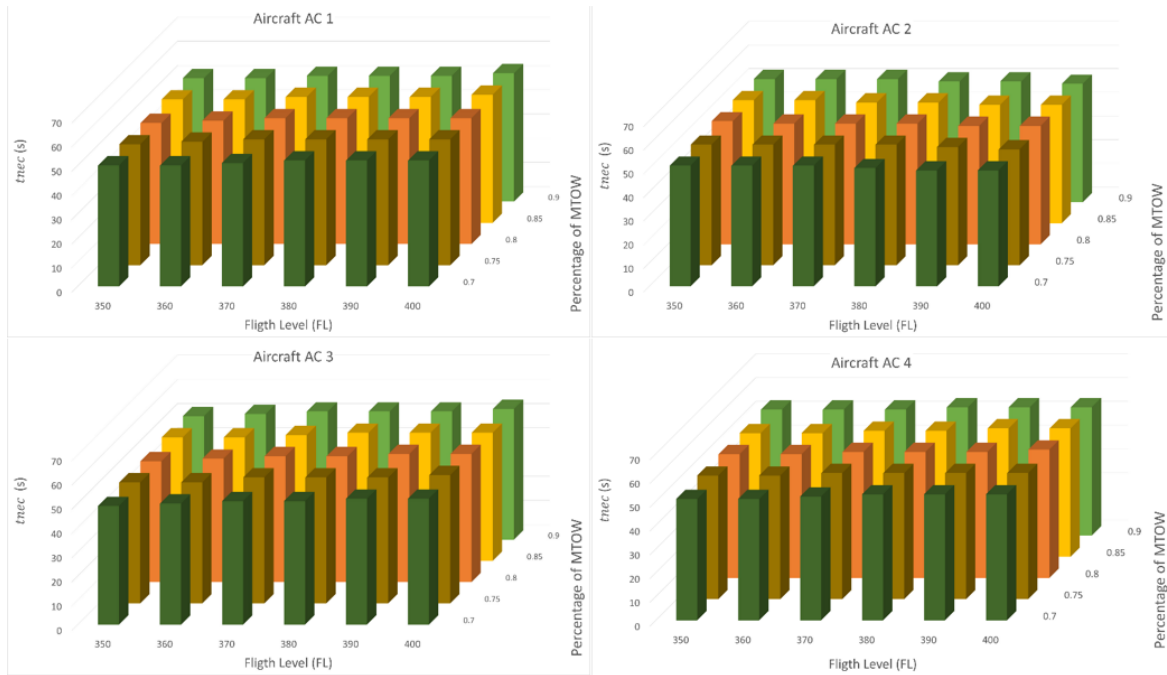


Figure 24. AC1, AC2, AC3, AC4 t_{nec} for a Descent_UNL AM with unconstrained ROD at different FLs and masses.

The variation in the t_{nec} for the descent AM with mass and FL is the same as for the climb AM. The higher the FL and the greater the mass, the more time the aircraft requires to execute the descent manoeuvre. However, this variation is practically negligible, as the difference is 2–3s between FL400 and FL350 and 0.7 MTOW and 0.9 MTOW. The results presented are calculated considering that the ROD is not limited (descent_UNL). If the ROD is limited to 1500ft/min (descent_LIM), the results are the same for all aircraft, all FL and all masses.

4.2.4.3. *TCPA* Results

Figure 25 and Figure 26 show the *TCPA* variation with different parameters. As mentioned above, the *TCPA* decreases when the separation minimum is reduced. Additionally, it decreases when the encounter geometry (intersection angle) is higher due to the fact that the closing speed rate increases when the intersection angle is greater (Figure 25). In Figure 26, *TCPA* values are calculated for aircraft encounters of MM, MH and HH aircraft pairs, as a function of different intersection angles. This is because the Mach cruise for M aircraft and H aircraft is not the same; hence, the *TCPA* depends on the specific encounter. Nevertheless, as can be shown, the temporal difference in seconds between the *TCPA* values for different encounters is negligible.

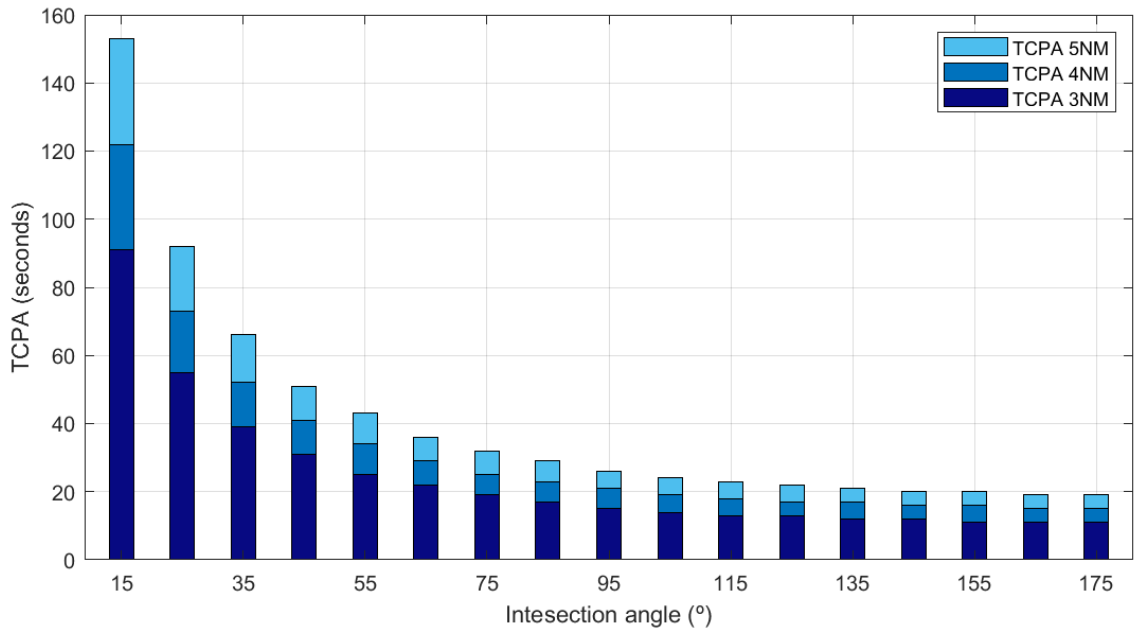


Figure 25. *TCPA* variation with separation minima and encounter geometry.

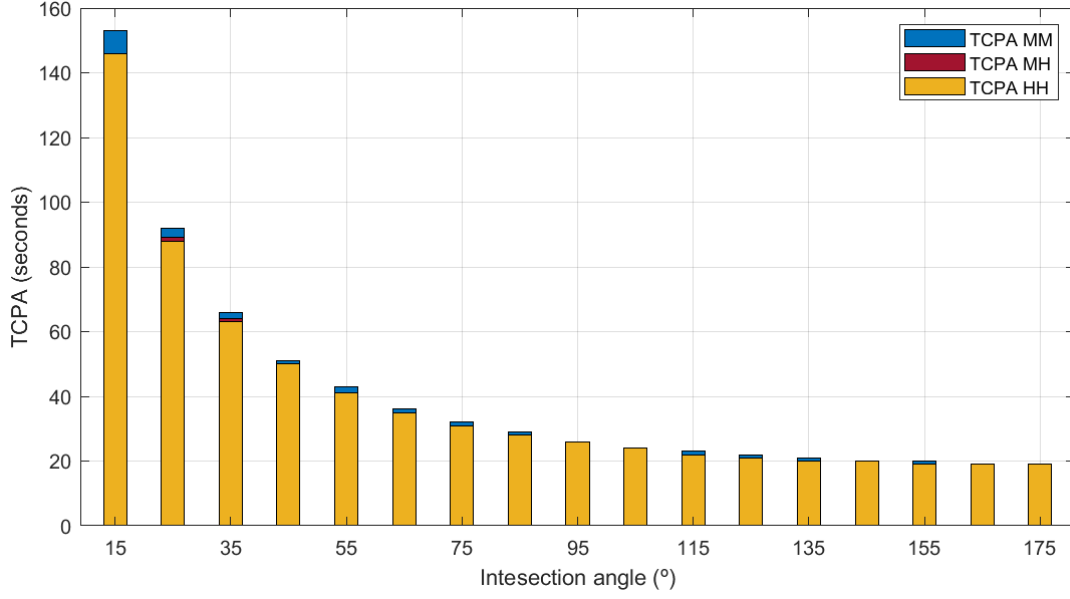


Figure 26. *TCPA* variation in encounters with MM aircraft, MH and HH aircraft.

The influence of the speed of both aircraft on the *TCPA* is not as clear as the influence of encounter geometry and separation minima, due to the fact that the speed of aircraft, the entering points to the sector and the distance from these points until the CPA are all important. This effect of distance to CPA and aircraft speed on *TCPA* can be understood, to some extent, through the closing speed rate, which expresses how fast aircraft are approaching as a function of aircraft speeds. The closing speed rate ($\|\dot{\bar{r}}_{21}(t)\|$) could be determined according to Equation (18) [114]. Parameters $\bar{r}_{21}$ (Equation (17)) and $\bar{v}_{21}$ stand, respectively, for the relative position and relative speed of the non-maneuvring (2) with respect to the manoeuvring aircraft (1), while $\bar{r}_{21}(t_0)$ and $\bar{v}_{21}(t_0)$ (Equations (15) and Equation (16)) are the relative position and speed at the initial time.

$$\bar{r}_{21}(t_0) = \bar{r}_{21}^0 = (x_{02} - x_{01}) \cdot \bar{i} + (y_{02} - y_{01}) \cdot \bar{j} \quad (15)$$

$$\bar{v}_{21}(t_0) = \bar{v}_{21}^0 = (v_2 \cos \alpha - v_1) \cdot \bar{i} + v_2 \sin \alpha \cdot \bar{j} \quad (16)$$

$$\bar{r}_{21}(t) = \bar{r}_{21}(t_0) + \bar{v}_{21}(t_0) \cdot t \quad (17)$$

$$\|\dot{\bar{r}}_{21}(t)\| = \frac{(\bar{r}_{21}^0 \cdot \bar{v}_{21}^0) + t \cdot (\bar{v}_{21}^0 \cdot \bar{v}_{21}^0)}{\|\bar{r}_{21}(t)\|} \quad (18)$$

Figure 27 represents the evolution of the distance between aircraft pairs in the simulations performed (Figure 27a) and the closing speed rate (Figure 27b). The closing speed rate corresponds to the derivative of the distance evolution curve between the aircraft pair. The distance evolution curve is U-shaped for all encounters, except when there is a collision between the aircraft pair, which is V-shaped. Because collision is triggered in these simulations, the curves of Figure 27a are V-shaped. Only a few angles are depicted in Figure 27a, where in addition to the distance evolution plot, there are three horizontal lines corresponding to the separation minima values: 5NM (red), 4NM (green) and 3NM (blue). For larger intersection angles, the curve closes, resulting in a lower *TCPA*. The lower the separation minima value, the lower the *TCPA*. In Figure 27b, the closing speed rate values are higher for larger intersection angles. Hence, the higher the intersection angles, the higher the closing speed rate and the lower the *TCPA*.

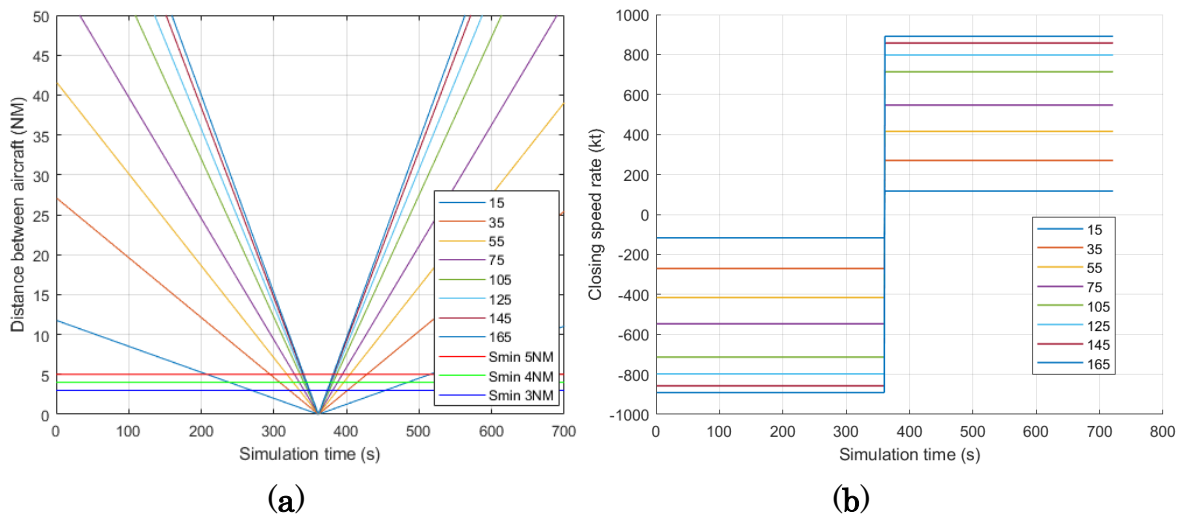


Figure 27. (a) Distance evolution between aircraft for different angles; (b) Closing speed rate for different angles.

4.3. Preliminary feasibility study of the ADSM: deterministic approach

For the theoretical definition of the ADSM (deterministic simulations), the work is focused on the immediate layer of the IRP model (from LOS to collision). This is to demonstrate if it would be operationally feasible to reduce the separation minima and in which situations. Once it has been demonstrated, the determination of the ADSM will be performed based on the collision risk metric (absolute method), as established by the ICAO in [22]. This will be presented in the next Chapter.

The application of the Ad Hoc separation is potentially feasible whenever $t_{nec} < TCPA$. Therefore, a comparison is made between these two variables to obtain, a priori, those potential situations in which Ad Hoc separation could be applied. This is because it would imply that, for that separation minimum applied to that particular situation for which these values of t_{nec} and $TCPA$ have been calculated, the collision would not occur since the AM could be executed. This is a deterministic approach because uncertainties are not considered (ideal) and it is assumed a collision risk value of 0.

It is noteworthy that, for a specific situation (characterised by the aircraft pair models, manoeuvring aircraft mass, encounter geometry, FL and HF), three t_{nec} exist against a unique $TCPA$ value (corresponding to the three possible AM). This is graphically shown in Figure 28, in which for a specific situation (A319-A320 encounter, being the A319 the manoeuvring aircraft with a mass of 0.8MTOW, FL360, HF40 seconds) the t_{nec} is plotted for the three different AM (climb, descent_UNL, descent_LIM). Note that descent_LIM refers to the simulated descent for a ROD of 1500ft/min while descent_UNL corresponds to the ROD obtained from simulations with BADA model (ROD values greater than 2000ft/min, unconstrained ROD). On the x-axis, closure rate is represented, while in the y-axis is range (separation minima). Current horizontal separation minima value (5NM) is represented by a blue dashed line.

In Figure 28, the slope of the three lines corresponding to the different AM is the value corresponding to each of the t_{nec} , while the slope of the line corresponding to the TCAS RA is 35s (TCAS RA for a SL of 7, which is the SL for the ENR phase).

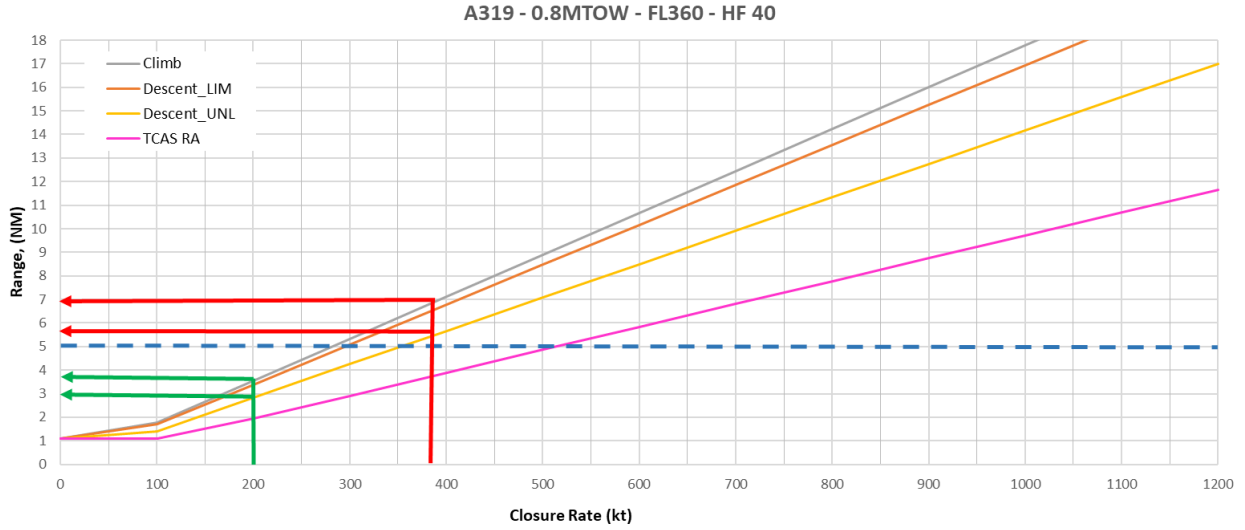


Figure 28. Different t_{nec} for a specific situation (unique value of $TCPA$).

The closure rate value corresponds to an encounter geometry (angle of intersection) and constant aircraft speeds, as a consequence of the characteristics of this study (theoretical analysis and therefore, deterministic study). Thus, for example, considering a pair of M aircraft both flying at Mach 0.78 and at FL360, a 25° geometry corresponds to a closure rate of 195kt while a 50° geometry corresponds to a value of 380kt.

From Figure 28 it is possible to know the combinations of separation minima and closure rate that result in $t_{nec} = TCPA$ for that specific case. Thus, in the case of an encounter geometry of 25° , a closure rate value of 200kt is obtained (green lines from Figure 28), which means that the $TCPA$ corresponding to 3NM is equal to the t_{nec} corresponding to the descent_UNL AM. Whereas if the t_{nec} corresponding to the AM of climb or descent_LIM is considered, in order to make the $TCPA$ equal to the t_{nec} values the minimum separation should be close to 4NM.

If another geometry is considered, such as 50° (red lines from Figure 28), the separation minima values are 5.5NM for a $TCPA$ equal to the t_{nec} corresponding to the descent_UNL AM and 7NM to be equal to the t_{nec} corresponding to the climb and descent_LIM AM.

Therefore, it is already inferred from this theoretical study that the potential cases where it will be possible to apply an ADSM lower than the current value of 5NM will be for small angles.

The results of the simulations performed for the BADA worst-case scenario for all the situations are presented. This study has been performed for the different aircraft (AC1-AC4), AM, masses, FL and HF. Figure 29 shows, for a climb AM performed by the manoeuvring aircraft, for different manoeuvring aircraft masses and different FL and for a HF value of 40s, what the maximum possible angle between tracks would have to be to ensure that the t_{nec} never exceeds the $TCPA$, calculated for a separation minimum of 5NM. Different geometries have been considered (angles between tracks from 15° to 175°), in each case obtaining the highest possible value of the angle between tracks.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	NA	NA	15	15	15
	390	NA	15	15	15	25
	380	NA	15	15	25	25
	370	15	15	25	25	25
	360	15	25	25	25	25
	350	15	25	25	25	35
	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC2	400	15	15	25	25	25
	390	15	25	25	25	35
	380	25	25	25	25	35
	370	25	25	25	35	35
	360	25	25	35	35	35
	350	25	35	35	35	35
	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC3	400	25	25	25	25	25
	390	25	25	25	25	35
	380	25	25	25	25	35
	370	25	25	25	35	35
	360	25	25	35	35	35
	350	25	35	35	35	35
	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC4	400	NA	15	15	25	25
	390	15	15	15	25	25
	380	15	15	25	25	25
	370	15	25	25	25	25
	360	25	25	25	25	35
	350	25	25	25	35	35
HF 40						

Figure 29. Maximum possible angle between tracks: climb AM results, HF 40s. $TCPA$ 5NM.

The best results are obtained for AC 3, while the worst are for AC 1. The maximum value between tracks for this specific case is 35° , in order to ensure that t_{nec} is strictly lower than $TCPA$ for each specific situation. It should be noted that when the 'best results' are mentioned, it is referred not only to higher angle values but also to more situations in which this higher angle can ensure that t_{nec} is lower than $TCPA$. For instance, an angle of 35° between tracks is only possible in one situation (FL350 and 0.7 MTOW), for AC 1, while for AC 3, eleven different situations are possible.

The notation N/A (Not Applicable) appears in some cells, indicating that it would not be possible for that manoeuvring aircraft to perform a climb AM for that given FL and the specified mass conditions. This may be either because the FL is close to its operational ceiling, or because the combination of that FL and those generally restrictive mass conditions means that the t_{nec} is far in excess of the $TCPA$ for any of the possible angles. It should be noted that climb AM gives the worst result in comparison with the descent manoeuvre for the limited and the unconstrained ROD (descent_LIM and descent_UNL AMs respectively). Moreover, 40s has been considered for the HF value; however, it is a rather restrictive value that has been obtained from the values of ATCO and pilot reaction times and communication time that were obtained many years ago.

When reading these results (Figure 29), it is important to consider the following. The angle value appearing in each cell indicates that collision avoidance is possible if the separation minima between that aircraft pair and for that specific situation (FL, mass and AM) is lower than that $TCPA$. This is true for the angle between tracks or for any angle smaller than indicated.

It is striking that for a current separation value of 5NM, the intersection angles between aircraft tracks are limited. However, there are two issues to take into account. Firstly, a worst-case scenario is being considered in the simulations, in which the aircraft arrive at the intersection point between airways at the same time (collision is provoked), which is a rather less probable situation. Secondly, and more paramount, it should be considered that this study strictly analyses, in terms of encounter geometry, aircraft performance and speeds, whether with a given separation minima value it is possible to perform the AM in 100% of the cases ($t_{nec} < TCPA$), that is, only the immediate layer from the IRP Model is being considered.

According to the ICAO, the defined separation minima values are also associated with a separation mode (strategic and tactical layers in IRP Model) and a risk of collision. Therefore, other elements need to be considered for a complete picture of the system. For instance, nowadays, the number of situations in which there would not be time to execute an AM with a 5NM separation is limited (e.g., opposite flights flying at different FL and not in the same FL); the ATCO most often resolves any conflict situation long before it occurs and the TCAS system often triggers before the separation between two aircraft is lost.

The rest of the results calculated for descent_LIM AM and descent_UNL AM (separation minima of 5NM) and for separation minima values of 3NM and 4NM are presented in ANNEX D. The results are displayed in a heat map to aid in understanding the best (green) and worst (red) results. Different HF times have been considered (40, 30 and 20s), since when calculating the t_{nec} variable, the largest contribution is due to the HF, while the smallest is relative to the time required by the aircraft to respond and perform the AM. The time relative to the HF can be reduced from 40 to 30 or 20s, depending on the ATC support tools and the communications. Through this factor, it is possible to envisage how an advance in technology could reduce the times relative to the HF and how this would lead to a greater number of situations in which a lower separation minima than the actual one could be applied.

As expected, it is observed from these results (see ANNEX D) that the most restrictive angle values occur for the *TCPA* corresponding to 3NM and for the climb AM. The best results are obtained for descent_UNL manoeuvres, considering that the preferable situation is one in which the angular difference between tracks is larger. Observing the results, it is worth noting that in no specific situation angles greater than 75° occur. This suggests that the concept of Ad Hoc separation will be feasible for geometries with small angles (below 75°). Finally, since different HF values were considered in the simulations in order to analyse the sensitivity of this parameter within the results, it should be noted that a reduction of 10s in the HF time means the possibility of increasing the angle between tracks by 10° , while ensuring that the t_{nec} is lower than *TCPA*.

It should be noted that no new separation minima values are being defined. However, these results show that, to some extent, it would be potentially feasible to apply different separation minima values for different situations (Ad Hoc CONOPS). Therefore, ADSM values will be determined based on a risk assessment presented in the following Chapter.

4.4. Summary

In this Chapter, the model for the development of the Ad Hoc separation is presented. This model is defined as a layer-based model in which aircraft manoeuvrability and HF are taken into account. In particular, it focuses on the set of activities that must be performed to prevent a LOS from becoming a collision in the time dimension (time buffer). This approach is followed in accordance with the results obtained from the analysis presented in ANNEX C on the factors contributing to separation minima and the principles enunciated by Mehadhebi [92] and Brooker [64] of modelling risk from operational errors, considering separation minima as time buffers.

The framework of the ADSM model is presented which is based on the EUROCONTROL IRP Model and the Encounter Timeline Concept. The variables t_{nec} and $TCPA$ used to define ADSM (in the next Chapter) are discussed. Their behaviour with the parameters that define them is analysed. These variables are calculated for specific cases in simulations with the BADA model in a worst-case scenario. The application of the Ad Hoc separation is potentially feasible whenever $t_{nec} < TCPA$. Finally, from the analysis of these simulation results, it is possible to state that the concept of the Ad Hoc separation is preliminarily feasible (theoretical/deterministic analysis), specifically for encounter geometries of small angles between tracks. The ADSM values will be determined based on the collision risk (absolute method) presented in the following Chapter.

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5. ADSM DETERMINATION

5.1. Introduction

In this Chapter, the computation of the ADSM is performed. Initially, the CRM developed for this purpose is introduced, as none of the CRMs examined in the literature review is deemed suitable. Subsequently, the methodology designed for determining the ADSM is presented.

Ad Hoc separation values are derived from Montecarlo simulations applied to encounters between aircraft pairs. Consequently, the characteristics of the simulations and the adopted approach are discussed upon. ADSM values are established specifically for the LECMZMU ENR sector, fitting the simulation data with the distinctive features of this sector.

A fundamental assumption of the methodology is that new separation minima values only will be determined in situations deemed safe. That is, where the risk of collision is below a predefined threshold. The determination of this threshold is presented and a sensitivity analysis of the results is included.

Ultimately, the innovative concept is applied in the LECMZMU sector, in order to perform a safety analysis and determine the safety requirements necessary to maintain current safety levels.

The work presented in this chapter is based on the following submitted paper:

Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, Fedja Netjasov, Eduardo S. Ayra, Irene García Moreno and Juan Sánchez-Cano Mas-Sardá. Risk assessment for the determination of the Ad Hoc Separation Minima for en-route airspace. *Journal of Air Transport Management*. [Submitted].

5.2. ADSM CRM

As mentioned previously, ICAO[8] defines the separation minima as the minimum displacements between an aircraft and a hazard (which could be another aircraft) that ensure the risk of collision remains at an acceptable level of safety. The separation mode is an approved set of rules, procedures and conditions of application associated with separation minima. Therefore, to determine new separation minima values, the ICAO absolute method [22] is followed. A CRM is necessary to be developed and the collision risk metrics should be compared with a TLS value.

Risk is defined as the combination of the overall probability or frequency of occurrence of a harmful effect induced by a hazard and the severity of that effect [115]. However, as stated in [25], in the context of a MAC it is generally assumed that any MAC is always fatal to all occupants of both aircraft, being any MAC equally severe. Therefore, collision probability and collision risk are often used interchangeably since the severity is a constant value and equal to 1 (Equation (19)).

$$\text{Collision Risk} = P(\text{collision}) \cdot \text{Severity}_{\text{Collision}} = P(\text{collision}) \quad (19)$$

The CRM proposed in this research is in line with the CRM developed in [52], which, in turn, is based on the principle stated in [27], [28], [29]. Marks and Reich referred to that “the task of relating collision risk to a traffic configuration can be taken in two parts: first, determining the frequency with which aircraft are exposed to risk by passing close together (i.e. LOS) and secondly, determining what chance of collision is inherent in the passing”. Therefore, Equation (19) is rewritten as Equation (20).

$$\text{Collision Risk} = P(\text{collision}) = \text{Frequency}_{\text{LOS}} \cdot P(\text{Collision} | \text{LOS}) \quad (20)$$

Nevertheless, the term $\text{Frequency}_{\text{LOS}}$ is related to the behaviour of the scenario (traffic configuration, separation mode, etc.). According to the ICAO in [13] the traffic density is reduced to a specific pair of aircraft when trying to determine a separation minima value. For this reason, the traffic density is reduced to one aircraft pair in order to determine the Ad Hoc separation.

The primary hypothesis of this study is that it is possible to define new separation minima values as long as the collision risk associated with them is equal to or less than the maximum collision risk associated with the immediate layer (IRP Model / Conflict management layer) for a minimum separation value of 5NM (current horizontal separation value). Consequently, the model developed for one aircraft pair yields a collision risk value corresponding to the immediate layer, which ranges from LOS to collision. Thus, the expression used for the calculation of the collision risk for a traffic density equal to an aircraft pair is Equation (21). Subsequently, the term $Frequency_{LOS}$ will be considered afterwards to calculate the collision risk of the LECMZMU scenario (considering the whole traffic density).

$$Collision\ Risk_{aircraft\ pair} = P(collision)_{aircraft\ pair} = P(Collision | LOS) \quad (21)$$

The term $P(Collision | LOS)$ is split into two terms and could be rewritten as Equation (22):

$$Collision\ Risk_{aircraft\ pair} = P(LOS_{critical} | LOS) \cdot P(Collision | LOS_{critical}) \quad (22)$$

Where:

- $P(LOS_{critical} | LOS)$: this variable is the conditional probability that represents the probability of a critical LOS occurring when a LOS between a pair of aircraft takes place as a consequence of geometry and relative speed. A critical LOS is defined as a LOS in which the minimum distance reached in the encounter ($DCPA$) has been 500ft or less.
- $P(Collision | LOS_{critical})$: this variable is the conditional probability that represents the probability of a collision occurrence. That is, a collision occurs because the critical LOS occurred and the t_{nec} to avoid the collision was greater than the $TCPA$ of the encounter (which means that the collision AM could not be executed and the aircraft collided). As mentioned above, safety nets are not considered, which is in line with the ICAO requirement in [22].

5.3. Methodology for the Ad Hoc separation determination

Throughout this section, the methodology followed to calculate the ADSM values for each aircraft pair is explained in detail. The collision risk metric is the key element for the determination of the ADSM in each specific situation. This collision risk is calculated from aircraft encounter Montecarlo simulations and shall be compared to a threshold.

According to the ICAO [8], separation minima are associated, on the one hand, with a risk of collision that must be lower than a safe threshold and, on the other hand, with an operational/separation mode, that is, a way of working (from the strategic layer, barriers are working to avoid the collision).

The collision risk can be differentiated depending on two approaches:

- Separation minima is calculated: the traffic density is reduced to a pair of aircraft, according to [13]. An encounter between a pair of aircraft is characterised as a function of the combination of factors such as aircraft models, FL, encounter geometry, aircraft speeds, etc. Each simulated encounter between aircraft pairs will result in a collision risk value.
- Scenario safety is analysed: the traffic density is the whole traffic of the scenario, considering the traffic flows and the interaction between them. Generally, the collision risk associated with a system is of the order of $10^{-8} - 10^{-9}$ collisions per flight hour.

The main assumption made in this dissertation for the determination of the ADSM is as follows:

As the separation minima is intended to be calculated, the traffic density is reduced to the aircraft pair. Considering only the horizontal dimension, a separation value of 5NM is currently applied, which has an associated collision risk value and is judged to be safe (air traffic is currently operating with this separation minimum). If different encounter situations between aircraft pairs in the worst-case scenario are analysed in terms of geometry and relative speeds (strictly in the immediate layer, from LOS to collision), in some of these situations, the collision could not be avoided, as there would not be time to execute an avoidance manoeuvre.

However, the separation mode (strategic and pre-tactical layers) is also associated to the separation minima. That is, a set of rules and procedures are associated with separation values. According to the current CONOPS, there is a whole system that limits the possibility of such situations occurring (situations in which with a separation of 5NM collision could not be avoided). Examples are:

- A procedure is established for aircraft flying on opposite tracks (collision course) to fly at different FLs.
- In general, the ATCO mode of operation involves issuing instructions to aircraft as soon as possible when they are flying (or about to fly) close to the separation minima. This enables the aircraft to execute manoeuvres to prevent them from getting too close to the separation minima.
- At certain combinations of speeds and geometries, the TCAS system [116] issues an RA before the aircraft pair reach a distance of 5NM.

Focusing on the immediate layer and considering an aircraft pair as the traffic density, a key assumption of the methodology is that new values of separation minima will be defined in those situations in which is safe. That is, in those situations where the risk of collision is below a defined threshold. The value corresponding to the current collision risk associated with the 5NM will be used as the safety threshold value. Actually, there will be different values of collision risk associated with different encounters between aircraft pairs for a separation minimum of 5NM. The threshold value will be the highest of these values (which tends to a constant value).

From the developed CRM and Montecarlo simulations, the TLS will be determined (explained in more detail in section 5.3.3). Subsequently, encounters will be simulated considering separation minima values of 3NM and 4NM for different encounter situations between aircraft pairs, depending on the encounter geometries (angles between tracks), different wind directions and intensities, different FLs, different aircraft models and different t_{nec} values.

In those situations where the collision risk for 4NM or 3NM is lower than the reference TLS, it is possible to apply the minimum separation of 4NM or 3NM. Figure 30 shows the flow diagram of the methodology.

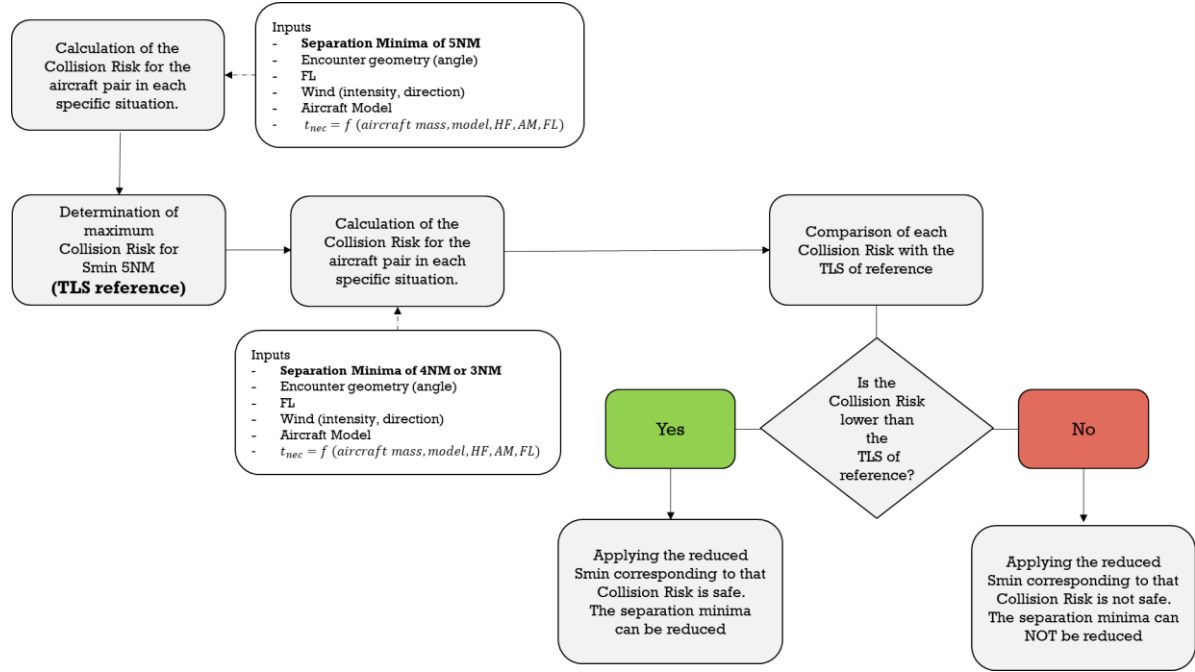


Figure 30. Flow diagram for the determination of the ADSM value for each situation.

5.3.1. General considerations of the simulations

For determining the ADSM for each specific situation the collision risk metric is crucial. This metric is the output of the Montecarlo simulations. Since it is intended to calculate the collision risk of the aircraft pair in the immediate layer (LOS-Collision), in the simulations performed the LOS is sought. Therefore, encounters between aircraft pairs are simulated focusing the attention on the LOS – Collision evolution.

To consider all possible aircraft operating conditions, uncertainties are introduced in the model and Montecarlo simulations are performed. Montecarlo simulation is a mathematical technique used based on the simulation of random variables [117]. The following assumptions are considered in the simulations:

- Aircraft trajectories intersect at a specific angle;
- Simulations are calculated for different intersection angles in order to simulate a wide range of cases;
- Aircraft fly at the same FL. This is because the model is applied to 2D. Simulations are performed separately for each FL considered;

- Five different aircraft models are considered to simplify the study. Three of them are M and two H type¹¹. The selected aircraft models are those that fly the most in LECMZMU sector.
- Both aircraft fly at their specific cruise Mach number (not necessarily the same);
- Wind direction/intensity are introduced in the model as an input. Since an aircraft encounter is simulated, it lasts a small period of time during which the wind is considered constant.
- The model is stochastic. Uncertainties are considered corresponding to navigation and speed errors;
- Navigation error: cross-track (lateral, XTT) and along-track (longitudinal, ATT) errors are considered because the model is focused on the horizontal plane. Moreover, because a new concept is being proposed, improvements on technology are considered. According to the study performed in [11] by UPM and included in ANNEX A, aircraft flying RNAV 5 navigation specification (ENR airspace) with GNSS sensor have an upper bound deviation of 0.4NM. Therefore, the errors are modelled as $XTT=N(0,0.4)NM$ and $ATT=0.8*XTT$.
- Speed error: speed error is obtained from [77] and is modelled as $N(0,15)kt$.
- Number of simulations performed for each encounter situation is 10^4 .
- In each encounter situation, specific value of $TCPA$ is calculated in the simulations, which, depending on the values of wind conditions, FL, aircraft speed, encounter geometry, separation minima value and the uncertainties introduced, will differ. t_{nec} values calculated in the previous worst-case scenario simulation for the different aircraft model, masses, FL, AM and HF considered (Chapter 4) are an input in the simulations.

An encounter situation is characterised by the combination of the different factors that define the Ad Hoc separation, which are, aircraft model, mass, speed, encounter geometry, avoidance manoeuvre (AM), FL, wind conditions (direction and intensity), FL, HF.

Therefore, one encounter situation is the AC1-AC3 encounter flying at FL360 with a geometry of 42° (this value corresponds to the angular difference between tracks

¹¹ Due to confidentiality issues with BADA licence it is not possible to mention the specific aircraft models, as comparisons between them could be made based on results obtained.

of two of the busiest airways in LECMZMU), in which AC1 performs a climb AM with 0.8MTOW of mass, with a wind direction of 215° and 55kt intensity and considering a HF of 20s for a separation minimum of 4NM. This encounter situation gives a collision risk value. Other encounter situations, which give other collision risk values are, for example, from the situation referred above, the variation of some of the factors such as the AM, instead a climb AM an UNL descent, or instead of a FL360, FL390, etc.

The combination of all these factors results in a large number of situations for which the collision risk is calculated in Montecarlo simulations. It is considered whether it is possible to define a minimum separation of 4NM or 3NM for these situations, depending on whether they are safe when compared to the TLS.

5.3.2. Simulation approach

In the simulations performed, the aim is to calculate the collision risk between the aircraft pairs in the immediate layer, that is, from LOS to Collision. Therefore, the LOS is sought. Thus, while the manoeuvring aircraft starts from a fixed point on airway 1 (d_h from the intersection point), the starting point of aircraft 2 (non-maneuvring) is calculated so that the requirement is met, which is, both aircraft starting from both points, during the simulation lose the separation at some point (Figure 31). Therefore, the procedure followed in the simulation is:

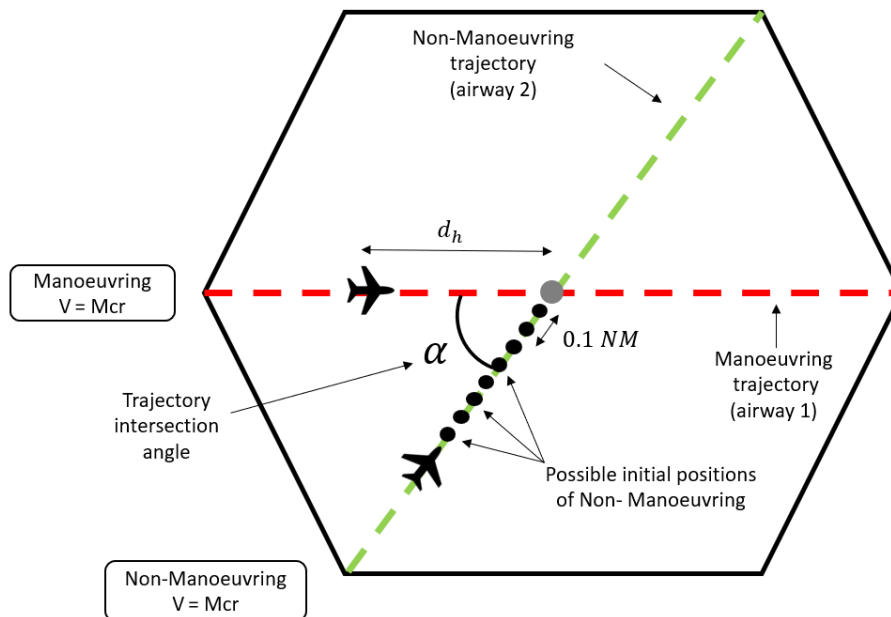


Figure 31. Conceptual representation of the scenario used in the simulations for determining the collision risk for an aircraft pair.

- The initial position of the manoeuvring aircraft in the horizontal plane is determined a fixed distance (d_h) from the intersection point. d_h is called critical distance and is calculated according to Equation (23):

$$d_h = \frac{S_{min}}{\sin \alpha} \quad (23)$$

Where:

S_{min} is the separation minimum applied, and

α is the intersection angle between tracks.

- The initial position of the non-manoevring aircraft is not fixed. Instead, it is calculated as an iterative process in which the points on airway 2 are defined at a distance of 0.1NM from each other, starting from the intersection point.
- Positioning the non-manoevring aircraft at that point and the manoeuvring aircraft at its starting point, 10^4 simulations are performed, considering navigation and speed errors for both aircraft.
- In each simulation, the algorithm calculates whether a LOS exists between both aircraft.
 - If LOS occurs, it is also calculated if this LOS is critical ($DCPA < 500ft$).
 - If there is a critical LOS, it is calculated whether the collision could develop or not. That is, t_{nec} is compared with $TCPA$ and if $t_{nec} > TCPA$, there is a collision.
 - If there is no LOS in any of the 10^4 simulations at the calculated point (point O in Figure 32), it is verified that, at a significant distance (regarding d_h) beyond point O (e.g. 10NM), there is no other point on the airway 2 where, positioning the non-manoevring aircraft and simulating 10^4 encounters, there is no LOS. If this condition is met, point O is defined as the upper or lower limit (depending on the direction in the definition of the points separated 0.1NM) of the LOS distribution over the non-manoevring airway.

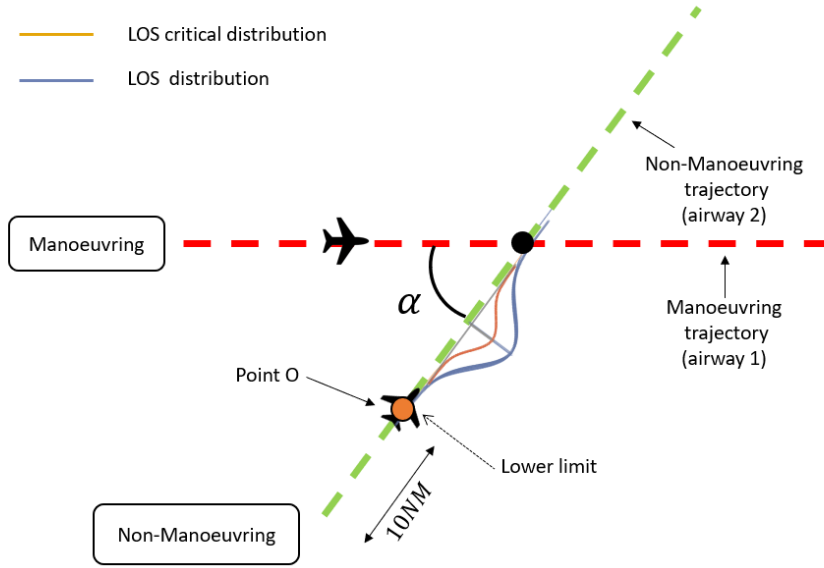


Figure 32. Lower limit of the LOS distribution.

Algorithm 2 summarises the pseudo-code used for computing the collision risk for different situations, explained above.

Algorithm 2. Algorithm for computing *Collision Risk*.

1.	Input: $Wd, Wi, angle_{egeom}, Num_{sim}, sep_{min}, col_{dist}, FL, AC1_{data}, AC2_{data}, AC3_{data}, AC4_{data}, AC5_{data}, t_{nec}$ (worst-case), $lim\_distance, \Delta incr$
2.	For $angle_{egeom} = 1 : (angle_{egeom})_{max}$ do
3.	For every wind direction (Wd) and intensity (Wi) combinations do
4.	For $sep_{min} = 1 : (sep_{min})_{max}$ do
5.	For $FL = 1 : FL_{max}$ do
6.	For every aircraft pair combination classified per Mach do notation hereinafter: $ac_{manoeuvring} = 1$; $ac_{non-manoevring} = 2$
7.	Calculate the projection of the angle for both aircraft trajectories (TK_{1proj}, TK_{2proj})
8.	Calculate the temperature (from ISA Model) and the V_{TAS} of both aircraft
9.	Calculate the $\overline{GS}$ of both aircraft considering the effect of wind (direction and intensity projection)
10.	Calculate the initial position of ac -manoeuvring (1) from the critical distance (d_n)
11.	While $LOS > 0 \parallel lim\_distance < 10\text{ NM}$ do
12.	For $i = -1:2:1$ do
13.	For $\Delta dist = 0: i \cdot \Delta incr : (i \cdot 50\text{ NM})$ do
14.	For $1 : Num_{sim}$ do
15.	Calculate navigation (ATT, XTT) and speed (v) uncertainties for both aircraft $XTT = N(0, 0.4)\text{ NM}$; $ATT = 0.8 * XTT$. $v = N(0, 15)\text{ kt}$; The speed error is applied randomly regarding the track of ac1 or ac2. When applied to ac 1 (it is projected to ac 2) and vice versa. Thus, it is simulated as the influence of wind uncertainty.

16.	<i>Simulate the aircraft trajectories with uncertainties</i> $\overline{V_{UW1}} = v_1 \cdot TK_{1proj} + \overline{GS_1}$ $\overline{V_{UW2}} = v_2 \cdot TK_{2proj} + \overline{GS_2}$ $\overline{try_1}(t = 0) = \text{crossing point} - d_h \cdot TK_{1proj} + (ATT_1, 0) + (0, XTT_1)$ $\overline{try_2}(t = 0) = \text{crossing point} + \Delta dist \cdot TK_{2proj} + (ATT_2, XTT_2) \cdot TK_{2proj}$ $\overline{try_1}(t) = \overline{try_1}(t = 0) + \overline{V_1} \cdot t$ $\overline{try_2}(t) = \overline{try_2}(t = 0) + \overline{V_2} \cdot t$
17.	<i>Calculate the Euclidean distance (d) between both trajectories every second</i> $d(t) = \text{norm}(\overline{try_{ac1}}(t) - \overline{try_{ac2}}(t))$
18.	If any $d < sep\_min$ then, $LOS = 1$ end if
19.	If any $d < col\_dist$ then, $LOS_{critical} = 1$ Calculate $t_{DCPA}, t_{LOS}, T CPA$ Then, Search t_{nec} values (from worst-case simulations) considering encounter geometry, FL, aircraft models and wind conditions of this simulation for all HF, percentage MTOW and AM available.
20.	For each of these t_{nec} values obtained If $t_{nec} > T CPA$ then, $Collision = 1;$ end if
21.	end if
22.	if $LOS = 0$ & a LOS has taken place before then, $lim\_distance = lim\_distance + \Delta incr;$ else $lim\_distance = 0;$ end if
23.	end for
24.	end for
25.	end for
26.	end while
27.	Count the number of $LOS, LOS_{critical}, Collision$ for each situation simulated (characterised by the aircraft pair, FL, wind conditions, encounter geometry, separation minima) for the different values of HF, percentage of MTOW and AM considered (which are embedded in the t_{nec} variable).
28.	Calculate $P(LOS_{critical} LOS)$ and $P(Collision LOS_{critical})$ for each situation simulated
29.	Calculate $Collision Risk_{each sit} = P(LOS_{critical} LOS) \cdot P(Collision LOS_{critical})$
30.	end for
31.	end for
32.	end for
33.	end for
34.	end for
35.	Output $Collision Risk_{dif sit}$

Table 7 summarizes control and target variables and their nomenclature in the previous pseudo-code:

Table 7. Control and target variables in Montecarlo simulations.

Target Variables		
Nomenclature	Explanation	Values in the simulation
$CollisionRisk_{dif\ sit}$ (scalar value)	Collision risk calculated for different situations	> 0
Control Variables		
Nomenclature	Explanation	Values in the simulation
$ac_{manoeuvring}$ (vector)	Aircraft that executes the AM	AC1(M), AC2(M), AC3(M), AC4(H), AC5(H)
$ac_{non-manoeuvring}$ (vector)	Aircraft that does not execute the AM	AC1(M), AC2(M), AC3(M), AC4(H), AC5(H)
$AC1\_data, AC2\_data, AC3\_data, AC4\_data, AC5\_data$ (array)	Aircraft data	MTOW, Mach, surface wing, FL Maximum Aerodynamics (drag coefficients) Engine thrust (climb/descent thrust coefficients...) Fuel flow (fuel consumption coefficients)
Wd (vector)	Wind direction	$0 < Wd < 360$
Wi (vector)	Wind intensity	$Wi > 0$
FL (vector)	FLs considered	350, 360, 370, 380, 390 or 400
$angle_{geom}$ (vector)	Encounter geometries	$0 \leq angle_{geom} < 180$
Sep_min (vector)	Separation minima	3, 4 or 5NM
col_dist (scalar value)	NMAC Distance	500ft
XTT ATT (scalar value)	Cross Track Navigation error Along Track Navigation error	$XTT = N(0, 0.4) NM$ $ATT = 0.8 * XTT$
v (scalar value)	Speed error	$v = N(0, 15) kt$
t_{nec} (scalar value)	Necessary Time	> 0
Other Variables		
$TCPA$	Available Time	> 0
t_{DCPA}	Time at the CPA	> 0
t_{LOS}	First moment when the distance between aircraft is below the separation minima	> 0
GS	Aircraft TAS speed and wind (ground speed)	> 0
V_{UW}	Aircraft speed with uncertainties and wind	> 0
Simulation parameters		
t (scalar value)	Simulation time	$0 : 1 : 1000$ seconds
Num_sim	Number of simulations	10^4
$lim\_distance$	Limit distance	$0 < lim\_distance < 10NM$
$\Delta incr$	Step size	0.1

As mentioned above, the t_{nec} depends on the aircraft model, aircraft mass, AM, HF and FL factors. The $TCPA$ depends on the separation minima, the closing speed, the geometry of the encounter, the wind conditions and the FL. The $TCPA$ is calculated in these simulations while the t_{nec} is obtained from the worst-case simulations presented in Chapter 4. Therefore, it is important to note that in these Montecarlo simulations, the aircraft model, aircraft mass, HF and AM factors are intrinsically considered in the t_{nec} variable.

5.3.3. TLS determination

The TLS is the benchmark used to compare the collision risk values calculated for the different encounter situations. It will be determined from the collision risk values associated with the different encounters for a separation value of 5NM. This is considered safe as these situations are currently being flown with this separation minimum value. Particularly, the TLS shall be the maximum collision risk value obtained for the minimum separation of 5NM.

The encounter geometries simulated are according to the current CONOPS. For instance, encounters where aircraft are on opposite courses (180°) will not be simulated as, according to the CONOPS, this situation would not occur because the aircraft should be flying at different FL and therefore separated, by at least 1000ft.

The TLS takes a constant value. According to Equation (22) for the calculation of the collision risk between a pair of aircraft ($Collision Risk_{aircraft pair}$), two factors need to be considered $P(LOS_{critical} | LOS)$ and $P(Collision | LOS_{critical})$. These factors are calculated in the simulations according to the following Equation (24) and Equation (25).

$$P(LOS_{critical} | LOS) = \frac{\text{Number of } LOS_{critical}}{\text{Number of } LOS} \quad (24)$$

$$P(Collision | LOS_{critical}) = \frac{\text{Number of Collision}}{\text{Number of } LOS_{critical}} \quad (25)$$

(25) The collision was defined in Equation (11). Equation (25) is equal to unity (the maximum value, as it is a probability) whenever $t_{nec} > T_{CPA}$, since the $LOS_{critical}$ has been defined as the situation where $DCPA < 500ft$. Therefore, the highest collision risk value for 5NM (TLS) occurs when $P(Collision | LOS_{critical})$ equals 1. In this situation, the TLS value corresponds to $P(LOS_{critical} | LOS)$, which solely depends on the separation minimum. This is explained further in section 5.3.5.

It should be noted that the order of magnitude of this TLS is 10^{-2} (as will be shown in Table 9 and Table 10), a large value. However, it is reminded that this order of magnitude only considers the collision risk corresponding to the immediate layer. That is, the risk of collision once the LOS has occurred, accentuated, moreover, by the fact that only the horizontal dimension is being considered and the performance of the safety nets is neglected. If the strategic and pre-tactical layers are added, i.e. the associated mode of operation is considered (CONOPS), the order of TLS decreases to values of $10^{-8} - 10^{-9}$.

5.3.4. ADSM values determination for LECMZMU sector

A practical case is simulated to show some results of the proposed methodology. Specific values of FLs, aircraft models, encounter geometry (intersection angle), aircraft mass and wind data are considered. These data are related to the operational and geometrical characteristics of the LECMZMU ENR sector. Table 8 shows the data considered in the simulations. The simulations have been performed on the Margerit-3 computer system at the Madrid Supercomputing and Visualisation Centre of the UPM.

Table 8. Simulations data for LECMZMU reference scenario.

Variables	Data considered	Particularisation for LECMZMU sector (see ANNEX E for more information)
Aircraft models considered	AC1(M), AC2(M), AC3(M), AC4(H), AC5(H)	The selected aircraft models are those most commonly flown in LECMZMU sector (Airbus and Boeing models)
FL considered	FL350, FL360, FL370, FL380, FL390, FL400	The selected FL are the busiest in LECMZMU sector
Encounter geometry	14°, 42°, 56°, 74°, 121°	The intersection angles considered are those between the busiest airways in LECMZMU sector
Wind directions considered (regarding true north)	0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°	An analysis of historical meteorological data in the LECMZMU sector for FL380 - FL400 from 1979 to 2023 establishes that the mean values of wind intensity and wind direction are, respectively, 55kt and 255° (Figure 43). More wind direction and intensity values are included to consider more situations
Wind intensities considered	40kt, 55kt, 70kt	
Separation Minima	5NM, 4NM, 3NM	Potential Ad Hoc separation minima values
	It is an input in the simulations.	
<i>tnec</i>	It is calculated in a worst-case scenario simulation (Chapter 4) for the different aircraft models, FL, aircraft masses (0.9MTOW, 0.85MTOW, 0.8MTOW, 0.75MTOW, 0.7MTOW), AM (climb, descent_LIM, descent_UNL) and HF (20, 30, 40s) considered, particularised for LECMZMU sector	

A total of 27000 encounter situations are simulated (from the combination of the different factors such as aircraft model, FL, wind directions and intensities, etc.). In each of these cases, the collision risk has been calculated for 5NM, subsequently for 4NM and for 3NM. As mentioned above, in those situations where the collision risk for 4NM or for 3NM is equal to or lower than the maximum collision risk for 5NM (TLS), it is considered that a separation minimum value of 4NM or 3NM can be safely applied. If in a situation it is safe to apply 4NM or 3NM, the preferred situation is the lowest applicable separation minimum, i.e. 3NM.

Table 9 and Table 10 show the situations in which it is possible to apply a minimum separation of 3NM or 4NM, depending on the collision risk. Table 9a

analyses for the 3NM minimum separation value, the situation of an encounter geometry of 14°, wind intensity 40 kt, wind direction 315° (true north), FL360, HF 30s, AM 1 (climb) and an aircraft mass of 0.9 MTOW (90% MTOW). The green colour indicates situations in which the collision risk is lower than the reference TLS value. This occurs specifically when the manoeuvring aircraft is the AC3, being safe to apply the separation minimum of 3NM. Conversely, the red colour indicates situations where the collision risk is higher than the reference TLS. Therefore, a separation minimum of 3NM can be applied when the AC3 is the manoeuvring aircraft and performs a climb AM with 0.9 MTOW (or lower) considering a HF value of 30s, FL 360, 14° of encounter geometry, wind intensity 40kt and wind direction 315°.

Table 9b shows the same situation but for a separation minimum of 4NM. Based on the risk values, it can be stated that a separation of 4NM can be applied when the manoeuvring aircraft is AC 2, AC 3, AC 4 or AC 5 (green colour). However, when in the aircraft pair the manoeuvring aircraft is AC 1, the separation minimum of the encounter must be maintained at 5NM (red colour because the collision risk is higher than the TLS and it is not safe to reduce the separation minima from the current value).

It should be noted that for the same situation analysed in Table 9a-b (where the only difference is the separation minimum) and focusing on AC3 as the manoeuvring aircraft, it will always be preferable to apply 3NM rather than 4NM, as both separation minima values are safe and it is preferable to set the lower value.

Table 9. Collision risk values for an aircraft pair for a 14° of encounter geometry.

Crossing angle	14	Manoeuvring aircraft	Non-manoevring aircraft				
Wind intensity	40		AC1	AC2	AC3	AC4	AC5
Wind direction	315	AC1	2.63E-02	2.63E-02	2.63E-02	2.64E-02	2.63E-02
Sep Min	3	AC2	2.29E-02	2.29E-02	2.29E-02	2.31E-02	2.29E-02
FL	360	AC3	1.59E-02	1.59E-02	1.59E-02	1.58E-02	1.58E-02
HF	30	AC4	2.27E-02	2.27E-02	2.27E-02	2.47E-02	2.40E-02
AM	Climb	AC5	2.07E-02	2.07E-02	2.07E-02	2.24E-02	2.23E-02
MTOW	0.9						

(a)

TLS reference
1.64E-02

Crossing angle	14	Manoeuvring aircraft	Non-manoevring aircraft				
Wind intensity	40		AC1	AC2	AC3	AC4	AC5
Wind direction	315	AC1	1.69E-02	1.69E-02	1.69E-02	1.68E-02	1.68E-02
Sep Min	4	AC2	1.14E-02	1.14E-02	1.14E-02	1.13E-02	1.12E-02
FL	360	AC3	5.20E-03	5.20E-03	5.20E-03	5.12E-03	5.16E-03
HF	30	AC4	1.09E-02	1.09E-02	1.09E-02	1.35E-02	1.27E-02
AM	Climb	AC5	8.85E-03	8.85E-03	8.85E-03	1.05E-02	1.07E-02
MTOW	0.9						

(b)

TLS reference
1.64E-02

Table 10 shows two different situations for an encounter geometry of 42°, where the difference between them is the AM performed by the manoeuvring aircraft. In Table 10a the AM is a climb, while in Table 10b it is a descent_UNL. It would be possible to apply a separation minimum value of 4NM in the encounters for all aircraft pairs (green colour, Table 10b) if the AM executed by the manoeuvring aircraft is a descent_UNL. Nevertheless, if the AM is a climb (Table 10a), only it would be possible to apply a separation minimum of 4NM for encounters in which AC2 and AC5 are the manoeuvring aircraft (being the non-manoevring aircraft AC1, AC2 or AC3) and in situations in which AC3 is the manoeuvring aircraft (being the non-manoevring aircraft any of the other) if the AM is a climb (Table 10a).

Table 10. Collision risk values for an aircraft pair for a 42° of encounter geometry.

Crossing angle	42	Manoeuvring aircraft	Non-manoevring aircraft				
Wind intensity	70		AC1	AC2	AC3	AC4	AC5
Wind direction	315	AC1	1.82E-02	1.82E-02	1.82E-02	1.92E-02	1.89E-02
Sep Min	4	AC2	1.61E-02	1.61E-02	1.61E-02	1.78E-02	1.72E-02
FL	360	AC3	1.21E-02	1.21E-02	1.21E-02	1.44E-02	1.35E-02
HF	30	AC4	1.78E-02	1.78E-02	1.78E-02	1.91E-02	1.86E-02
AM	Climb	AC5	1.55E-02	1.55E-02	1.55E-02	1.74E-02	1.69E-02
MTOW	0.7						

(a)

TLS reference 1.64E-02

Crossing angle	42	Manoeuvring aircraft	Non-manoevring aircraft				
Wind intensity	70		AC1	AC2	AC3	AC4	AC5
Wind direction	315	AC1	3.11E-03	3.11E-03	3.11E-03	4.46E-03	3.94E-03
Sep Min	4	AC2	3.11E-03	3.11E-03	3.11E-03	4.46E-03	3.94E-03
FL	360	AC3	3.11E-03	3.11E-03	3.11E-03	4.46E-03	3.94E-03
HF	30	AC4	4.46E-03	4.46E-03	4.46E-03	6.32E-03	5.54E-03
AM	UNL_Des	AC5	4.81E-03	4.81E-03	4.81E-03	6.65E-03	6.25E-03
MTOW	0.7						

(b)

TLS reference 1.64E-02

These results show different situations defined depending on the combination of the mentioned parameters in which it is possible to apply different values of separation minima. Therefore, it is possible to apply different separation minima values depending on the situation (Ad Hoc separation). Table 11 presents the general results obtained from the point of view of the percentage of situations in which it is possible to apply a minimum separation different from 5NM for LECMZMU.

Table 11. Percentage of situations (from 27000) where it is possible to apply 4NM or 3NM of separation minima.

Encounter geometry Intersection angle between tracks (°)	Separation Minima	HF (s)	Number (No.) of situations analysed	No. of situations in which the collision risk is lower than the maximum collision risk for 5NM	Percentage of situations (%) in which it could be applied that Separation Minima
14°	3 NM	20	27000	21802	81
		30	27000	19048	71
		40	27000	10714	40
	4 NM	20	27000	24945	92
		30	27000	24242	90
		40	27000	23015	85
42°	3 NM	20	27000	3015	11
		30	27000	0	0
		40	27000	0	0
	4 NM	20	27000	18239	68
		30	27000	7948	29
		40	27000	538	2
56°	3 NM	20	27000	0	0
		30	27000	0	0
		40	27000	0	0
	4 NM	20	27000	6315	23
		30	27000	18	0.1
		40	27000	0	0
74°	3 NM	20	27000	0	0
		30	27000	0	0
		40	27000	0	0
	4 NM	20	27000	50	0.2
		30	27000	0	0
		40	27000	0	0
121°	3 NM	20	27000	0	0
		30	27000	0	0
		40	27000	0	0
	4 NM	20	27000	0	0
		30	27000	0	0
		40	27000	0	0

As can be seen in Table 11, for small encounter geometries (intersection angles between tracks), it would be safe to reduce the separation minimum to 4NM and 3NM. In particular, for the 14° angle, if a HF value of 20s is considered, it is

possible to reduce the separation minimum to 3NM in 81% of the situations analysed, while 4NM could be applied in 92% of the situations.

To enhance comprehension, the following will provide a detailed explanation. The encounter geometry value of 14° corresponds to the crossing of the BARDI-ZMR and TOSDI-ZMR airways, which experience the highest traffic volume in the sector. By setting a requirement of a HF of 20s, it is determined that out of the 27000 simulated encounters for this geometry (considering aircraft models, wind conditions, FLs, etc.), a separation minimum of 3NM between aircraft pairs could be applied in 21802 encounters while maintaining the current safety levels (TLS). Furthermore, if the 4NM separation minimum is considered, it is possible to define this separation minimum in 24945 encounters, which represents 92% of the total. Therefore, different encounter situations allow different separation minima values to be defined. In some encounter situations, it will be safe to apply the minimum separation of 3NM (in these cases, the option of 4NM is also viable, though the minimum allowable separation will always be applied), while in others, it will only be feasible to reduce from 5NM to 4NM.

For the encounter geometry of 42° it is possible to apply 3NM in 11% of the situations and 4NM in 68% of the situations considering a HF value of 20s. Therefore, for intersection angles between 14° and 42° it is possible to apply separation minima values of 3NM or 4NM.

Table 11 shows that for an intersection angle of 56° it is not possible to safely apply a separation minimum of 3NM, but it would be possible to reduce the separation minimum to 4NM in 23% of the situations analysed. It is observed that for geometries with intersection angles between 56° and 74° the reduction of the separation minima is only possible in very few situations. For geometries with intersection angles greater than 74° , it can be concluded that it is practically impossible to reduce the separation minima.

5.3.5. Sensitivity analysis

A sensitivity analysis is defined as the influence study of certain parameters on the results of a model. The two factors of the CRM developed to determine the Ad Hoc separation minima are analysed based on the simulation data of Table 8 to get a better understanding of the proposed model. Each factor of the Equation (22) is analysed separately ($P(LOS_{critical} | LOS)$ and $P(Collision | LOS_{critical})$).

- $P(LOS_{critical} | LOS)$: conditional probability of a critical LOS from a LOS.

Through this component, the probability of a critical LOS occurring when a LOS between a pair of aircraft takes place is calculated. The main parameters that influence this component are the encounter geometry, the relative speed and the separation minima.

Figure 33 shows a scheme of what is simulated. Figure 33a represents deterministic results and, Figure 33b shows stochastic results by introducing uncertainty. In Figure 33a the black rectangle represents the geometric location of the LOS, that is, it represents the positions where being an aircraft located in point A and another aircraft located in region B simultaneously, a LOS will occur at some point of the simulation. The red rectangle (C) represents the $LOS_{critical}$ geometric location, i.e. it represents the positions where, if an aircraft is located in point A and another aircraft is located in region C simultaneously, a $LOS_{critical}$ will occur at some point in the simulation. Then, the factor $P(LOS_{critical} | LOS)$ is obtained as the quotient between the length of the red rectangle and the black rectangle for deterministic results and the quotient of the areas below the blue and yellow distribution curves for stochastic results.

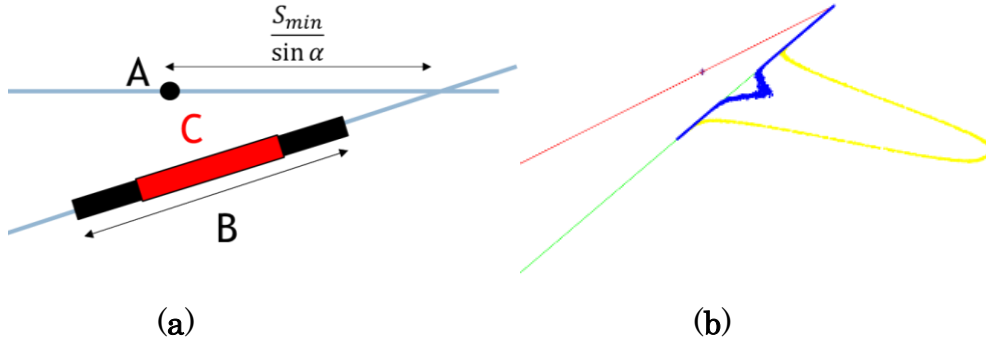


Figure 33. Scheme of the results obtained in the simulations. (a) Deterministic simulation, (b) Stochastic simulation.

Figure 34 shows the influence of the encounter geometry on this factor for the deterministic simulations (the same for the stochastic simulations). As can be seen, the rectangle lengths (or the areas in stochastic simulations) increase as the angle increases ($\alpha_5 > \alpha_1$). However, the probability value calculated from the quotient is constant because both lengths or areas

(corresponding to LOS and $LOS_{critical}$ geometric locations) increase proportionally with the angle.

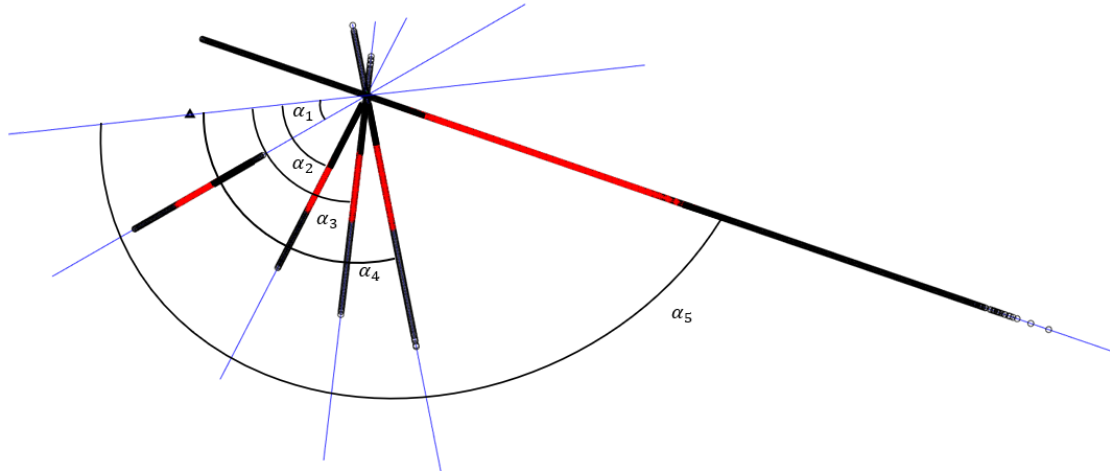


Figure 34. LOS section and critical LOS section variation with angle (α).

Regarding the influence of the relative speed, the variation of $P(LOS_{critical} | LOS)$ as a function of aircraft mix (MM, MH, HH) in the encounter can be assumed constant, as well as with wind intensity. This is due to the fact that LOS is provoked in the simulations (i.e. for determining $P(LOS_{critical} | LOS)$ it is assumed that a LOS has occurred). The speed of the aircraft influences the LOS occurrence (LOS probability), but not the conditional probability $P(LOS_{critical} | LOS)$. Regarding the influence of the separation minima on this factor, it is considerable. It increases when the separation minimum is decreased. Table 12 shows the influence of relative speed and separation minimum on this factor.

Table 12. $P(LOS_{critical} | LOS)$ values for different aircraft encounters (MM, MH, HH) and separation minima values (3NM, 4NM and 5NM). Constant factors: intersection angle 14° , 40kt of wind intensity, 0° wind direction.

Aircraft encounters			
$P(LOS_{critical} LOS)$	MM	MH	HH
	0.016284	0.016365	0.016256
Separation Minima			
$P(LOS_{critical} LOS)$	5NM	4NM	3NM
	0.016284	0.020578	0.027123

- $P (Collision | LOS_{critical})$: conditional probability of a collision from a critical LOS.

This is the probability of the collision occurrence. That is, a collision occurs because the $LOS_{critical}$ occurred and the t_{nec} to avoid the collision was greater than the $TCPA$ of the encounter. As mentioned above, the variable t_{nec} varies significantly as a function of aircraft model, aircraft mass, HF, AM and FL. Generally, the lower the aircraft mass and the lower the FL and HF, the lower the t_{nec} . The descent AM is the one that provides lower t_{nec} compared to the climb AM.

$TCPA$ varies significantly with the encounter geometry (angle between tracks) and separation minima. Aircraft speed also affects $TCPA$. The higher the crossing angles, the higher the relative speed and therefore the lower the $TCPA$. The smaller the separation minima, the lower the $TCPA$, as it is measured as the time from LOS to collision.

Figure 35 and Figure 36 show the variation of $P (Collision | LOS_{critical})$ factor as a function of the parameters aircraft mass and FL for a climb AM performed by AC 3. Lower values of aircraft mass and FL lead to lower t_{nec} and consequently, there are a greater number of situations in which the AM could be performed (because $t_{nec} < TCPA$) reducing the $P (Collision | LOS_{critical})$.

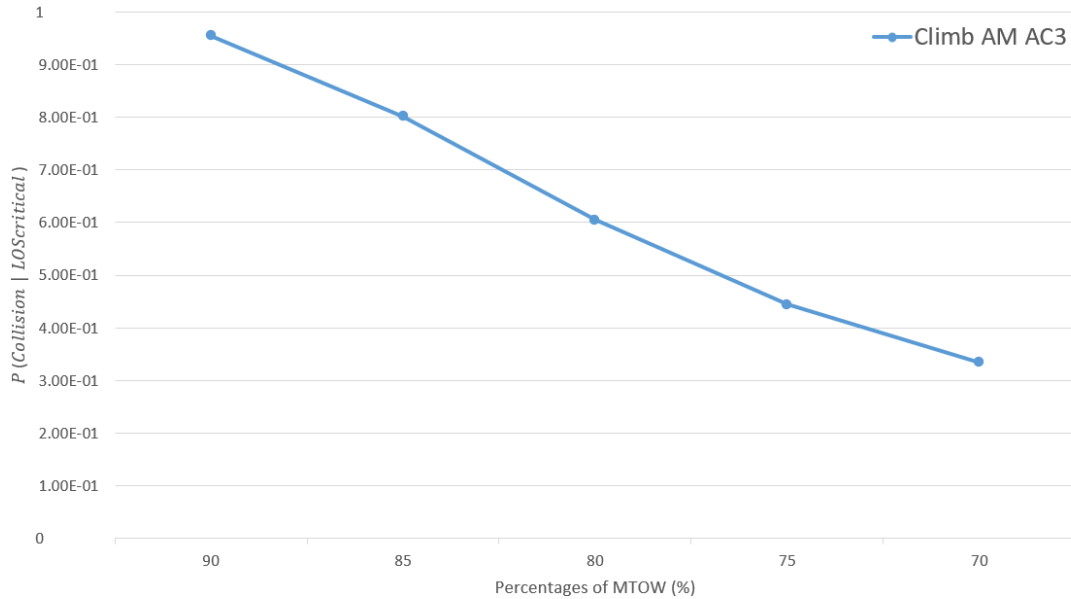


Figure 35. $P (Collision | LOS_{critical})$ variation with aircraft mass.

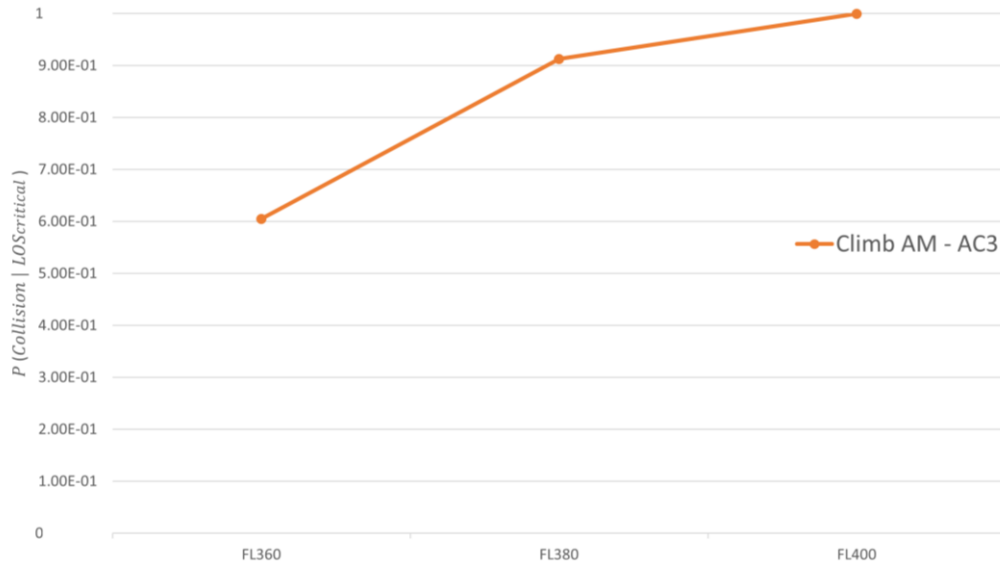


Figure 36. $P(\text{Collision} | LOS_{critical})$ variation with FL.

Figure 37 shows the variation of the $P(\text{Collision} | LOS_{critical})$ factor with aircraft model and AM. Generally, the climb AM assumes higher t_{nec} and it is more influenced by aircraft performance (engine thrust). In descent AM the t_{nec} values are lower and generally all aircraft have similar behaviour in this manoeuvre. Therefore, the values of $P(\text{Collision} | LOS_{critical})$ are practically constant regardless of the aircraft model for the descent AM and always lower than for the climb AM. Regarding the HF factor, Figure 38 shows that lower HF times mean lower t_{nec} and, consequently, lower $P(\text{Collision} | LOS_{critical})$.

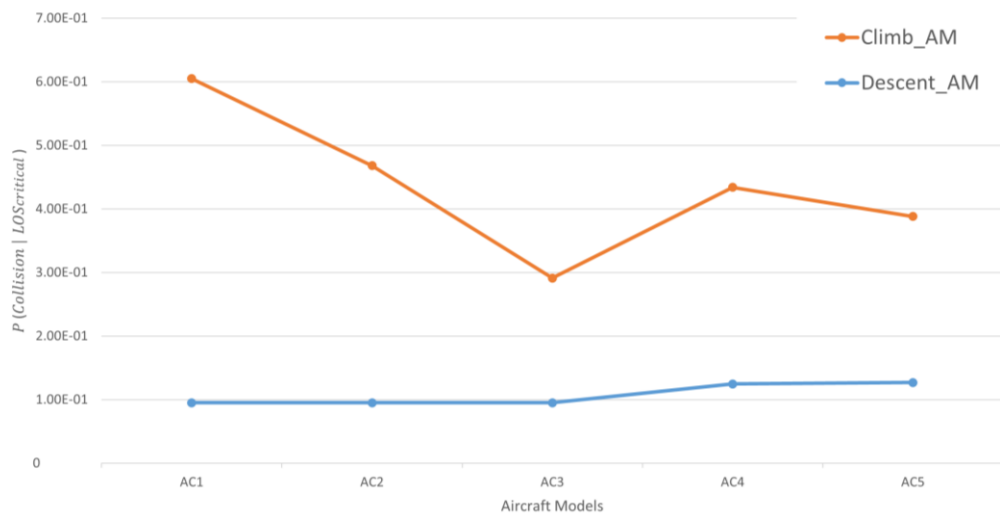


Figure 37. $P(\text{Collision} | LOS_{critical})$ variation with aircraft models and AM.

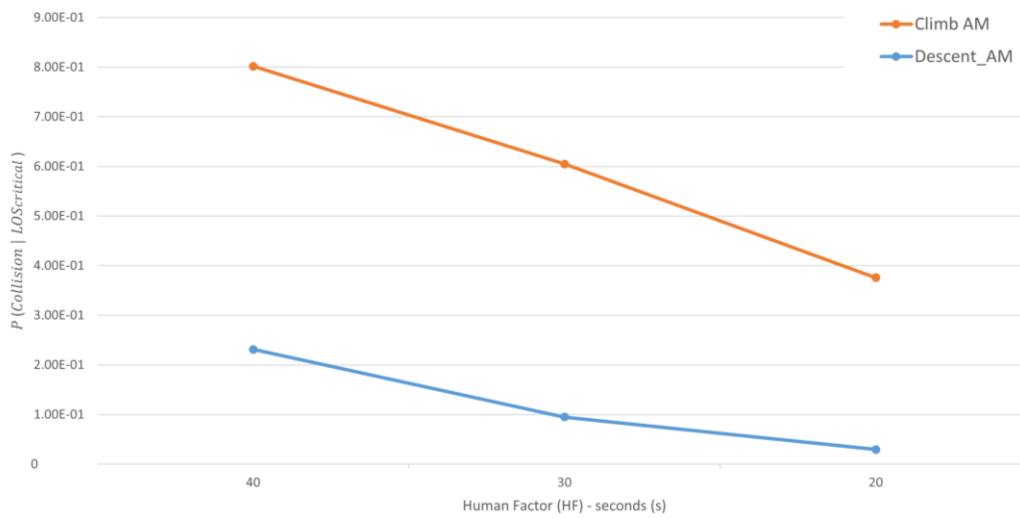


Figure 38. $P(\text{Collision} | LOS_{critical})$ variation with HF and AM.

Regarding the influence of the wind direction and intensity on the $P(\text{Collision} | LOS_{critical})$ factor, Figure 39 shows the data obtained in the simulation of the aircraft pair encounter. The manoeuvring aircraft has a heading of 360° and the non-manoevring aircraft has a heading of 346° . For a tailwind (180°) and a wind intensity of 70kt, the values of $P(\text{Collision} | LOS_{critical})$ are higher as the GS of the aircraft is greater and the $TCPA$ is lower. However, for a headwind (0°) and a wind intensity of 70kt, the $TCPA$ is higher because the aircraft has a lower GS and therefore the values of $P(\text{Collision} | LOS_{critical})$ are lower.

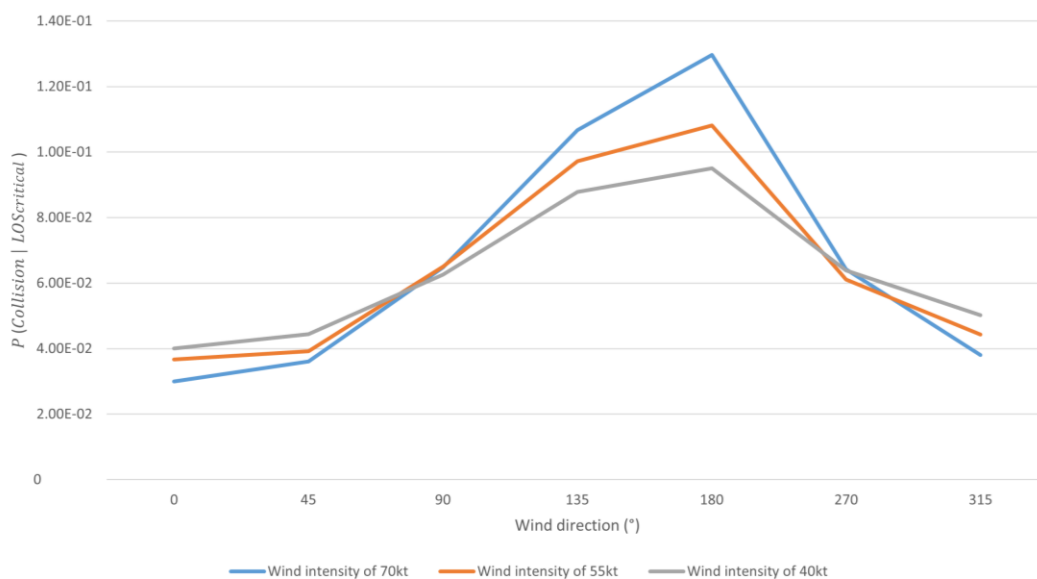


Figure 39. $P(\text{Collision} | LOS_{critical})$ variation with wind intensity and direction.

- Collision Risk

Figure 40 shows, for a specific encounter situation, the variation of the collision risk metric with the separation minima. As can be seen, the collision risk increases as the separation minimum decreases. Furthermore, the increase is not proportional. The variation between the risk for 4NM and 3NM is significantly greater than the variation between the risk for 5NM and 4NM.

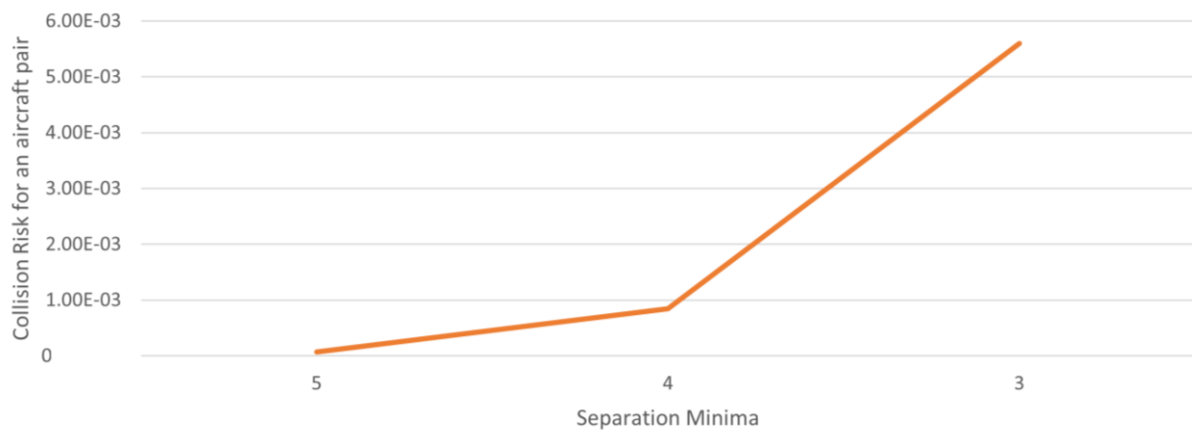


Figure 40. Collision Risk of an aircraft pair. Simulation with wind intensity 70kt, tailwind, HF 20s, descent AM, FL380, 0.9MTOW and encounter geometry of 14° between aircraft trajectories.

5.4. Case study of the application of Ad Hoc separation in LECMZMU sector: safety analysis

5.4.1. CRM for a sector

Once the Ad Hoc separation values have been obtained for each specific situation (in which the traffic density was reduced to a pair of aircraft and for given conditions: FL, AM, etc.), the collision risk is calculated for the operational scenario. The main difference is the traffic density, which corresponds to the sector air traffic flows. Therefore, it is possible to operationally evaluate the application of the concept in a scenario in terms of safety. The collision risk of the sector is determined from the collision risk associated with each pair of aircraft and is obtained from Equation (26).

$$CR_{Sector} = P_{LOS} * \sum_{i=1}^p \sum_{j=1}^q (C_{via1} * C_{via2})_{ij} * \left(\sum_{k=1}^r \sum_{l=1}^r \sum_{m=1}^s ((C_k)_{via1_{ij}} * (C_{mk})_{via1_{ij}} * (C_l)_{via2_{ij}} + (C_k)_{via2_{ij}} * (C_{mk})_{via2_{ij}} * (C_l)_{via1_{ij}}) * P(COL|LOS)_{ijklm} \right) \quad (26)$$

Where:

- P_{LOS} = LOS Frequency. It is defined as the number of LOS per flight hour in the sector. These data are obtained from historical data of the sector from many years;
- p = number of FL considered;
- q = pairs of converging airways (different encounter geometries depending on the angles between tracks);
- r = number of aircraft models;
- s = number of ranges of aircraft masses¹² considered; Aircraft are ranked according to their TOW, which is expressed as a percentage of their MTOW. For instance: <0.7 MTOW, <0.75 MTOW, etc.
- $(C_{via1} * C_{via2})_{ij}$ are the weighting factors of the traffic flows in two converging airways for a specific FL. These data are obtained from historical data;
- $(C_k)_{via1_{ij}} * (C_{mk})_{via1_{ij}} * (C_l)_{via2_{ij}}$ are the weighting factors of the aircraft models in a flow and aircraft masses for an aircraft model in a flow. These data are obtained from historical data¹³;
- $P(COL|LOS)_{ijklm}$ is the probability that a collision occurs once the LOS has taken place for a specific situation (FL, encounter geometry, aircraft model, etc.). This is the factor determined for a specific aircraft pair and conditions described in the previous section.

The model defined in Equation (26) reflects the proactive and reactive parts of the system. The P_{LOS} factor quantifies the performance of the system, i.e., it presents how the system behaves in a particular scenario. The system works to minimise the number of times the separation minima are lost (LOS occurrence). This is the proactive part of the model. The reactive part is the summation factor ($\sum \sum factor$).

¹² Calculated from the model used by RAMS [119], which is based on the flight's planned distance.

¹³ In the case of mass, the city pairs are derived from historical data. The mass is calculated from the model used by RAMS based on the origin and destination of the route.

It represents the ability of the system to react effectively when a LOS occurs, preventing it from escalating into a collision.

There is a clear limitation in trying to apply the Equation (26) to the concept of Ad Hoc separation. This is due to the fact that for the estimation of the P_{LOS} factor it is necessary to have historical data, which are not available for a concept that is not yet implemented. Therefore, this factor will be obtained after solving the Equation (26), as a result of assuming as the TLS of the sector for the Ad Hoc separation concept the collision risk value obtained with the current separation value (5NM). That is, the collision risk element of Equation (26) will be equal by applying the Ad Hoc separation concept and the current separation minima. This will allow to know how the P_{LOS} factor should vary so that the application of the Ad Hoc separation concept in a scenario is as safe as the current operation. In the following subsection, what has been explained is applied to LECMZMU scenario.

5.4.2. Application to LECMZMU ENR sector

The ADSM values were determined for the reference scenario, LECMZMU ENR sector, as explained in section 5.3.4. Information regarding LECMZMU is included in ANNEX E. By means of Equation (26) the safety analysis of the application of the Ad Hoc separation concept in a scenario is performed and a set of requirements for its safe implementation is obtained.

Historical traffic data from the year 2019 are obtained from the Aeronautical Information Regulation and Control (AIRAC) cycles in NEST software [118]. These data have been considered to determine the weighting factors for the calculation of the sector collision risk. Since this is an illustrative application, the following assumptions are considered to simplify the calculation.

1. Only the traffic that flies through the following six airways within the sector is considered, representing 65% of LECMZMU's traffic:
 - UN873: entry WP BARDI
 - UN745: entry WP TOSDI
 - UL155: entry WP ADORO
 - UM30: entry WP OMESI
 - UN976: entry WP NEA
 - UN733: entry WP DESAT

2. Traffic between FL350 and FL400 is considered, since 98% of the traffic in the sector flies at those FL.
3. Only five aircraft models are considered which account for 90% of the aircraft models in the sector and correspond with AC1, AC2, AC3, AC4 and AC5, respectively, in the previous simulations.
4. Radar traces of the years 2017-2019 have also been analysed to determine the number of LOS (Figure 41 and Figure 42) and flight hours in the sector (P_{LOS}).

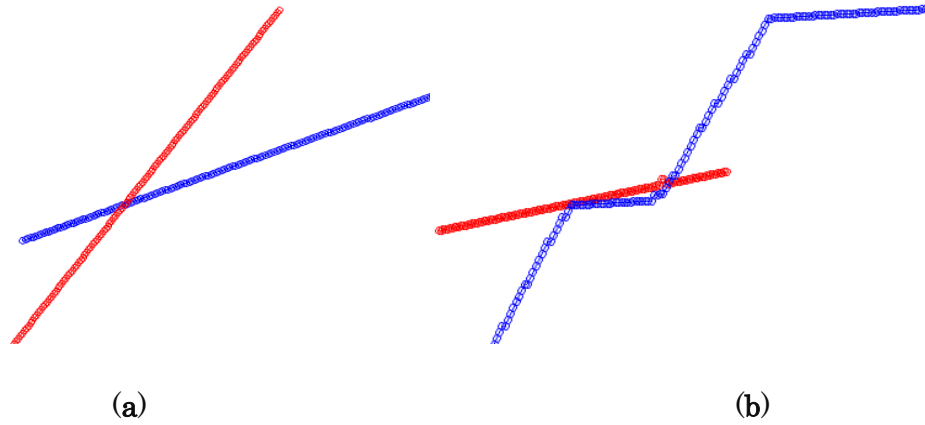


Figure 41. LOS 1, detected from radar traces analysis. Red traces correspond to aircraft A, blue traces to aircraft B. (a) Floor plan view; (b) Profile view.

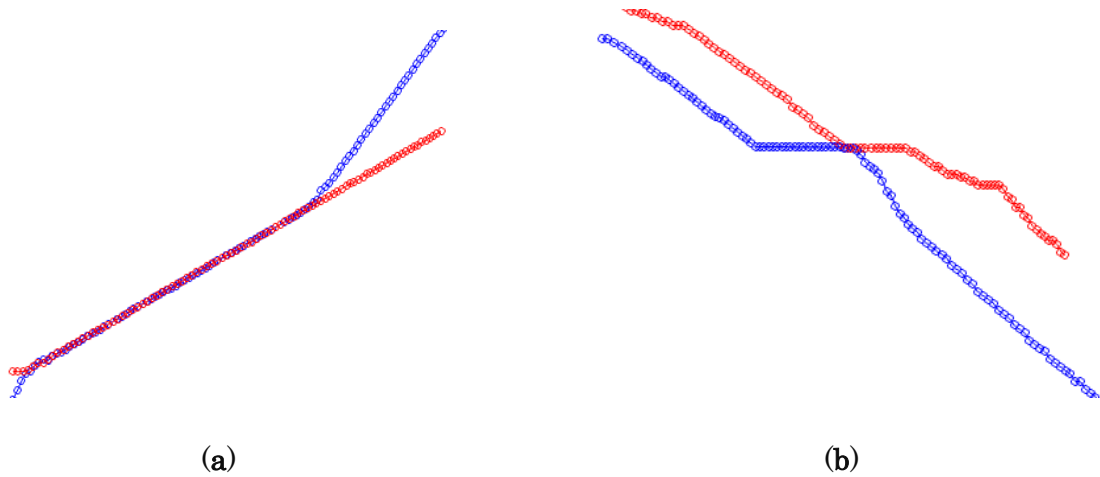


Figure 42. LOS 2, detected from radar traces analysis. Red traces correspond to aircraft A', blue traces to aircraft B'. (a) Floor plan view; (b) Profile view.

5. The aircraft mass data have been obtained from the model used by RAMS [119]. The initial mass of the aircraft is calculated as a percentage of the MTOW based on the flight's planned distance. The mass is considered constant during the time the aircraft is flying in the sector and equal to the value corresponding to the initial mass (conservative assumption).
6. As input data, the HF is considered to be 20s and the wind data (values specified in the next point) are given. Actually, the HF would be defined as a requirement and the wind data would be an input from the aircraft (via ADS-C reports). For simulation purposes these values have been introduced.
7. A meteorological study using National Oceanic and Atmospheric Administration (NOAA) wind data [120] has been conducted. This analysis of historical meteorological data in the LECMZMU sector for FL380-FL400 from January 01, 1979 to January 31, 2023 establishes that the mean values of wind intensity and wind direction are, respectively, 55kt and 255° (Figure 43).

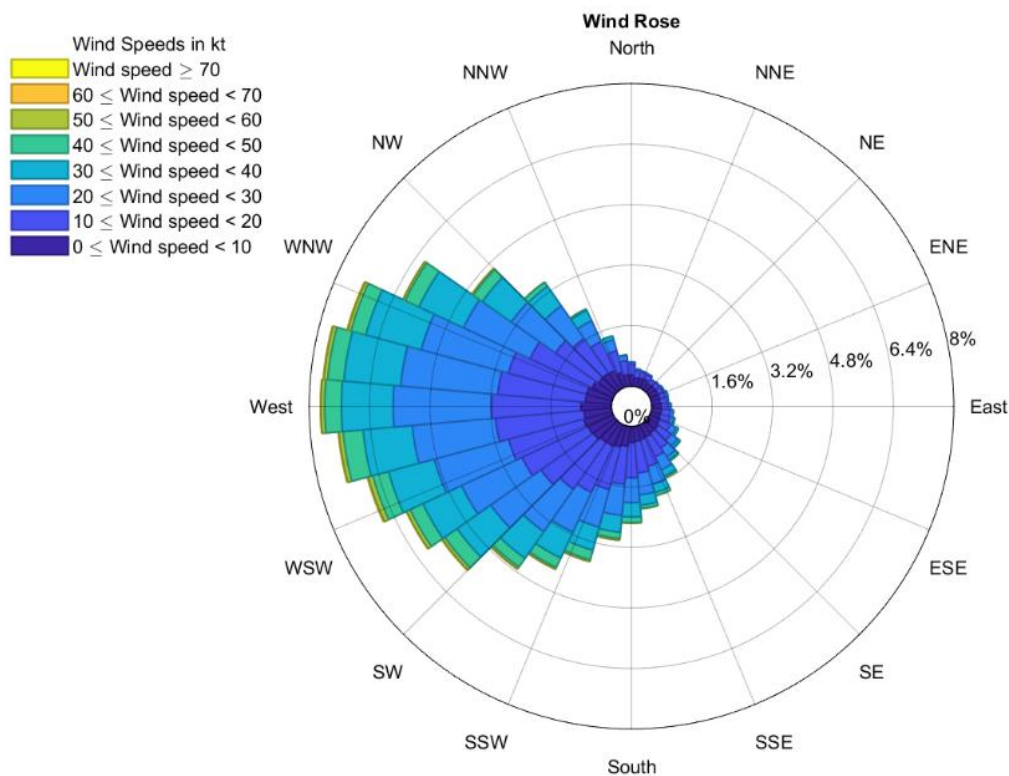


Figure 43. LECMZMU wind rose. Historical data from 1979 to 2023.

Table 13 shows the results for the sector collision risk (Equation (26)). From the results can be inferred that the P_{LOS} must be reduced by half to maintain current safety levels (collision risk equal to $4.4 \cdot 10^{-8}$). P_{LOS} value of $6.18 \cdot 10^{-5}$ (current separation minimum of 5NM) corresponds to a total of 4 LOS occurrences in the period 2017-2019 in the LECMZMU sector, where the flight hours for these three years are 64725. Reducing this factor by half means accepting no more than 2 LOS occurrences in a 3-year period. Therefore, the causes that lead to a LOS must be mitigated for the safe application of the Ad Hoc separation concept.

Table 13. Results of the collision risk values in LECMZMU, considering HF 20s, wind intensity 55 kt and wind direction 255°.

Collision Risk of the sector		
5 NM Sep. Min.	Factor (P_{LOS} 5NM Sep. Min.)	$6.18 \cdot 10^{-5}$
	Factor ($\sum$ elements 5NM Sep. Min.)	$7.21 \cdot 10^{-4}$
	Collision Risk for a Sep. Min. of 5NM	$4.4 \cdot 10^{-8}$
ADSM	Factor (P_{LOS} ADSM)	$3.03 \cdot 10^{-5}$
	Factor ($\sum$ elements ADSM)	$1.45 \cdot 10^{-3}$
	Collision Risk for ADSM	$4.4 \cdot 10^{-8}$

From the LOS criticality contributing factors study (ANNEX C), a more in-depth analysis of ATC and Crew error types was conducted. Figure 44 shows the results obtained. It is observed that, regarding the ATCO, the most common errors were erroneous clearance issuance, traffic monitoring and conflict resolution (CR).

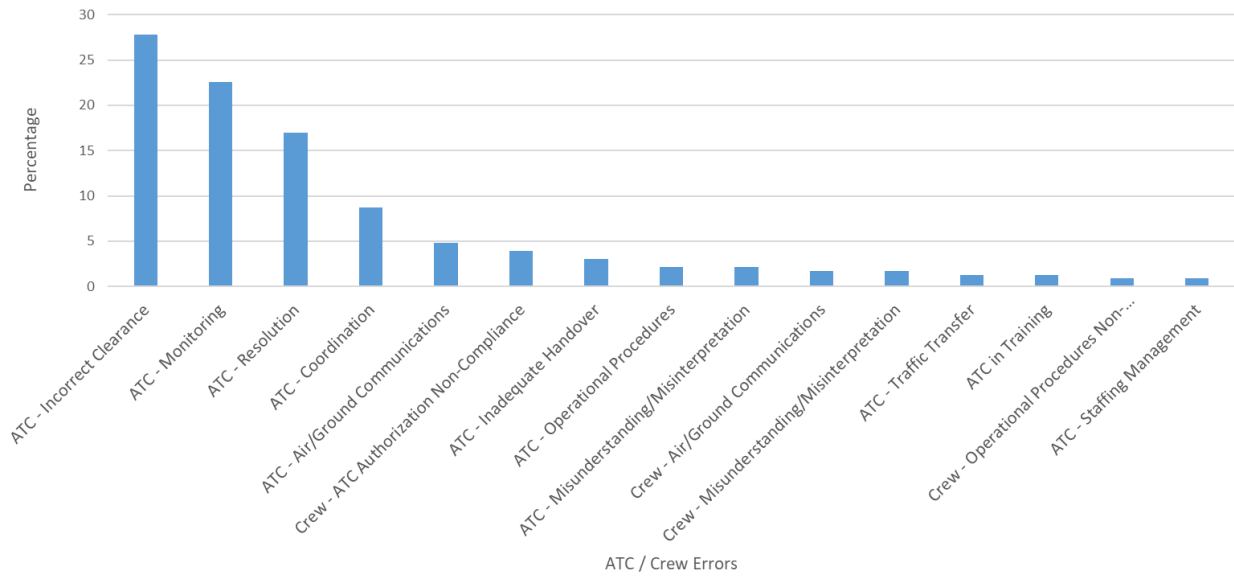


Figure 44. Contributing factors of ATC and Crew error to LOS occurrence.

Therefore, the mitigation of these causes could be done by adding or replacing current ATC support tools with more sophisticated ones. In particular, new functionalities such as "what if" or "what else" allow ATCO to verify whether the ATC instruction is conflictive with other traffic or not. Similarly, CD&R tools (for different time horizons) could contribute to reduce errors in monitoring and resolving conflicting situations. In fact, the ASMT for the implementation of the Ad Hoc separation concept in a scenario includes advanced functionalities for ATCO support (such as CD&R).

In addition, new operating concepts are emerging, which are compatible and beneficial to the Ad Hoc separation concept, such as TBO, in which each aircraft trajectory, which integrates ATM and airport constraints, is agreed by the airspace users and ANSPs and is strategically free of conflicts from its origin. Nevertheless, this latest point is out of the scope of the present work.

If the sector collision risk analysis is now performed for all wind intensities and directions considered in the simulations, it is possible to calculate an overall P_{LOS} reduction value to maintain the current safety level in LECMZMU by applying the concept of Ad Hoc separation minima. The purpose of this analysis is to verify that the order of magnitude of the P_{LOS} reduction factor is not different from that obtained for the LECMZMU mean values of wind intensity and wind direction (55kt and 255°). Table 14 shows the results.

Table 14. P_{LOS} reduction factor for the Ad Hoc implementation in LECMZMU, different wind intensities and directions.

Wind Intensity (kt)	Wind direction (°)	P_{LOS} 5NM Sep. Min.	$\sum \sum$ factor 5NM	$\sum \sum$ factor Ad Hoc Separation	P_{LOS} reduction factor needed
40	0	6.18E-05	5.06E-04	1.54E-03	3.0
	45	6.18E-05	4.85E-04	1.40E-03	2.9
	90	6.18E-05	5.02E-04	1.55E-03	3.1
	135	6.18E-05	6.07E-04	1.62E-03	2.7
	180	6.18E-05	6.72E-04	1.39E-03	2.1
	225	6.18E-05	6.75E-04	1.38E-03	2.0
	270	6.18E-05	6.65E-04	1.60E-03	2.4
	315	6.18E-05	5.88E-04	1.55E-03	2.6
55	0	6.18E-05	4.96E-04	1.55E-03	3.1
	45	6.18E-05	4.67E-04	1.43E-03	3.1
	90	6.18E-05	4.91E-04	1.54E-03	3.1
	135	6.18E-05	6.41E-04	1.63E-03	2.5
	180	6.18E-05	7.20E-04	1.46E-03	2.0
	225	6.18E-05	7.21E-04	1.45E-03	2.0
	270	6.18E-05	7.03E-04	1.65E-03	2.3
	315	6.18E-05	6.06E-04	1.56E-03	2.6
70	0	6.18E-05	4.79E-04	1.57E-03	3.3
	45	6.18E-05	4.52E-04	1.37E-03	3.0
	90	6.18E-05	4.80E-04	1.53E-03	3.2
	135	6.18E-05	6.69E-04	1.64E-03	2.4
	180	6.18E-05	7.70E-04	1.53E-03	2.0
	225	6.18E-05	7.73E-04	1.53E-03	2.0
	270	6.18E-05	7.43E-04	1.69E-03	2.3
	315	6.18E-05	6.17E-04	1.57E-03	2.5

The results show that, if all wind directions and intensities are considered, the P_{LOS} factor should be reduced up to 3 times (mean value of all intensities and directions), thus going from 4 LOS occurrences in the period 2017-2019 to 1 LOS occurrence. This result is of the same order of magnitude as that obtained for the mean values of wind intensity and wind direction (55kt and 255°). However, this is considered a very conservative approach. The NOAA analysis (Figure 43) shows that the predominant wind data are those with wind directions between 180° - 315°, the rest being negligible. If only data from these directions are considered, the P_{LOS} factor should be reduced up to 2 times, as was the case with the mean wind intensity and wind direction values (55kt and 255°) of the sector. Assuming this latter requirement (reduction factor of 2), that is a P_{LOS} of $3.03 \cdot 10^{-5}$ for the Ad Hoc separation concept, the collision risk of the sector is determined for the three wind intensities considered and all wind directions (Figure 45).

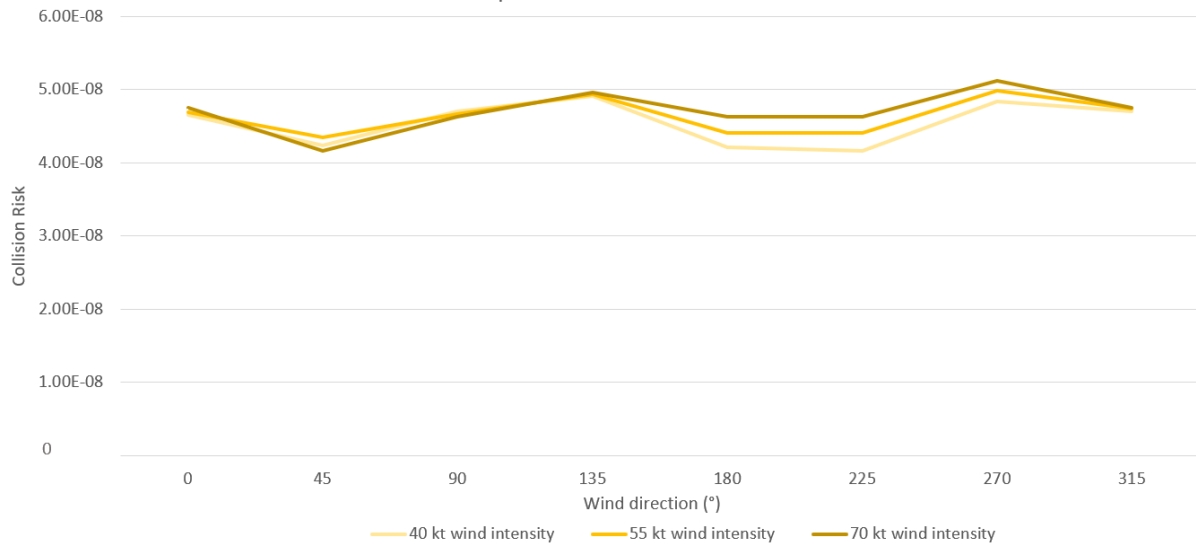


Figure 45. Representation of the Ad Hoc collision risk values LECMZMU for different wind intensities and directions.

Figure 45 shows that the higher values of collision risk in the sector are for 70kt of wind intensity and 135° and 270° directions. Nevertheless, the values of collision risk for the ADSM in LECMZMU are mostly between $4.00 \cdot 10^{-8}$ and $5.00 \cdot 10^{-8}$. In [121] these values correspond to ultra-safe systems. Consequently, if the P_{LOS} is reduced by half in the further years, the implementation of the ADSM concept in a sector would be as safe as the current operational concept.

5.5. Summary

The aim of the research presented in this Chapter was to quantify the new ADSM for ENR airspace. A novel CRM was developed for this purpose as none of the CRMs examined in the preceding literature review were deemed suitable.

Montecarlo simulations were used to derive Ad Hoc separation values for aircraft encounters. The characteristics of the simulations and the approach followed were defined, with the key assumption being that new separation minima values are only defined in safe situations, where the risk of collision is below a predefined TLS. The TLS was determined as the maximum collision risk value obtained for the separation minimum of 5NM, which is considered safe (as is the current value applied) and is a constant value.

ADSM values were determined specifically for the LECMZMU ENR sector, fitting the simulation data with the distinctive features of this sector. A sensitivity analysis of the CRM to certain parameters (FL, HF, AM, wind direction and intensity, etc.) was conducted in this research, which allows to understand better how the model behaves. The results of the simulations show that separation minima can be reduced to 4NM or 3NM mainly in encounter geometries where the intersection angle between tracks is small. Conversely, it is not possible to reduce the separation minima from the current value (5NM) for intersection angles greater than 74° . This is because the collision risk values obtained in the simulation exceed the TLS defined.

Moreover, the novel concept is applied in the reference scenario, the LECMZMU sector, to analyse the safety levels. If current safety levels are to be maintained, it would be necessary to reduce the probability of LOS (P_{LOS}) by half in the scenario in which the ADSM concept is implemented compared to the current value of P_{LOS} for 5NM.

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6. ASMT: ATC SUPPORT TOOL FOR THE IMPLEMENTATION OF THE AD HOC SEPARATION

6.1. Introduction

In this Chapter the ASMT architecture is presented. The ASMT is the necessary tool to be implemented in an Ad Hoc separation environment. The aim of this Chapter is to identify ASMT functionalities and to present a general overview of the architecture.

The algorithms developed for the Ad Hoc separation are implemented in a prototype developed in MATLAB®. This prototype computes the Ad Hoc separation between the aircraft pairs and presents this information to the ATCO. Additionally, the tool includes CD&R functionalities. Therefore, it provides some information regarding the current and future position of the aircraft, alerting about Ad Hoc conflict situations and proposing resolution manoeuvres when the Ad Hoc LOS probability is higher than a threshold. The models used for prediction and conflict detection are kept simple because the goal is to illustrate the behaviour of the tool through practical exercises, rather than to design a tool intended for real-world use. In real cases these modules should be developed in detail. Lastly, two practical examples of ASMT application in LECMZMU are presented.

The work presented in this chapter is based on the following paper:

Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, Juan Sánchez-Cano Mas-Sardá. “Preliminary design of an ATC support tool for the implementation of the Ad Hoc Separation Minima concept in an en-route sector”. <https://doi.org/10.1088/1742-6596/2716/1/012079>. *13th EASN International Conference on Innovation in Aviation and Space for opening New Horizons. Salerno (Italy)*. 2023.

And on the following Bachelor thesis:

“Diseño conceptual y desarrollo del prototipo de la herramienta Ad Hoc Separation Minima Tool para la implementación del concepto operacional de separación Ad Hoc”. Developed by Juan Sánchez-Cano Mas-Sardá and supervised by Lidia Serrano Mira.

6.2. ASMT architecture

In general, ATC support tools provide automatically or semiautomatically specific information (traffic situation, weather, etc.) about the sector in which the ATCOs provide control service. This is to facilitate the ATC labour, allowing them to be aware of other kind of information, although not exempting them of their responsibility as ATCOs. The tool presented herein, denoted ASMT, aims to provide ATCOs with Ad Hoc separation values for aircraft pairs. ASMT informs ATCO with preventive information in a two-step process: by identifying conflicting situations and suggesting manoeuvres to resolve them. The main difference from a typical CD&R tool is that ASMT calculates specific Ad Hoc separation values for each aircraft pair and CD&R tasks are performed according to that Ad Hoc value.

The ASMT was developed for the tactical ATCO, who continuously monitors the state of the aircraft throughout the airspace. It is composed of different modules: trajectory prediction module, SI detection and characterisation module, Ad Hoc separation determination module, CD module and CR module (Figure 46). These are presented in the following subsections.

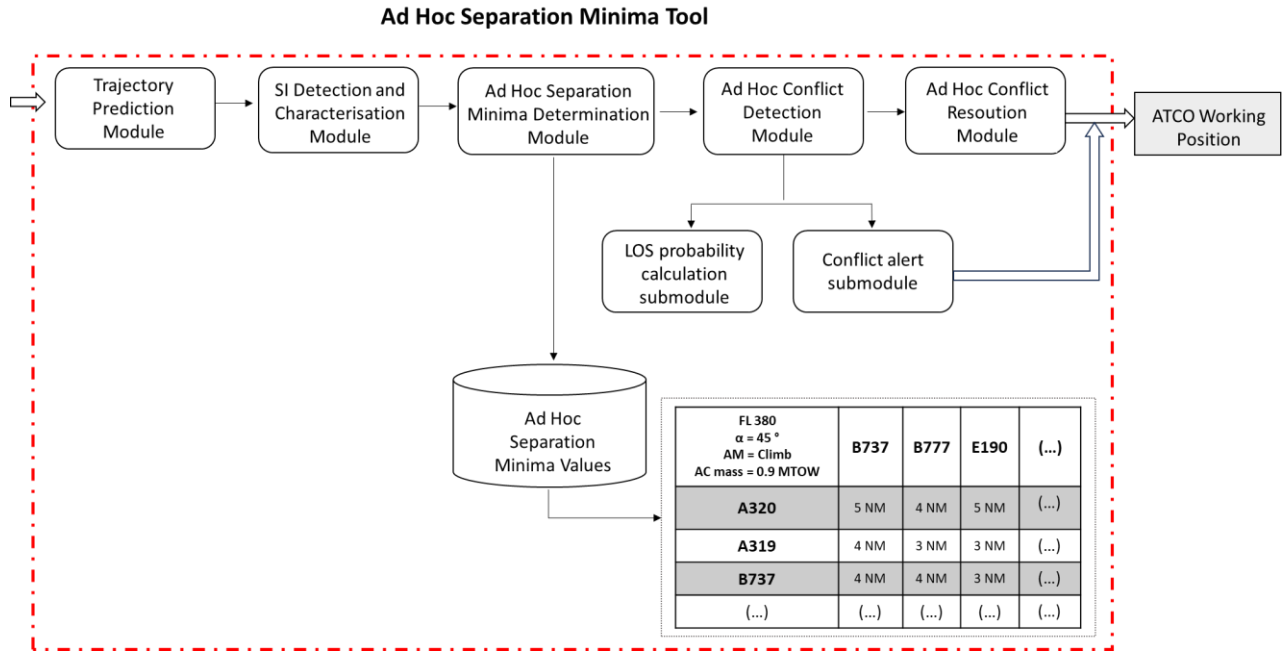


Figure 46. ASMT architecture.

Note that the development of the ASMT tool follows the development of the Ad Hoc separation concept. Currently, the concept of Ad Hoc separation is only applicable to ENR sectors between aircraft that fly in the horizontal plane (2D). Therefore, the ASMT tool is currently designed to be applied in ENR scenarios and between aircraft in level flight. In the future, fully developed versions of ASMT are expected to replace STCA tool in those scenarios where the Ad Hoc concept is implemented. As a CD&R tool, ASMT will include all STCA functionalities.

6.2.1. Trajectory prediction module

The trajectory prediction is the process of estimating the future states of the aircraft based on the current state of the aircraft, the estimation of the pilot and the ATCO intention, the expected environmental conditions and the computer models of aircraft performance and procedures [122].

The ASMT makes predictions based on the evolution of the aircraft throughout the airspace, the FPL information and the information provided by the aircraft such as aircraft mass and wind conditions (this is assumed as a requirement in the Ad Hoc CONOPS). The predictions depend on the t_{LAT} (look ahead time) and the operational features of both aircraft. The ASMT updates the prediction every c seconds and considers the aircraft within the sector and the aircraft that will pierce into the airspace in the following m minutes. t_{LAT} , c and m values should be

defined in advance by ANSPs. In this research the values used are t_{LAT} , 5 minutes, c , 5s and m , 30 minutes, for computing limitations. Nevertheless, the trajectory prediction can be provided by an external tool, being the predictions an input for the ASMT. The trajectory predictions shall comply with a minimum quality factor to achieve the required accuracy level.

For aircraft trajectory prediction, as a first approach, the BADA model has been applied [106]. This model is based on the Total Energy Model (TEM). The TEM equation is simplified, as shown below, because the following assumptions are considered:

1. Flights are flying at an established FL (2D). Climbs and descents are not modelled in this first stage.
2. The mass of the aircraft is considered constant.
3. The Mach cruise is considered constant.
4. As there is no variation in FL or speed, the TEM equation reduces to $Thr = D$ as the potential and kinetic energy components cancel out.

Due to the scarcity of data, the information used for the prediction in this initial stage is obtained from the FPL (from NEST DDR2 files [118]) and the BADA model. Nevertheless, ADS-C or radar data could be integrated into the ASMT if available. The following data are considered:

- the route of each aircraft (sequence of WPs given by latitude (φ), longitude (λ) and altitude (h));
- the actual position of the aircraft;
- the indicated airspeed (IAS); and
- heading (θ).

The prediction is modelled from the general equation of uniform rectilinear motion and depends on the immediately preceding position, aircraft speed and flight time. It is assumed that the current position of the aircraft is known. For GS determination, wind is assumed constant (as a first stage of the ASMT development), being the wind direction 360° and wind intensity 40kt. The prediction ($\overline{try_{LAT}}$) is addressed by calculating the time required to arrive to the following WP_i (t_{WP_i}) of the FPL. Once this time is calculated using the current

speed (GS_{WP_i}) for each segment of the route, the last WP with a needed time (t_{WP}) lower than t_{LAT} is selected and the position of the aircraft is calculated according to the uniform rectilinear motion. Using the position of this WP, the GS_{WP} and the time corresponding to $t_{LAT} - t_{WP}$, the prediction of the aircraft is calculated (Figure 47).

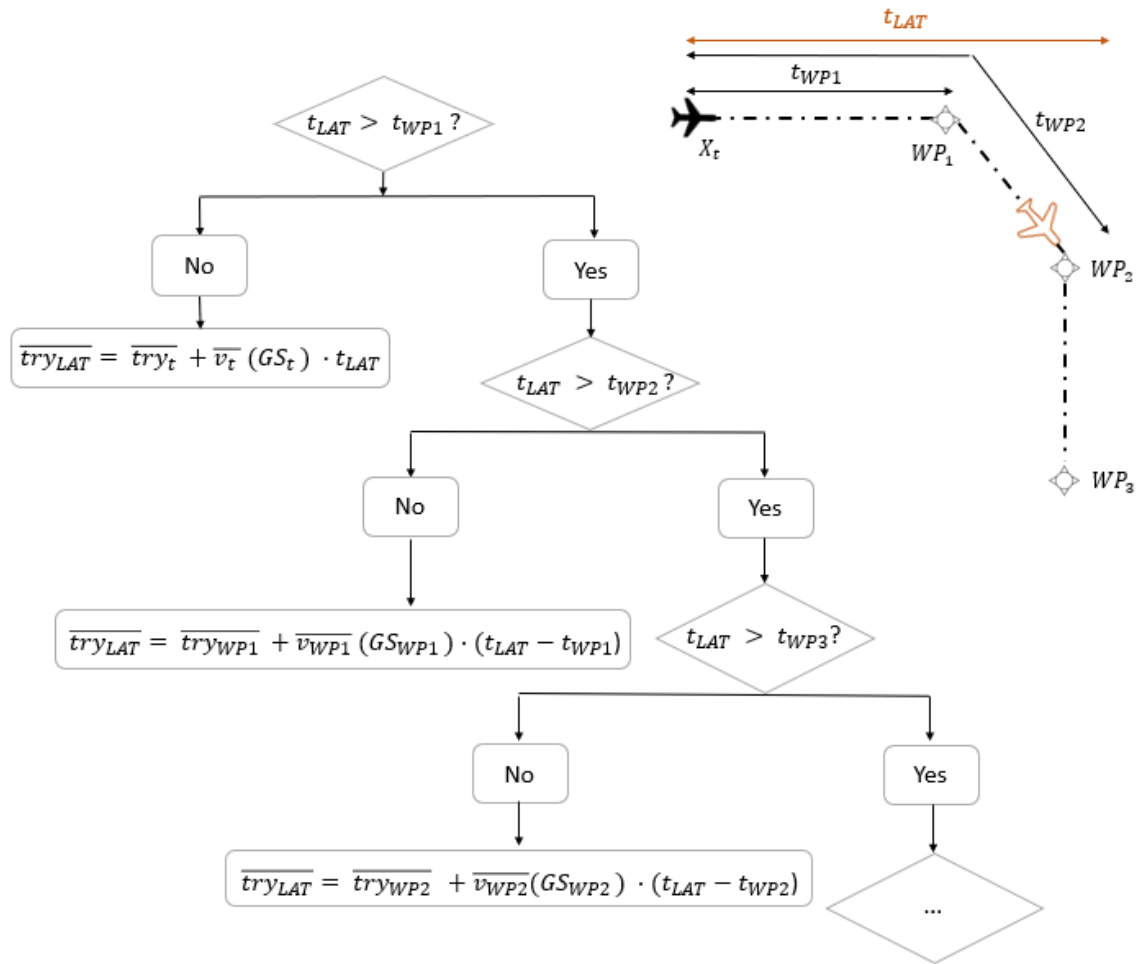


Figure 47: ASMT trajectory prediction flowchart.

6.2.2. SI detection and characterisation module

From the aircraft trajectories prediction, SI are analysed. A SI is a situation in which an aircraft pair is expected to intersect with a horizontal separation smaller than a predefined distance [81]. Typically, this predefined separation is specified by the ANSP and is larger than the separation minima. In this work 10NM was defined. Therefore, if the Euclidean distance between two predicted aircraft

trajectories (positions) is going to be lower than 10NM and both aircraft are in the same FL, a SI is detected.

The concept of SI is used for two reasons. The first is to avoid critical missed alerts. That is, when a separation infringement has occurred between an aircraft pair, but the system erroneously calculates that no separation infringement will occur due to the uncertainties associated with the aircraft position related to navigation and surveillance. SI are conflict situations, that is, situations wherein the separation minima could be compromised in a short time horizon and a LOS could occur. The second reason is as a filter for the search of the Ad Hoc separation between a pair of aircraft in a database. Aircraft crossing at more than 10NM are discarded from the ADSM search process; if two aircraft cross at more than 10NM, there is enough margin for the Ad Hoc separation not to be violated (the ADSM are always equal to or less than the current horizontal separation value of 5NM). Whereas, if two aircraft cross at less than 10NM, the ADSM to be applied between the aircraft pair is crucial.

When a SI is detected, to determine its Ad Hoc separation value applicable, the encounter is characterised by the ASMT according to the following features: aircraft models, aircraft mass, speeds of the aircraft, FL, crossing angle (encounter geometry) and wind conditions.

An additional prediction is done to estimate the *DCPA*, *TCPA* and *t2LOS* (time to LOS) of the encounter, the crossing point of the trajectories and the times at which the Ad Hoc separation is lost (5NM, 4NM and 3NM).

If the ASMT detects that an aircraft pair is expected to intersect with a horizontal separation smaller than 10NM but both aircraft are not in the same FL, the default value of the applicable separation minima is 5NM and 1000ft (i.e., the current values of separation minima).

6.2.3. ADSM determination module

After the characterisation of the SI, the ASMT searches for the applicable value in a database which contains the ADSM values for different situations and for a specific ENR sector. As mentioned in Chapter 5, ADSM values are strategically determined because they are calculated after a collision risk assessment [123]. To determine the Ad Hoc separation, the search process is as follows:

1. Once the SI has been characterised, the ASMT shall search in the database for the Ad Hoc separation value applicable according to the previous characterisation. These ADSM values are predetermined and are associated with an AM in the vertical plane, that is, climb or descent. Therefore, the ASMT would find in the database the ADSM (for climb and descent AM) corresponding to the most similar situation (according to the SI characterisation in terms of aircraft model, masses, FL, etc.) to this real one in the sector (with a conservative judgement from a safety viewpoint).
2. In this step, the ASMT evaluates whether to apply the Ad Hoc separation corresponding to the climb AM or to the descent AM¹⁴. The ASMT shall check, in the vertical plane, whether there are aircraft in the FL immediately above or below the one at which the aircraft is flying. There are three possible situations:
 - If there are no nearby aircraft¹⁵ flying at the immediate upper or lower FL, it shall choose the lower Ad Hoc separation, which will correspond to the descent_UNL AM.
 - If there are any nearby aircraft flying at the immediate upper FL, the ASMT disregards applying the Ad Hoc separation value corresponding to the climb AM and chooses the separation value corresponding to the descent AM (UNL or LIM). The same applies to the opposite case, that of nearby aircraft flying in the immediate lower FL.
 - If there are nearby aircraft flying at the upper and lower FLs, the default separation minimum value of 5NM shall apply.
3. Each value of the Ad Hoc separation is related to a collision risk value. The ASMT would apply the lowest Ad Hoc separation minimum value available (3NM better than 4NM and 4NM better than 5NM). If for a specific Ad Hoc separation value, there are more than one possibility (i.e. it is possible to apply 3NM to the AC1-AC2 encounter, regardless of whether AC1 performs

¹⁴ It should be noted that ADSM values have been calculated for different factors and, in particular, for specific aircraft conditions (in terms of mass, operating ceiling, etc.). In other words, there are situations where it is not possible to reduce the separation minima because the mass of the manoeuvring aircraft is excessive for a climb AM, or the climb would exceed its operational ceiling. The ADSM values defined already consider these issues.

¹⁵ Nearby aircraft: This term refers to any aircraft within 20NM relative to the CPA between aircraft pairs which configure the SI.

a climb AM or AC2 performs a descent AM) the ASMT will choose the Ad Hoc separation value corresponding to the lowest collision risk value.

In addition to determining the Ad Hoc separation to be applied for a SI, the ASMT calculates the *DCPA*, *TCPA* and *t2LOS* once the SI has been detected and characterised. To do so, after detecting an SI, the prediction of the trajectory is projected every second. These data (applicable Ad Hoc separation, *DCPA*, *TCPA* and *t2LOS*) are displayed on the ATCO screen by the ASMT.

6.2.4. CD module

This module consists of two submodules. The first is entitled "submodule for LOS probability calculation" and the second "conflict alert submodule". These are defined in more detail below.

6.2.4.1. LOS probability calculation submodule

The main task of ATCOs is the separation management in their airspace of responsibility, i.e. to avoid any LOS between aircraft. The ASMT is a tool that, in addition to determining and showing the Ad Hoc separation to be applied, aims to not increase ATCO workload (WL). It helps them in the task of detecting and resolving possible conflict situations before the occurrence of LOS. Trajectory prediction is influenced by several uncertainties. Consequently, it is not possible to predict a LOS with absolute confidence being more appropriate to refer to probability values.

The Ad Hoc separation applicable is different depending on the characterisation of the different SI. Thus, the LOS probability is calculated for each situation regarding the Ad Hoc separation value applied. For the calculation of the probability of LOS, the model proposed by Irvine and EUROCONTROL [124] has been used.

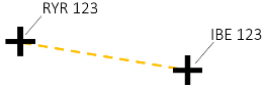
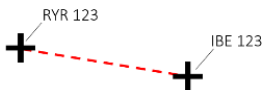
This is a geometric model in which the LOS probability is calculated in the horizontal plane (2D). The geometric locus of the conflict defines an elliptical region in a rectangular coordinate system in which the axes represent the trajectories flown by both aircraft. This is obtained by applying the cosine theorem to the encounter geometry when the aircraft are separated by the separation minimum value (which in the case of the Ad Hoc separation will be different for

each SI). The probability of LOS corresponds to the overlap of the distribution of the ratio of the average speeds of the two aircraft and the elliptical conflict region. Cross-track errors in the aircraft trajectory are not considered in this model as they are assumed to be negligible compared to the along-track errors. These are modelled from the normal distribution and are assumed to increase with flight time. In Chapter 2, subsection 2.6.4 the model was explained deeply.

6.2.4.2. Conflict alert submodule

This submodule is responsible for providing the ATCOs with information on the evolution of the conflict between the pair of aircraft classified as SI. In particular, this information shall be provided in sufficient time to allow any necessary action to be taken before a critical situation arises. Currently, this time is set to 2.5 minutes before the LOS, but it could be modified. Based on the LOS probability information and depending on the probability values, by means of a colour code and symbols, the unfavourable or favourable evolution in the resolution of the conflict situation is shown graphically. In this way, the ATCOs' situational awareness of a compromised traffic situation in their sector is maintained as today through graphical and audible displays. Table 15 shows the format used by the conflict alert submodule depending on the P_{LOS} values. Other information is presented to the ATCOs such as the $TCPA$, $DCPA$, $t2LOS$ and the Ad Hoc separation value.

Table 15. Legend of codes used for the conflict alert.

P_{LOS} value	Graphic Alert	Graphic representation	Sound alert (Morse code)
$0.1 \leq P_{LOS} < 0.3$	Grey dashed line		No
$0.3 \leq P_{LOS} < 0.5$	Orange dashed line		No
$0.5 \leq P_{LOS} < 0.7$	Red dashed line		Yes .. (low-pitched)
$P_{LOS} \geq 0.7$	Red line		Yes .- (high-pitched)

6.2.5. CR module

This module is intended to help the ATCOs to resolve a conflict situation. It proposes a set of manoeuvres in the horizontal plane (when possible, a maximum of four) by which the Ad Hoc separation LOS between an aircraft pair could be avoided.

It is relevant to note the difference between the AM manoeuvre and the LOS preventing manoeuvre (conflict resolution manoeuvre). Although both manoeuvres are provided by the ASMT to the ATCO, they have different purposes and one of them is strategic while the other is calculated in real time.

On the one hand, the AM is used to define the ADSM, for the collision avoidance (Encounter Timeline). It can be either a climb or descent (LIM or UNL). In the ICAO conflict management layer, it would correspond to the immediate layer. This AM is strategically determined and stored with the corresponding ADSM value. That is, the AM is determined when the collision risk is calculated, but the AM is not calculated in real time (although it is displayed to the ATCO in real time). This information is provided to the ATCOS at the appropriate time. ATCOs issue the AM instruction when determined by the ASMT.

On the other hand, the LOS preventing manoeuvre (conflict resolution manoeuvre) is the one calculated by the ASMT in real time (CR module) and it is a manoeuvre in the horizontal plane that aims to prevent the LOS from occurring. In other words, it corresponds to the provision of separation (tactical layer).

Once the CR module presents to the ATCOs the LOS preventing manoeuvres, it is up to them to decide when and whether to apply it. This information is presented to them as soon as it is calculated that for that SI there is a $P_{LOS} > 0.1$ and 2.5 minutes before the LOS (this time could be modified). The manoeuvres are determined based on the assumption that only one of the two aircraft will execute the resolution manoeuvre. These resolution manoeuvres are only determined for lateral LOS. For longitudinal LOS, an alarm is displayed to the ATCO, but no resolution manoeuvres are calculated. This is because the resolution of a longitudinal LOS is considered to be easier. In general, it is enough to change the speed or apply radar vectoring guidance.

To determine these manoeuvres, the first option is to evaluate if a "direct to" the next waypoint (WP) of the route defined in the FPL can avoid losing the Ad Hoc separation or reduce the P_{LOS} in order to meet the requirement of $0 \leq P_{LOS} \leq 0.1$. This should be calculated for both aircraft, although it is assumed that only one of them will execute it. The aim of this first option is to avoid or minimise any deviation from the aircraft's intended route in the conflict resolution manoeuvre.

In addition, it is calculated the possibility of giving other vectors for which both following requirements are met:

- $P_{LOS} < 0.05$ and,
- the avoidance of further LOS with the same aircraft when performing the resolution manoeuvre (the resolving aircraft is considered to fly behind the other aircraft).

These vectors are calculated at 5° intervals relative to the track from the aircraft's current position to the next WP (refer to Figure 48). This results in the calculation of a single vector (either port or starboard) with the smallest angular deviation that meets the above requirements. This process is repeated for both aircraft. As a result, ATCOs are presented with a maximum of four resolution manoeuvres, with two possible manoeuvres for each aircraft. The ATCOs must then decide which manoeuvre to clear preferentially and to which aircraft.

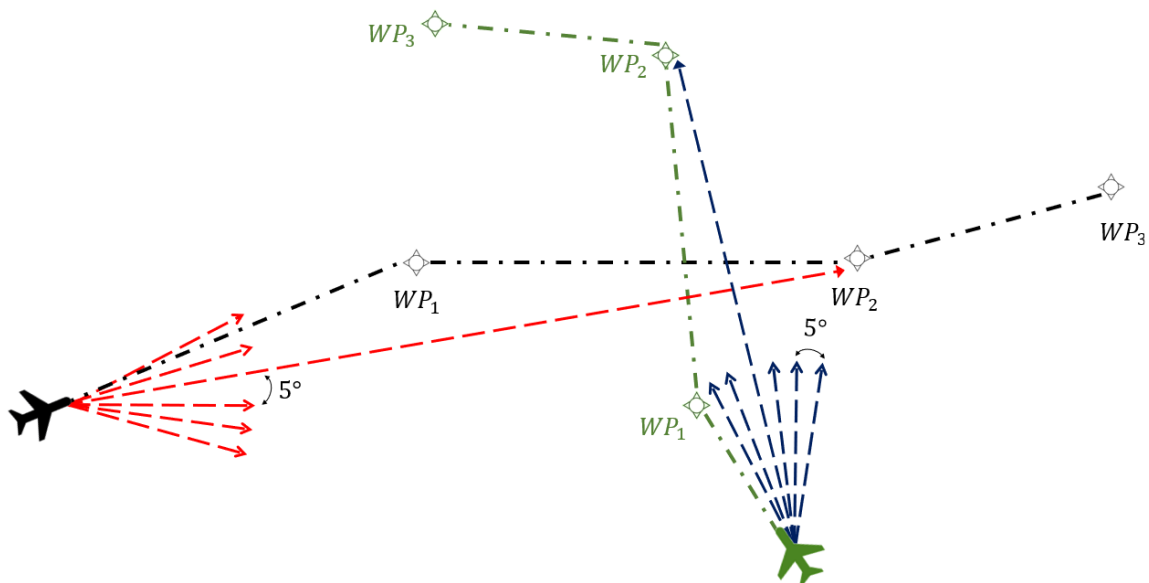


Figure 48. Possibilities considered by the ASMT for the determination of the CR manoeuvres.

6.3. Application in LECMZMU

This section shows the performance of the ASMT tool in the LECMZMU ENR sector. Two encounters are presented:

- Encounter 1 between AAL69 and RYR11M
- Encounter 2 between SWE2092 and AAL749

The following figures are intended to illustrate the behaviour of the ASMT tool. Data have been extracted from NEST and modified (sector entry time and speed adjustment) to generate some conflict situations and study the behaviour of the tool. Therefore, this is not real data from a specific day, but a simulation.

6.3.1. Encounter 1 - AAL69 and RYR11M

Figure 49 shows the traffic situation at LECMZMU. Aircraft AAL69 has just pierced into the sector while RYR11M is close. The ATCO is alerted about a longitudinal conflict situation between a pair of aircraft (TAP951 and TAP471), in order to issue a resolution manoeuvre. This is because the ASMT only determines resolution manoeuvres for lateral conflicts, but not for longitudinal conflicts.

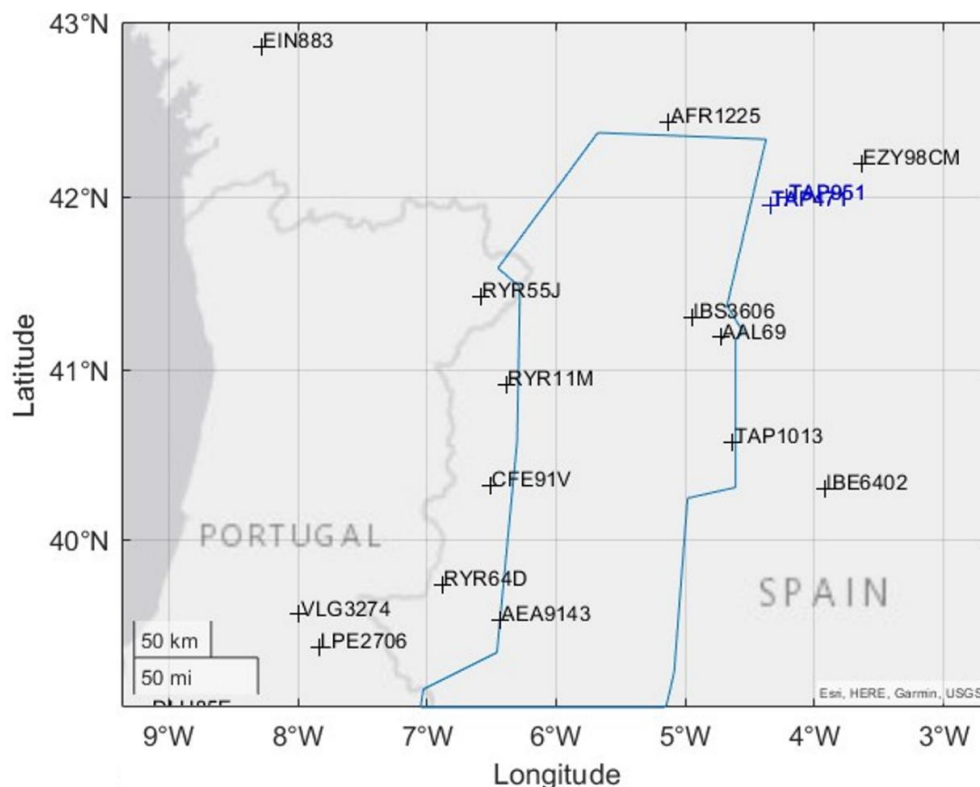


Figure 49. LECMZMU sector with traffic representation in ASMT.

The ASMT predicts aircraft positions based on the t_{LAT} and searches if any SI exists between a pair of aircraft. When the ASMT detects an SI, it is characterised by determining the different parameters of the encounter and other additional information. Furthermore, it calculates the probability of LOS between the aircraft pair. Some of these parameters are shown in Figure 50, such as the *DCPA* (0.26NM), the aircraft models, the FL, the ADSM that applies (5NM), etc. The presentation of these data is customisable and ATCOs/ANSPs can choose which parameters they want the ASMT to display. Figure 50 illustrates the data related to the SI for the aircraft pair AAL69 and RYR11M.

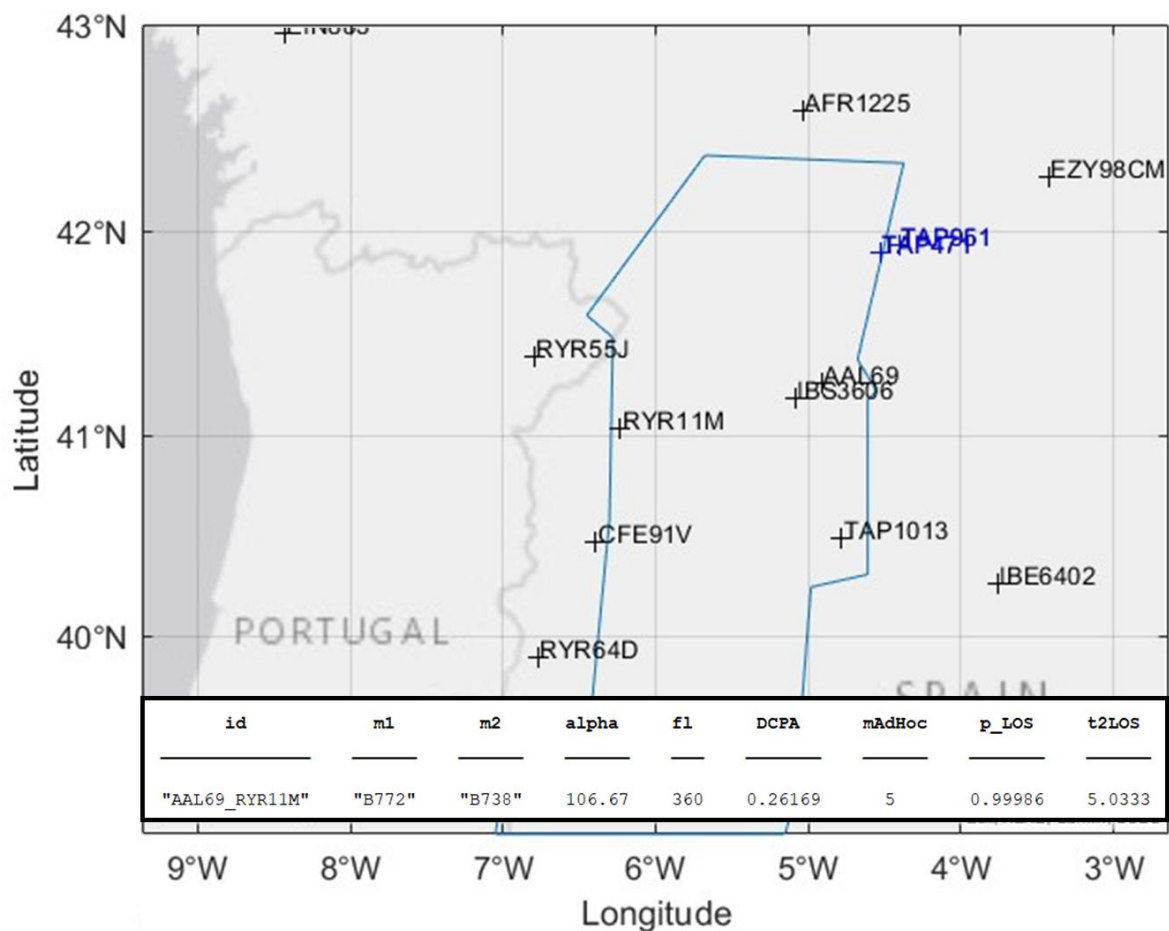


Figure 50. SI data representation to the ATCO after its characterisation.

When the estimated time to LOS ($t2LOS$) decreases below a predetermined value (in this case 2.5 minutes) the conflict is represented graphically (Figure 51). The layout of this representation is dependent on the probability of LOS. Since LOS probability is higher than 0.7, in fact it is 0.99, red line together with a sound alert are displayed.

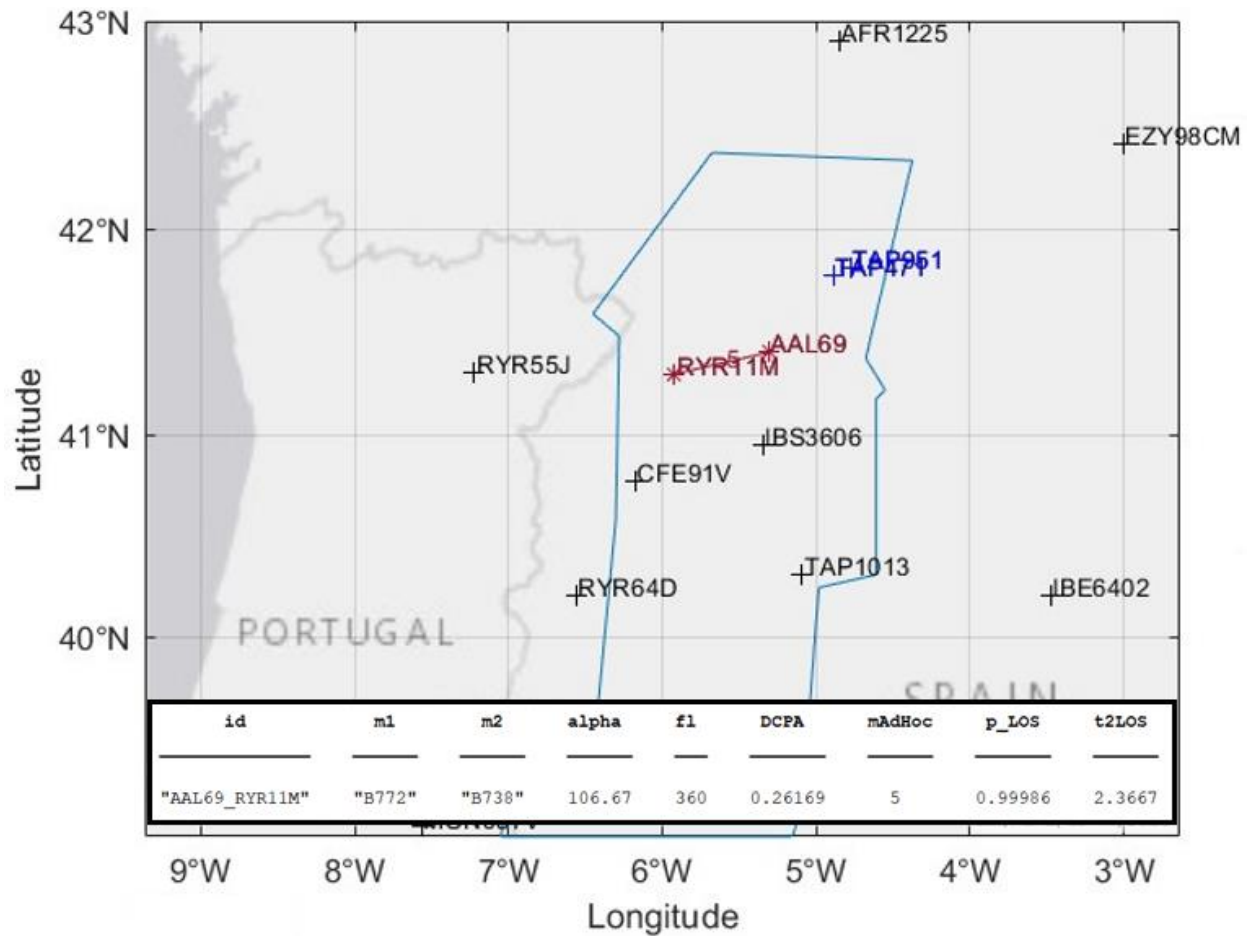


Figure 51. LOS representation between AAL69 and RYR11M to the ATCO.

At the same time, the resolution manoeuvres in the horizontal plane are calculated in order to avoid the LOS. These manoeuvres are presented to the ATCO by the ASMT. In Figure 52 four different manoeuvres have been computed, two for AAL69 and two for RYR11M. The ATCOs shall decide which manoeuvre prefer to clear and to which aircraft.

Other parameters that the ASMT presents to the ATCO but are not shown in Figure 52 are the distance between aircraft in real time and the AM associated to the Ad Hoc separation minima.

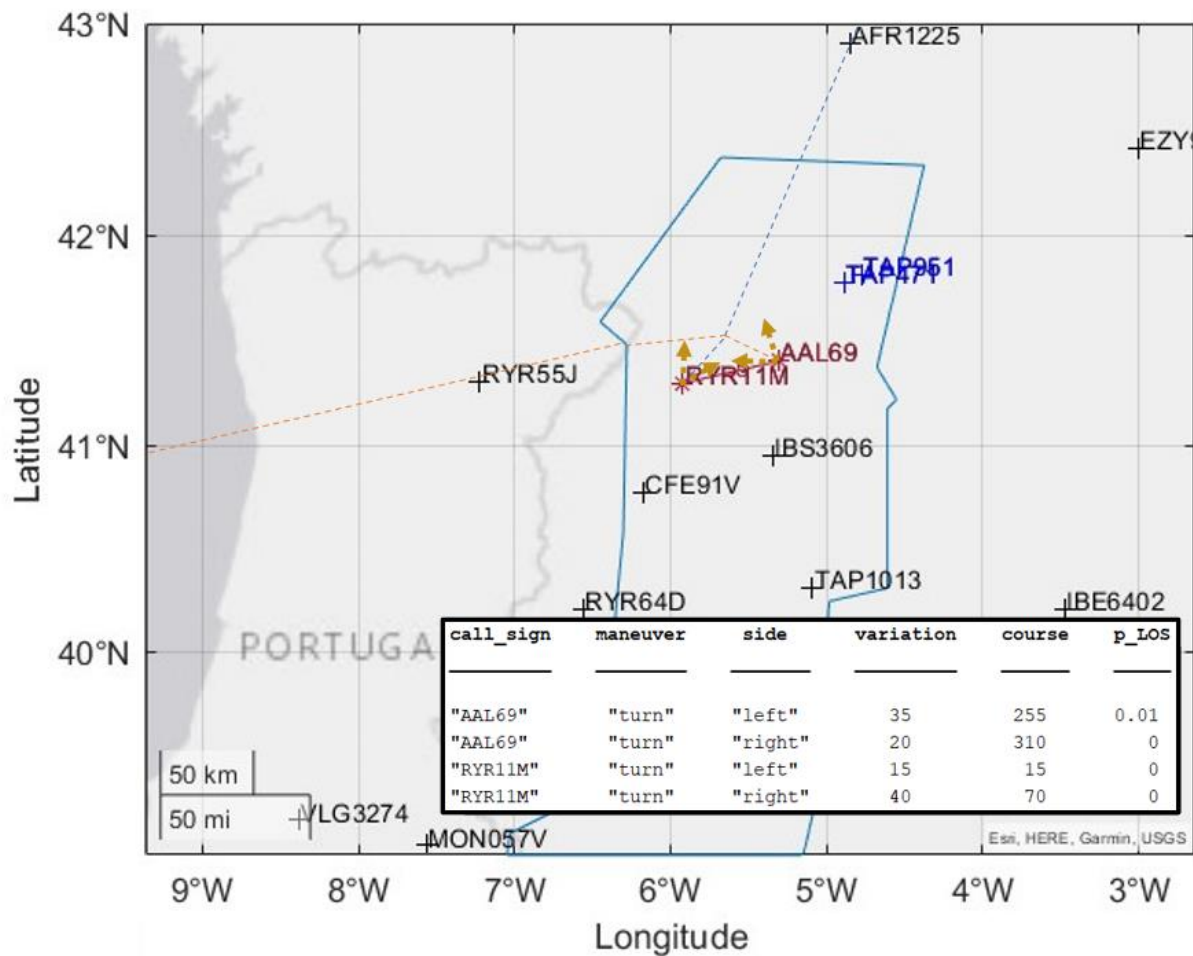


Figure 52. Conflict resolution manoeuvres presented to the ATCO by the ASMT.

6.3.2. Encounter 2 - SWE2092 and AAL749

Encounter 2 involves aircraft SWE2092 and AAL749. ADSM for this encounter is 4NM. Figure 53a shows the general traffic picture at LECMZMU. Both aircraft, SWE2092 and AAL749, are entering the sector where the Ad Hoc separation concept is applied. The ASMT tool predicts the trajectories of both aircraft as a function of t_{LAT} . The prediction of SWE2092 and AAL749 is presented in Figure 53b. The predicted position of both aircraft for a given time is highlighted with red crosses. The ASMT calculates the distance between both aircraft for the predicted positions in order to detect whether it is a SI.

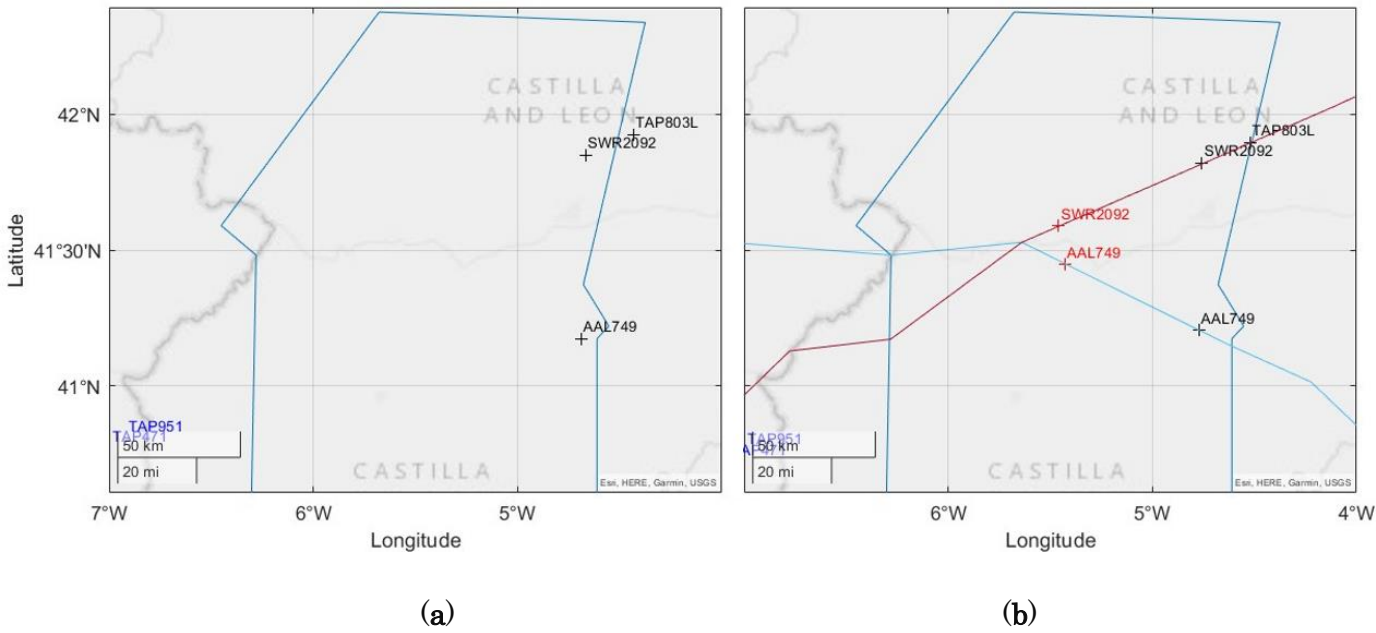


Figure 53. (a) LECMZMU traffic picture. (b) AAL749, SWR2092 position prediction (red).

After having identified that AAL749 and SWR2092 constitute an SI, the ASMT characterises it by determining the different parameters of the encounter and other additional information. Figure 54 shows data related to the aircraft pair AAL749 and SWR2092 encounter. The geometry of the encounter is 50°, the *DCPA* 1.9NM, the ADSM applied is 4NM, etc. Moreover, the ASMT calculates the probability of LOS between the aircraft pair.

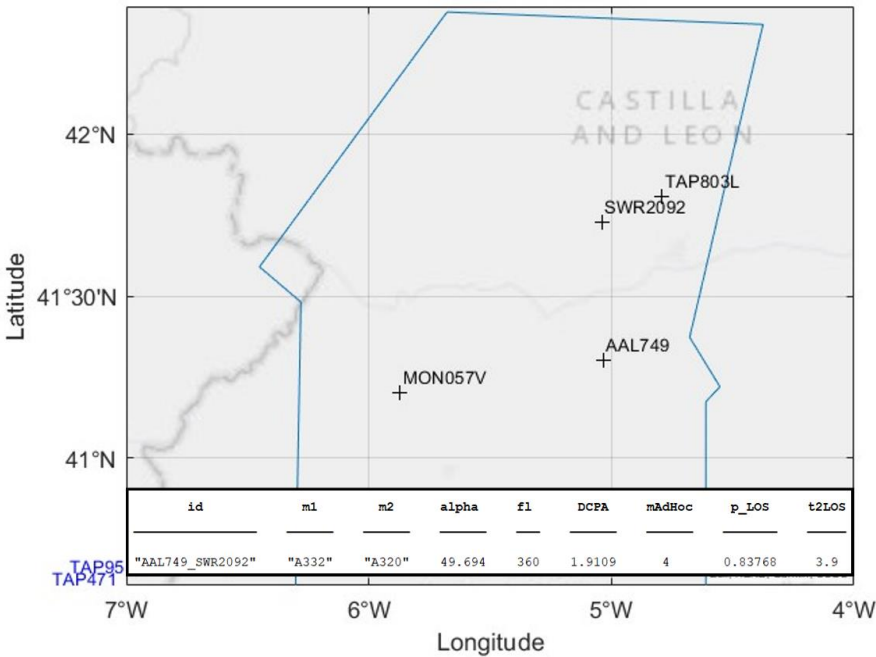


Figure 54. Representation of some of the SI data to the ATCO after its characterisation.

When the estimated time to LOS is close to a critical threshold, the alarm of the conflict situation is displayed (Figure 55) according to the probability of LOS. In this encounter, because LOS probability is higher than 0.7, in fact is 0.84, red line together with a sound alert are triggered. Furthermore, the value of the Ad Hoc separation for that SI is displayed (4NM).

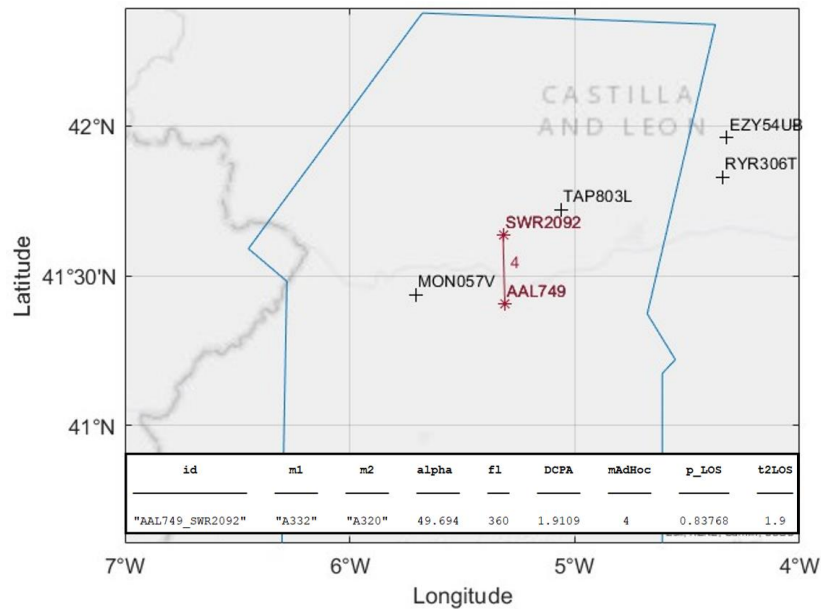


Figure 55. LOS representation between AAL749 and SWR2092 to the ATCO.

Concurrently, resolution manoeuvres to avoid the LOS occurrence in the horizontal plane are computed and presented to the ATCOs. In Figure 56 three different horizontal resolution manoeuvres have been computed, one for the SWR2092 and the other two for AAL749. The ATCOs shall decide which manoeuvre prefer to instruct and to which aircraft.

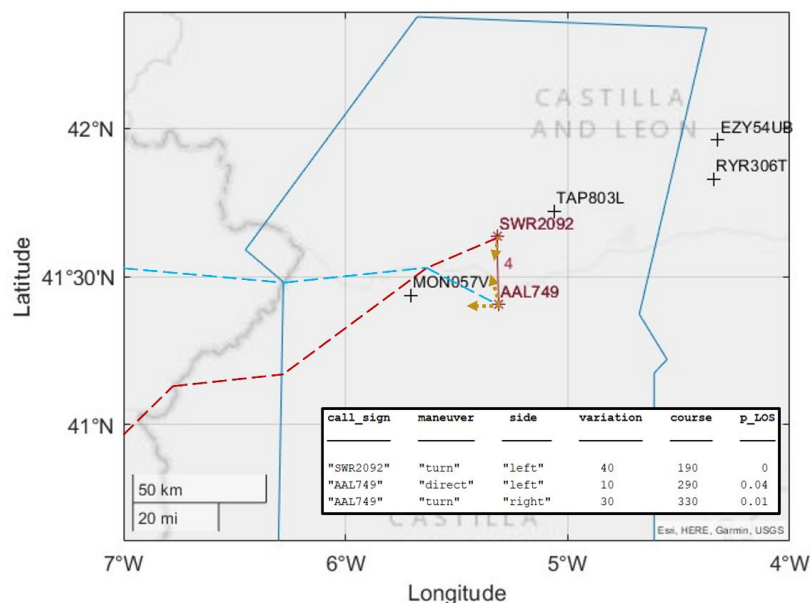


Figure 56. Conflict resolution manoeuvres presented to the ATCO by the ASMT.

6.4. Summary

In this chapter the ASMT tool is presented. The goal is to describe the ASMT architecture in a general overview, designed according to its functionalities. The primary functionality of the ASMT is to determine the ADSM to be applied between an aircraft pair and to display this information to the ATCO. Additionally, it incorporates CD&R functionalities. The main difference with a typical CD&R tool is that CD&R tasks are performed according to the Ad Hoc value for each specific separation minimum value.

This tool consists of different modules: trajectory prediction module, SI detection and characterisation module, Ad Hoc separation determination module, CD module and CR module. Each module is described separately.

The models employed for prediction and conflict detection are intentionally simple, with the primary goal of demonstrating the tool's behaviour through practical exercises, rather than creating a tool for real-world application. However, in actual scenarios, there is a need to enhance these modules for improved performance. Two practical examples of ASMT implementation in LECMZMU (Encounter 1 between AAL69 and RYR11M and Encounter 2 between SEW2092 and AAL749) are presented.

7. PRELIMINARY IMPACT ASSESSMENT OF THE AD HOC SEPARATION CONCEPT

7.1. Introduction

Validation is defined as an iterative process by which the fitness for purpose of a new operational concept being developed is established [125]. It is a complex process in which there are different stages, several actors are involved and various activities shall be performed. For this reason, this Chapter does not present a complete validation process, but a minor study on the preliminary impact of the Ad Hoc separation concept in different ENR sectors of the Madrid ACC.

Currently, the approach adopted in the ATM system is based on the PBA (performance-based approach). According to [126], PBA is a decision-making method based on three principles: strong focus on desired/required results; informed decision-making driven by those desired/required results; and reliance on facts and data for decision-making. Key Performance Areas (KPAs) and Key Performance Indicators (KPIs), among others, are key elements within the PBA concept for the analysis of system performance. The impact of applying the Ad Hoc separation concept in different scenarios is evaluated based on this approach.

The work presented in this chapter is based on the following submitted paper:

Lidia Serrano-Mira, Luis Pérez Sanz, Javier A. Pérez-Castán, Adrián Casado López, Eduardo S. Ayra, Marta Pérez Maroto. Preliminary Impact Assessment of the Ad Hoc Separation Minima, a new Separation Mode. *Applied Sciences* [Submitted].

7.2. KPAs and KPIs

KPAs are defined by ICAO [126] as the way to categorize performance aspects relative to high-level ambitions and expectations. Although ICAO defined eleven KPAs, which are, safety, aviation security, environment, cost-effectiveness, capacity, flight efficiency, flexibility, predictability, access and equity, participation and collaboration and interoperability, the European Commission focuses on the areas of Capacity, Safety, Cost-efficiency and Environment [127].

KPIs quantitatively express current, past or expected future performance as well as actual progress in achieving performance objectives [128]. The difference between KPIs and Performance Indicators (PIs) is that KPIs are those which have associated a Validation Target while PIs are those that do not.

For the preliminary impact assessment study of the Ad Hoc separation concept, the following KPAs and PIs have been selected (Table 16). Other studies with similar objectives also used these metrics [129], [130].

The main issue for the integration of the Ad Hoc separation concept is the connection between capacity and safety. The impact on capacity is discussed in this Chapter, but not the safety impact. The safety analysis was performed in Chapter 5. As a result, safety requirements to be applied in order to maintain current safety levels with the application of the Ad Hoc separation concept (in LECMZMU) were defined in section 5.4.2. The impact of this concept in the different KPAs selected (Capacity, Environment and Airspace User Cost-Efficiency) is presented in the following sections.

Table 16. KPAs, PIs defined for the preliminary impact assessment of the Ad Hoc separation concept.

KPA (SESAR)	PI	Units
Capacity	En-route throughput	No. of aircraft entering per hour
Environment	CO ₂ emissions reduction per LOS saved	Kg
	Fuel reduction per LOS saved	Kg
	Flown Distance reduction per LOS saved	NM
Airspace User Cost-Efficiency	Strategic Delay reduction per LOS saved	Minutes

7.3. Capacity assessment in LECMZMU

Capacity focusses on the capability of a challenging volume of airspace to handle an increasing number of movements per unit of time through changes in operational concept and technology [131]. En-route capacity is analysed in this research and is commonly estimated using Fast Time Simulations (FTS) employing models based on ATCO workload (WL). An in-depth analysis of the different models applied in European and North American countries is provided in [132].

The CAPAN methodology [133] has been used for capacity computation in this dissertation. This methodology was developed by EUROCONTROL. The capacity is estimated from the WL values of the tactical ATCO by means of FTS, being the ATCO WL expressed in time values. The ATCO WL threshold used to obtain the capacity value has been 70%, being a value commonly used by several countries such as Spain, Italy, Portugal or Norway. Therefore, the capacity calculated with this threshold is equivalent to a WL of 42 minutes in one hour (70%).

To determine the ATCO WL, FTS are performed in RAMS software [119]. For this purpose, a 24H traffic sample (FPL trajectories, i.e. not modified by ATCOs) is used, which is cloned repeatedly to have different traffic situations in the sector. The ATCO WL is calculated on an hourly basis, from the times associated with the different tasks assigned to the ATCO. These times have been obtained from [134] and are detailed in ANNEX G. The RAMS software simulates the real behaviour of the sector and provides values for the tactical ATCO (TC) and planner ATCO (PC) WLs. The capacity is calculated from the intersection of the curve representing the ATCO WL (found by regression) and the threshold value of 70%.

For the capacity computation in the LECMZMU sector, different days of the busy week (the one containing the busy day) have been simulated in RAMS (8 - 14 July 2019), determining the ATCO WL for each hour of each of the days. Three scenarios have been considered for the capacity study, Baseline Scenario, Scenario 1 and Scenario 2.

- Baseline scenario: current scenario in which the horizontal separation minimum value is fixed and corresponds to a value of 5NM (current value).

- Scenario 1: scenario where the concept of the Ad Hoc separation is applied and the supporting ASMT tool is available for the ATCO. However, this tool only includes the Ad Hoc determination functionality for each aircraft pair, but not the CD&R functionality.
- Scenario 2: scenario in which the concept of the Ad Hoc separation is applied and the ASMT support tool is available, which includes, among its functionalities, the CD&R.

A key assumption for the capacity computation in a scenario in which the concept of Ad Hoc separation is applied, is the issue that the ATCO WL could change. From the point of view of separation management, the concept of Ad Hoc separation may appear more complex. Nevertheless, it is assumed that, whenever this concept is implemented, the ATCO will have a support tool that displays the ADSM to be applied (ASMT). Moreover, this tool includes advanced CD&R functionalities. Therefore, the ATCO WL could be maintained or even reduced (as a consequence of these advanced functionalities).

The number of LOS decreases because of reducing separation minima. That is, LOS that with a separation value of 5NM could occur, now, with Ad Hoc separation may not occur (LOS saved). The ATCO time associated with each of these LOS saved (detection and resolution tasks), which translates into ATCO WL, should then not be considered. This would result in a new ATCO WL and therefore a new capacity value (Scenario 1). Additionally, if it is further considered that the ASMT includes advanced CD&R functionalities (Scenario 2), some of the time associated with CD&R tasks could decrease, resulting in a change in the ATCO WL and thus in the capacity.

ANNEX G shows the tasks and their associated times defined in RAMS for the computation of the ATCO WL, which have been extracted from [134]. These tasks are classified in five categories: Conflict Search, Flight Data Management, R/T Task, Co-ordination, Radar Task.

Radar Task category includes those tasks associated with CD&R actions (Table G1, ANNEX G). This category is divided into seven different tasks (Radar 1-7) depending on LOS conditions (e.g. stabilised flight, same direction, etc.). Each of these tasks encompass a set of actions, which are:

- Detection: generic ATCO action for conflict detection between aircraft pairs and the associated tasks.
- Decision-making & communication: determination of the conflict resolution manoeuvre and communication to the pilot (readback/hearback procedure).
- Resolution: ATCO monitoring of the implementation of the aircraft resolution manoeuvre.

Different meetings have been arranged with experts from EASA and Spanish ANSP, to quantify the different actions (detection, decision-making & communication and resolution) in these tasks (Radar 1 – 7 tasks). Figure 57 shows an example of how Radar 4 Task have been divided in the different actions with associated times.

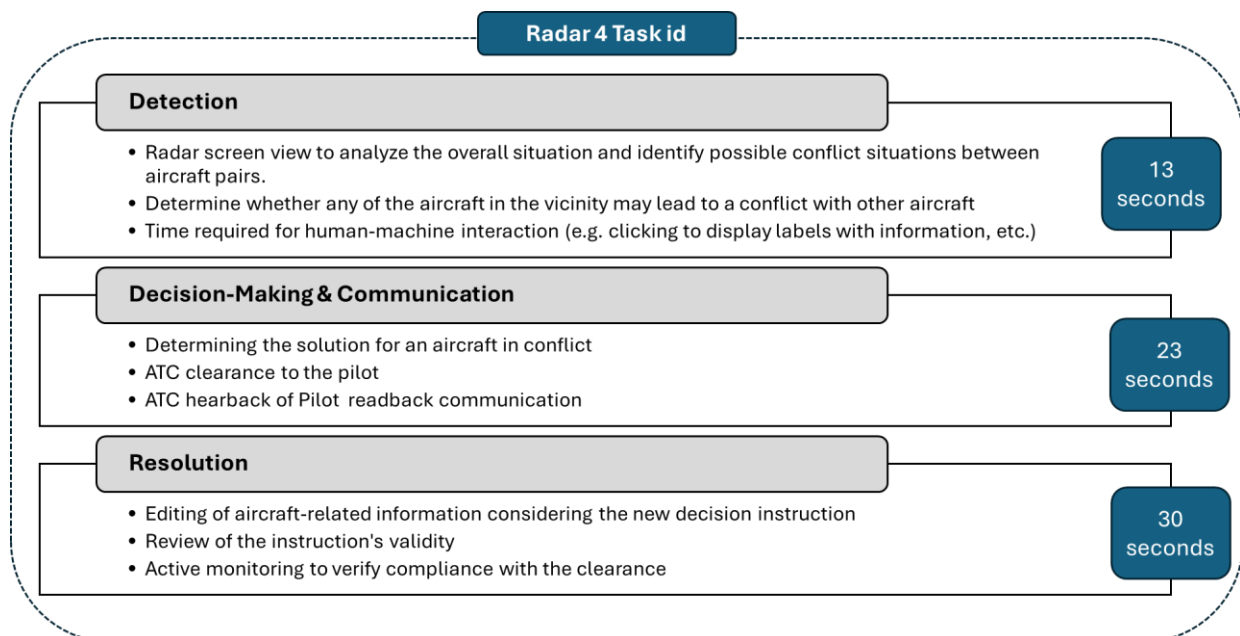


Figure 57. Radar 4 task split (from ANNEX G) based on expert judgement.

Based on expert judgement gathered from meetings with Spanish ANSP and EASA experts and in accordance with the ASMT prototype tool (Chapter 6), it is estimated a 50% improvement in the detection action and a 20% improvement in the decision-making action, if the ASMT with CD&R functionalities is available for the ATCO in a scenario.

The 50% improvement in detection is primarily attributed to a reduction in the time required to determining whether any of the aircraft in the vicinity may lead to a conflict with other. Meanwhile, the 20% enhancement in decision-making

action is due to the ASMT functionality to present a range of conflict resolution manoeuvres to the ATCO after having detected a conflict. Therefore, the ATCO time associated to the evaluation of the resolution manoeuvre is reduced. In Figure 57, for Radar 4 task split this means a time reduction of 6s in detection and 5s in decision-making.

- Capacity Determination in the Baseline Scenario

The capacity value obtained from the FTS is 46 aircraft/hour (46.95 aircraft/hour), as shown in Figure 58. The declared capacity of the LECMZMU sector is slightly lower, 45 aircraft/hour. Therefore, the value obtained from the CAPAN methodology is considered acceptable. This capacity value determined for the Baseline Scenario serves as a benchmark with which the capacity values associated with Scenario 1 and Scenario 2 can be compared.

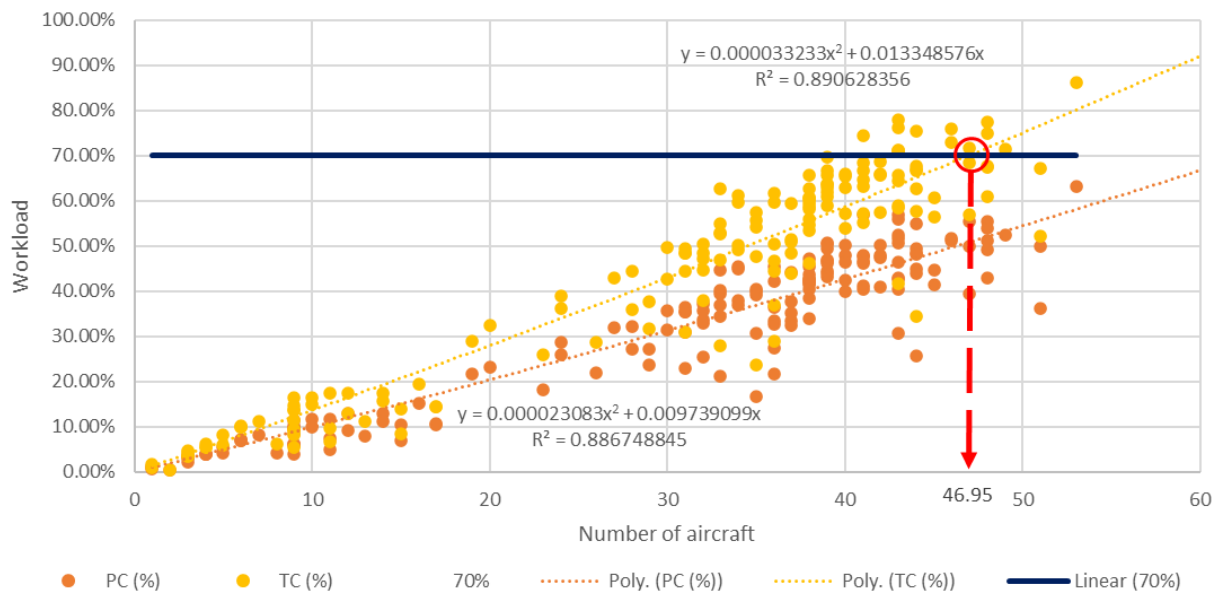


Figure 58. LECMZMU Capacity 5NM Separation – Baseline Scenario.

- Capacity Determination in the Scenario 1

The new tactical ATCO WL in the LECMZMU sector with the Ad Hoc separation concept applied results in a new capacity value. This is computed by simulating the LECMZMU scenario again but applying the ADSM between the different aircraft pairs. As shown in Figure 59, the result obtained is 47 aircraft/hour (47.79 aircraft/hour).

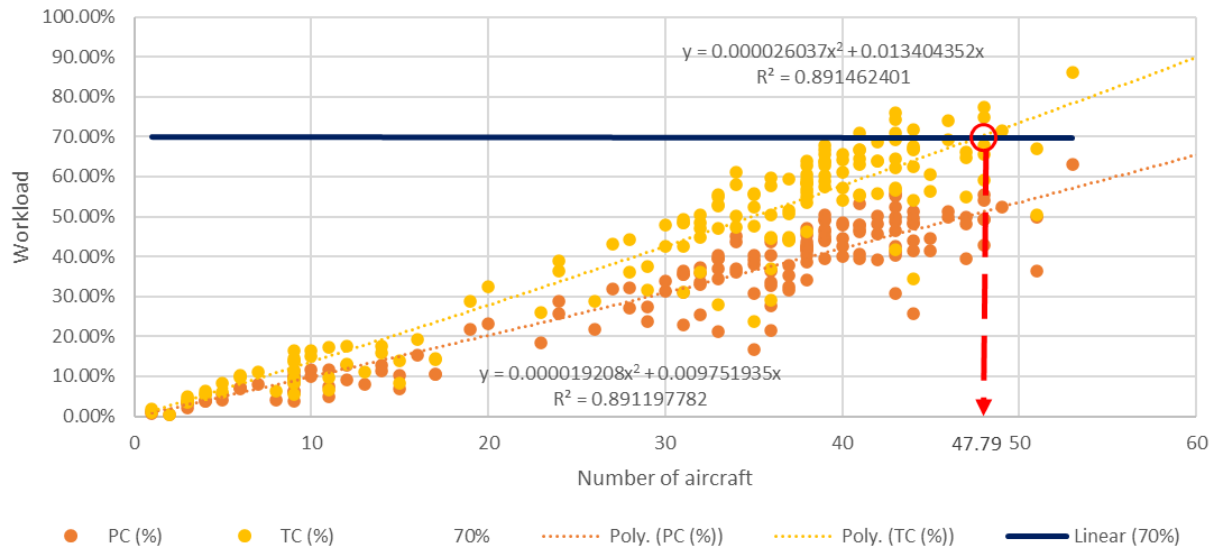


Figure 59. LECMZMU Capacity Ad Hoc separation – Scenario 1.

- Capacity Determination in the Scenario 2

Finally, considering that the ASMT tool includes CD&R functionalities, in a conservative perspective it can be assumed that it would be a 50% improvement in the detection task and a 20% improvement in the decision-making. This means a time reduction of 6s in detection and 5s in decision-making, as mentioned above. Therefore, by calculating the new ATCO WL value and subsequently the corresponding capacity, a value of 48 aircraft/hour (48.06 aircraft/hour) is obtained in Scenario 2, as shown in Figure 60.

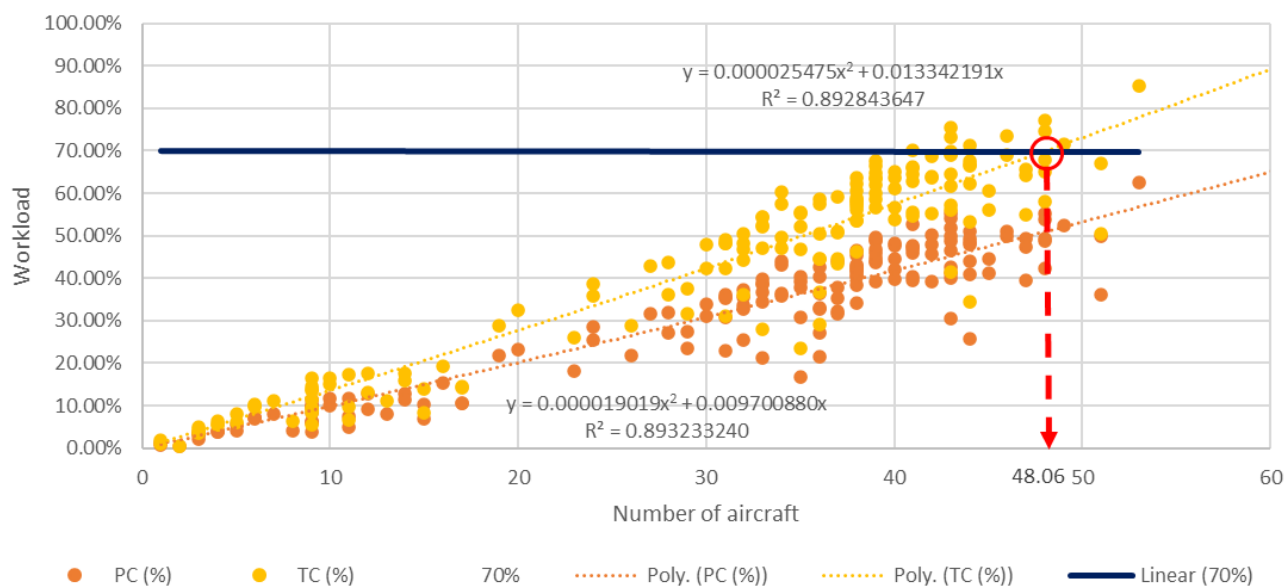


Figure 60. LECMZMU Capacity Ad Hoc Separation – Scenario 2.

Table 17 shows the summary of the numerical capacity results obtained from the CAPAN methodology for the three scenarios presented in LECMZMU. The application of the concept would increase capacity in relative terms by 2 aircraft/flight hour (from 46 to 48 aircraft), while in absolute terms it would be an increment of 1.1 aircraft/flight hour, which represents an increase of 2.3% of the current capacity of the sector.

Table 17. Capacity results in LECMZMU.

Scenario LECMZMU	Capacity (No. of aircraft / hour)	No. of aircraft / hour	Difference	Percentage of capacity increase (%)
Baseline Scenario	46.95	46	-	-
Scenario 1 ASMT (no CD&R)	47.78	47	0.83	1.8%
Scenario 2 ASMT (CD&R)	48.05	48	1.1	2.3%

7.4. Environmental and Airspace user Cost-Efficiency assessment in LECMZMU

Further KPAs in which the Ad Hoc separation concept could bring some benefits are in the environmental and airspace user cost-efficiency ones. In particular, the environmental impact has been analysed based on three indicators: flown distance reduction, fuel consumption reduction and CO_2 emissions reduction. Airspace user cost-efficiency KPA is quantified through the strategic delay.

For this purpose, based on previous FTS in the LECMZMU sector, the number of LOS that would not occur under the Ad Hoc separation concept has been considered. If the separation had been 5NM, the ATCO would have given a resolution instruction to at least one of the aircraft involved in the conflict, to prevent the LOS from occurring. The values of distance, fuel consumption, CO_2 , emission and delay related to such resolutions are computed. Thus, it is possible to define average, maximum and minimum values of flown distance (Equation (27)), fuel consumption (Equation (28)), CO_2 emissions (Equation (29), [135]) and delay (Equation (30)) reduction per LOS that could be saved.

$$\Delta \text{Distance reduction per LOS saved} = \text{sector flight distance}_{\text{actual}} - \text{sector flight distance}_{\text{scheduled}} \quad (27)$$

$$\Delta \text{fuel reduction per LOS saved} = \text{actual fuel} - \text{scheduled fuel} \quad (28)$$

$$\Delta CO_2 \text{ reduction per LOS saved} = \Delta \text{fuel per conflict saved} * 3.15 \quad (29)$$

$$\text{Delay reduction per LOS saved} = \text{sector flight time}_{\text{actual}} - \text{sector flight time}_{\text{scheduled}} \quad (30)$$

Table 18 shows the values obtained for the LECMZMU sector. These results are categorised by lateral LOS, longitudinal LOS and total LOS (lateral and longitudinal). This classification is made according to the type of resolution manoeuvre the ATCO of RAMS software has instructed the aircraft to perform, i.e. level change (FL) or horizontal manoeuvre (vector).

The greatest benefits are obtained in the resolution of lateral LOS by applying a horizontal manoeuvre (vector). According to EASA experts, resolution manoeuvres in the horizontal plane are preferred by ATCOs over vertical ones (FL changes). This is due to several factors such as less traffic disruption and aircraft may be flying at or near their optimum FL and no FL modification is desired.

These values should be placed in context regarding the sector's characteristics. According to NEST data [118], [136], in LECMZMU the average flown distance is 84NM and the average flight time in the sector is 11 minutes. Consequently, if lateral LOS with horizontal resolution manoeuvres are analysed, the results obtained are:

- Distance: reduction, on average, of 5.69NM per LOS saved, which represents 6.78% of the total flown distance in the sector.
- Delay: reduction, on average, of 0.68 minutes per LOS saved, which represents 6.18% of the total flight time in the sector.
- Fuel and CO_2 : reduction, on average, of 28.7 kg of fuel and 90.50 kg of CO_2 .

For longitudinal LOS, benefits are obtained, although they are smaller than for the lateral ones. The distribution of horizontal resolution manoeuvre and level change manoeuvres is equitable. Resolution manoeuvres by level change provide greater benefits in terms of fuel consumption and CO_2 emissions reduction. In general, favourable average results are obtained for the analysed indicators, all of them yielding positive outcomes. In other words, for each LOS saved, there is a decrease in flown distance, fuel consumption, CO_2 emissions and delay.

PRELIMINARY IMPACT ASSESSMENT OF THE AD HOC SEPARATION CONCEPT

Table 18. Environmental and Cost-Efficiency results for the LECMZMU sector.

LECMZMU

Lateral LOS

Resolution manoeuvre	Aircraft	Distance (NM)			Fuel (Kg)			CO2 (Kg)			Delay (min)		
		Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value
FL	7	0.00	0.32	-0.35	7.78	39.95	-9.77	24.52	125.84	-30.78	0.00	0.00	-0.01
Horizontal vector	10	5.69	26.16	-0.53	28.73	148.79	-2.56	90.50	468.68	-8.07	0.68	3.58	-0.25
Total	17	3.35	26.16	-0.53	20.11	148.79	-9.77	63.33	468.68	-30.78	0.40	3.58	-0.25

Longitudinal LOS

Resolution manoeuvre	Aircraft	Distance (NM)			Fuel (Kg)			CO2 (Kg)			Delay (min)		
		Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value
FL	16	0.00	0.00	0.00	12.50	298.96	-193.37	39.39	941.72	-609.11	0.08	0.00	-0.54
Horizontal vector	15	0.36	17.74	-11.22	1.13	87.58	-56.87	3.57	275.89	-179.14	-0.09	1.20	-1.51
Total	31	0.17	17.74	-11.22	7.00	298.96	-193.37	22.05	941.72	-609.12	-0.09	1.20	-1.51

Lateral and Longitudinal LOS

Resolution manoeuvre	Aircraft	Distance (NM)			Fuel (Kg)			CO2 (Kg)			Delay (min)		
		Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value
FL	23	0.00	0.32	-0.35	11.07	298.96	-193.37	34.86	941.72	-609.11	-0.06	0.00	-0.54
Horizontal vector	25	2.50	26.16	-11.22	12.17	148.79	-56.87	38.34	468.68	-179.14	0.22	3.58	-1.51
Total	48	1.30	26.16	-11.22	11.64	298.96	-193.37	36.67	941.72	-609.12	0.09	3.58	-1.50

7.5. Preliminary impact assessment of the Ad Hoc separation concept in other scenarios: LECMTLU and LECMDGU

The potential benefits of applying the Ad Hoc separation concept have been assessed in two other ENR sectors of the Madrid ACC, the LECMTLU sector (Toledo Upper) and the LECMDGU sector (Domingo Upper). ANNEX E includes the description of physical and operational characteristics of both sectors.

This is a potential assessment because the ADSM values used to analyse the impact of this concept in both sectors have been the ones determined for LECMZMU. Nevertheless, this application has been performed from a conservative approach. The Ad Hoc separation depends on the following factors: aircraft model, aircraft mass, aircraft speeds, FL, encounter geometry, AM, HF and wind conditions. Since in LECMTLU and LECMDGU the operational and geographical characteristics could be considered similar to those of LECMZMU, except for the encounter geometry factor, the separation minima computed for LECMZMU were applied. In LECMZMU the ADSM, obtained from Montecarlo simulations, were determined for encounter geometries of 14°, 42°, 56°, 74°, 121°. In LECMTLU and LECMDGU the geometries are different. Therefore, a conservative approach has been adopted, defining geometry ranges for these ADSM. Thus, for geometries up to 14°, the ADSM corresponding to 14° has been applied. Between 15° and 42°, the ADSM of 42° has been applied and so on. In the LECMTLU and LECMDGU sectors, encounter geometries are more likely to be lower than 42° (ANNEX E). Therefore, if the ADSM had been determined (from Montecarlo simulations) for these specific geometries, reduced separation values (lower than the current value of 5NM) could have been applied more times.

For these reasons, this is a potential assessment of the benefits of Ad Hoc separation in both sectors, but the results could actually be better. The analysis of the impact of such concept in the capacity, environment and airspace user cost-efficiency KPAs is presented below.

7.5.1. Capacity assessment

The CAPAN method has been used for the capacity determination in LECMTLU and LECMDGU, as in the LECMZMU sector. Moreover, the same methodology has been applied for both scenarios. The results obtained are presented below.

- LECMTLU

To compute the capacity in the LECMTLU sector, the days of the busy week (1 - 7 July 2019) have been simulated in RAMS, determining the ATCO WL for each hour of each of the days. As in LECMZMU, three scenarios have been considered for the capacity computation: Baseline Scenario, Scenario 1 and Scenario 2. These three scenarios have been defined following the same criteria as in LECMZMU.

- Capacity Determination in the Baseline Scenario

The capacity value obtained in the Baseline Scenario (Figure 61) from FTS in RAMS is 46 aircraft/hour (46.81 aircraft/hour). The declared capacity of the LECMTLU sector is slightly lower, 45 aircraft/hour (the same as for the LECMZMU sector). Therefore, the value obtained using the CAPAN methodology is considered acceptable. This capacity value determined for the Baseline Scenario serves as a benchmark for comparison with the capacity of Scenario 1 and the capacity of Scenario 2.

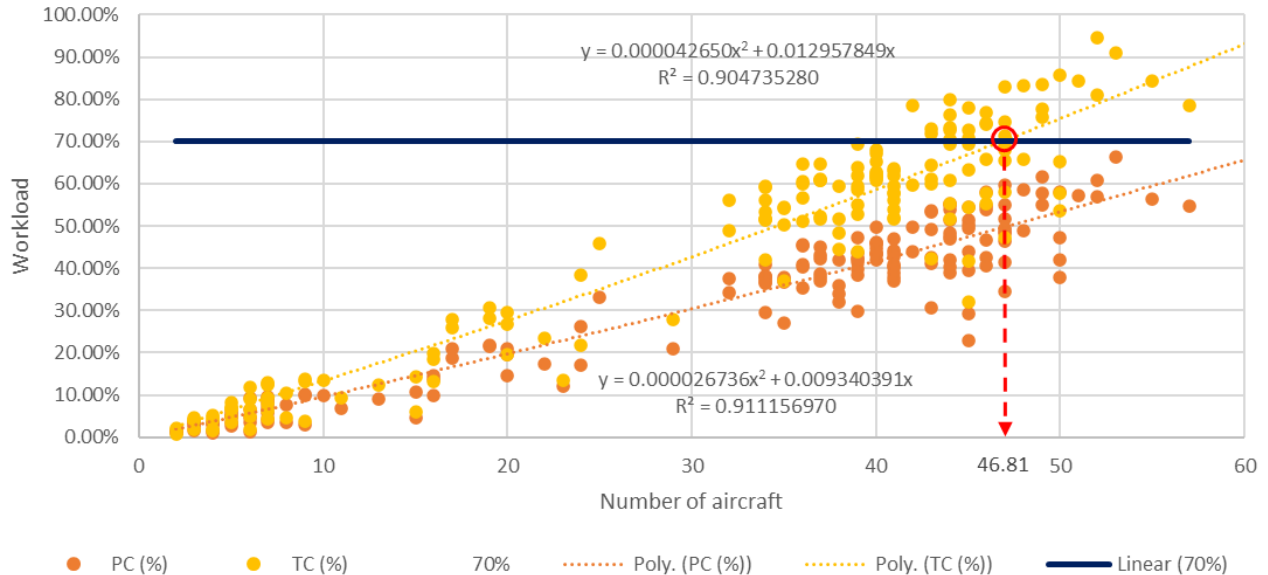


Figure 61. LECMTLU Capacity 5NM – Baseline scenario.

- Capacity Determination in the Scenario 1

The application of the Ad Hoc separation concept in the LECMTLU sector results in a new TC WL. This is calculated by simulating the LECMTLU scenario again but applying the different Ad Hoc separation minima values. Figure 62 shows the result obtained. The new TC WL yields a new capacity value of 47 aircraft per flight hour (47.24 aircraft/hour).

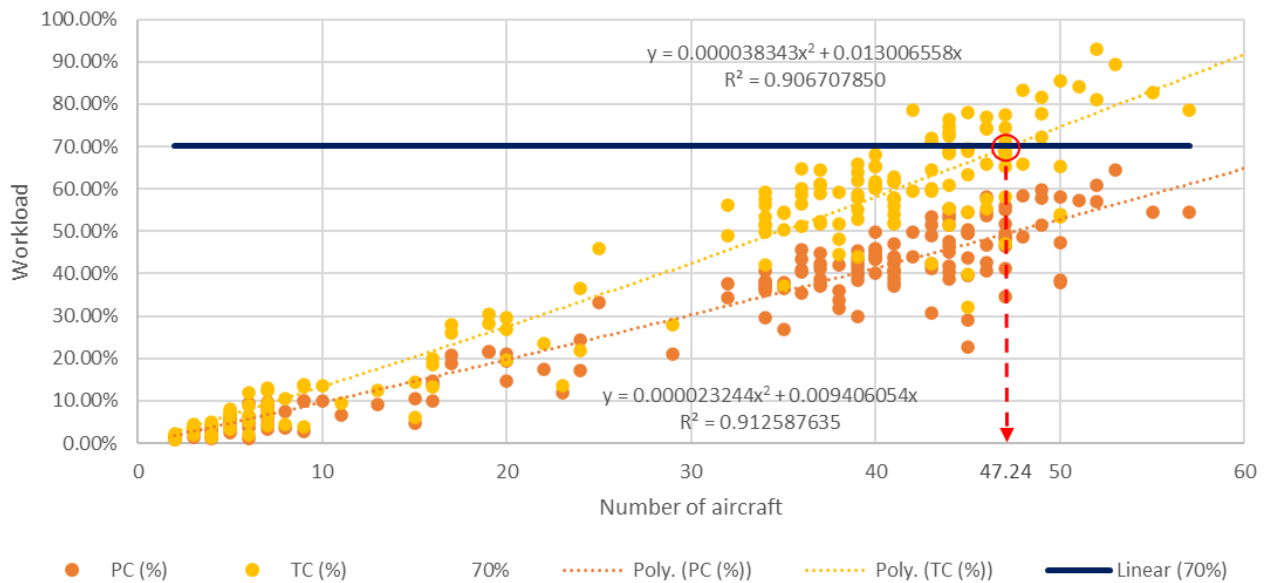


Figure 62. LECMTLU Capacity Ad Hoc Separation – Scenario 1.

- Capacity Determination in the Scenario 2

For the computation of the capacity in Scenario 2, the same assumptions are considered regarding the decrease in ATCO resolution times due to the CD&R functionalities of the ASMT tool. Thus, it is considered that there is a 50% improvement in detection and a 20% improvement in decision-making. Figure 63 shows the new capacity value for this scenario, 47 aircraft/flight hour (47.74 aircraft/flight hour).

PRELIMINARY IMPACT ASSESSMENT OF THE AD HOC SEPARATION CONCEPT

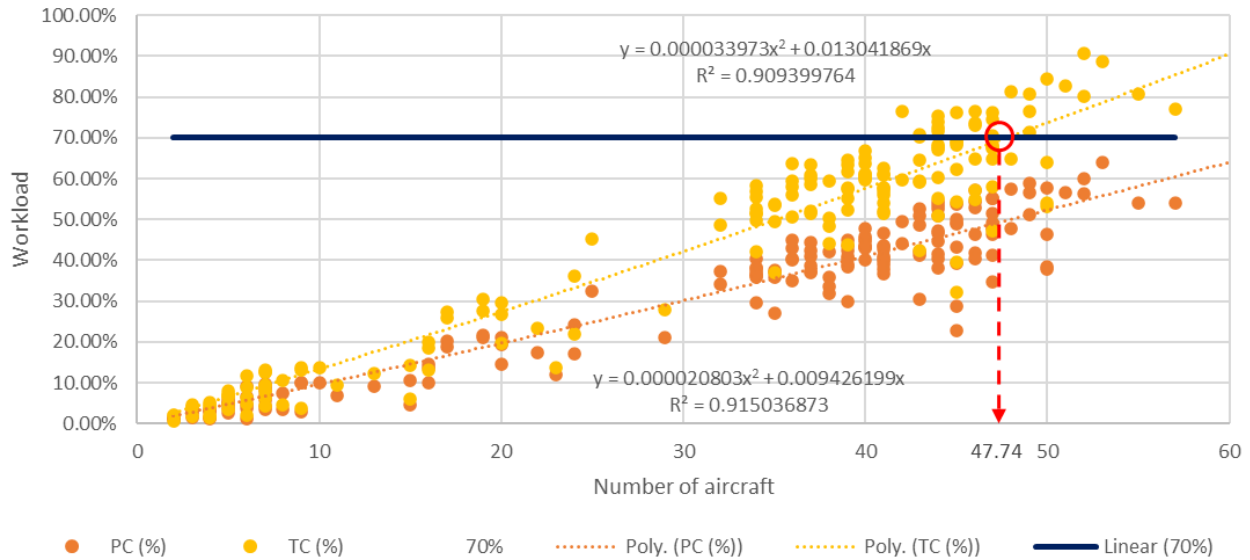


Figure 63. LECMTLU Capacity Ad Hoc Separation – Scenario 2.

Table 19 presents a comparison of the capacity outcomes achieved in the LECMTLU sector. These results are slightly lower than those obtained for the LECMZMU sector. In relative terms, however, the increase is from 46 aircraft/flight hour to 47 aircraft/flight hour. In absolute terms the increase in the capacity is nearly 1 aircraft/hour. This signifies a growth of 2% over the sector's capacity. Nevertheless, it is important to highlight that a conservative approach has been taken and separation minima for the LECMZMU sector have been applied.

Table 19. Capacity results in LECMTLU.

Scenario LECMTLU	Capacity (No. of aircraft / hour)	No. of aircraft / hour	Difference	Percentage of capacity increase (%)
Baseline Scenario	46.81	46	-	-
Scenario 1 ASMT (no CD&R)	47.24	47	0.43	0.9 %
Scenario 2 ASMT (CD&R)	47.74	47	0.93	2%

- LECMDGU

For the computation of the capacity in the LECMDGU sector, the same procedure was followed as in LECMZMU and LECMTLU. The days of the busy week (1 - 7 July 2019) were simulated in RAMS, computing the WL for each hour of each day.

- Capacity Determination in the Baseline Scenario

The capacity value obtained in the Baseline Scenario after performing the FTS in RAMS (Figure 64) was 46 aircraft/flight hour (46.74 aircraft/flight hour). The declared capacity of the LECMDGU sector is slightly lower, 44 aircraft/hour. That is, there is a difference of 2 aircraft/flight hour, whereas for the LECMZMU and LECMDGU the difference was only 1 aircraft/flight hour. Nevertheless, this capacity value should be considered as a benchmark to compare the capacity values associated with Scenario 1 and Scenario 2, as mentioned above.

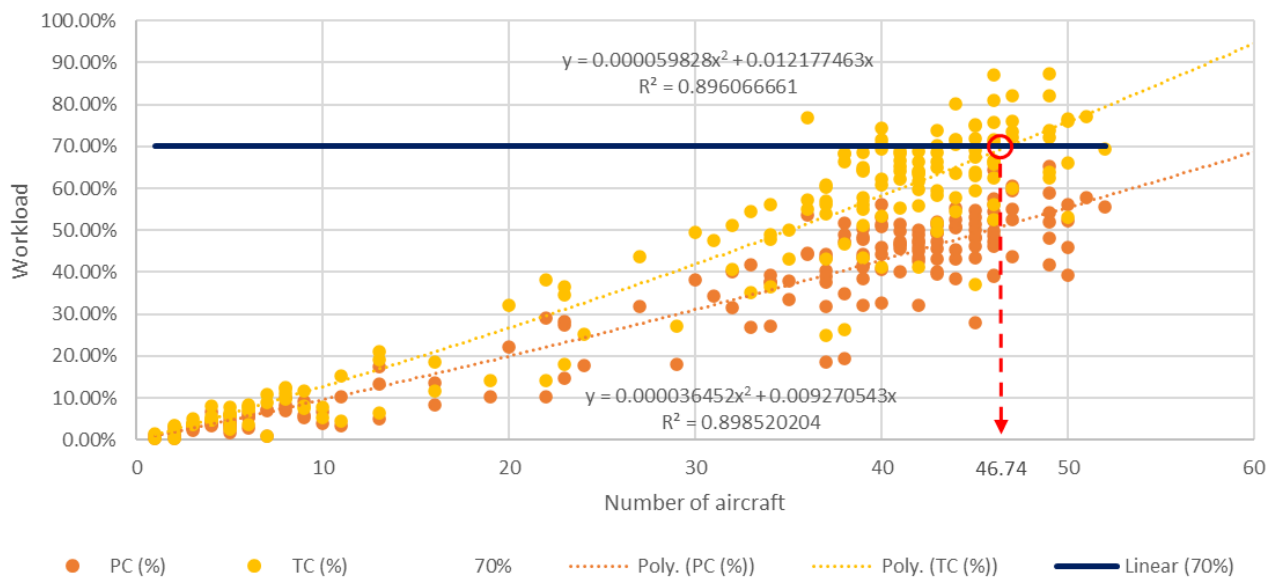


Figure 64. LECMDGU Capacity 5NM – Baseline Scenario.

○ Capacity Determination in the Scenario 1

Figure 65 presents the capacity determined in Scenario 1 from the new ATCO WL in the LECMDGU sector with the Ad Hoc separation concept applied. The result is 47 aircraft/flight hour (47.17 aircraft/flight hour).

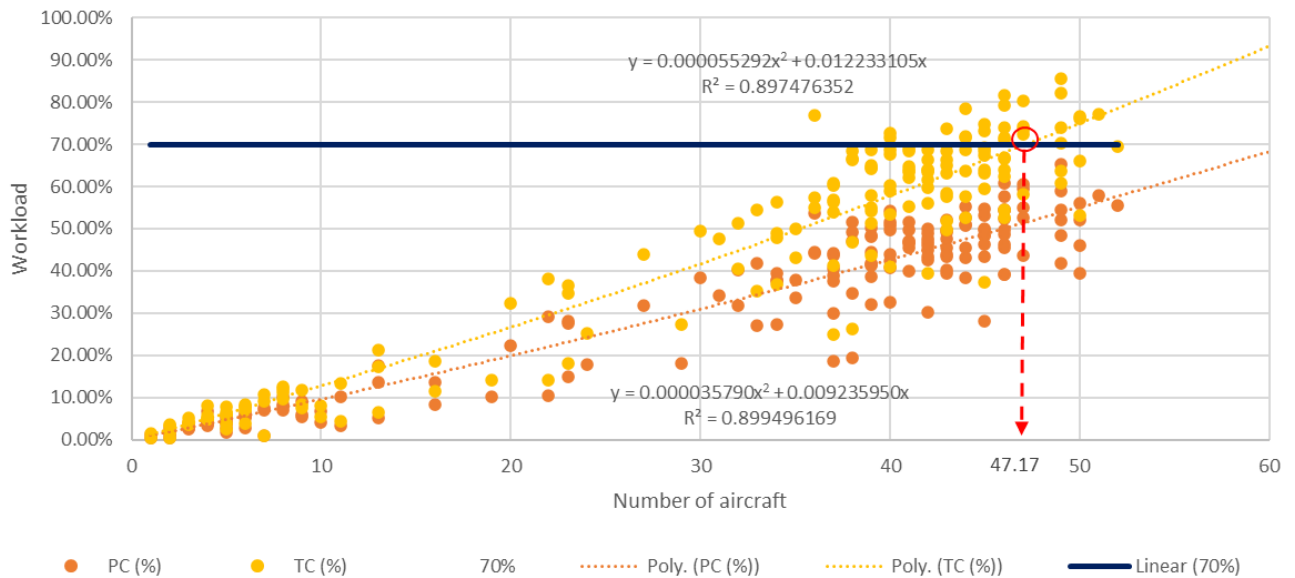


Figure 65. LECMDGU Capacity Ad Hoc Separation – Scenario 1.

○ Capacity Determination in the Scenario 2

Given the assumptions outlined regarding the influence on detection and decision-making times of the CD&R functionality within the ASMT tool, the computed capacity for the LECMDGU sector (Figure 66) in Scenario 2 stands at 47 aircraft/flight hour (47.63 aircraft/flight hour).

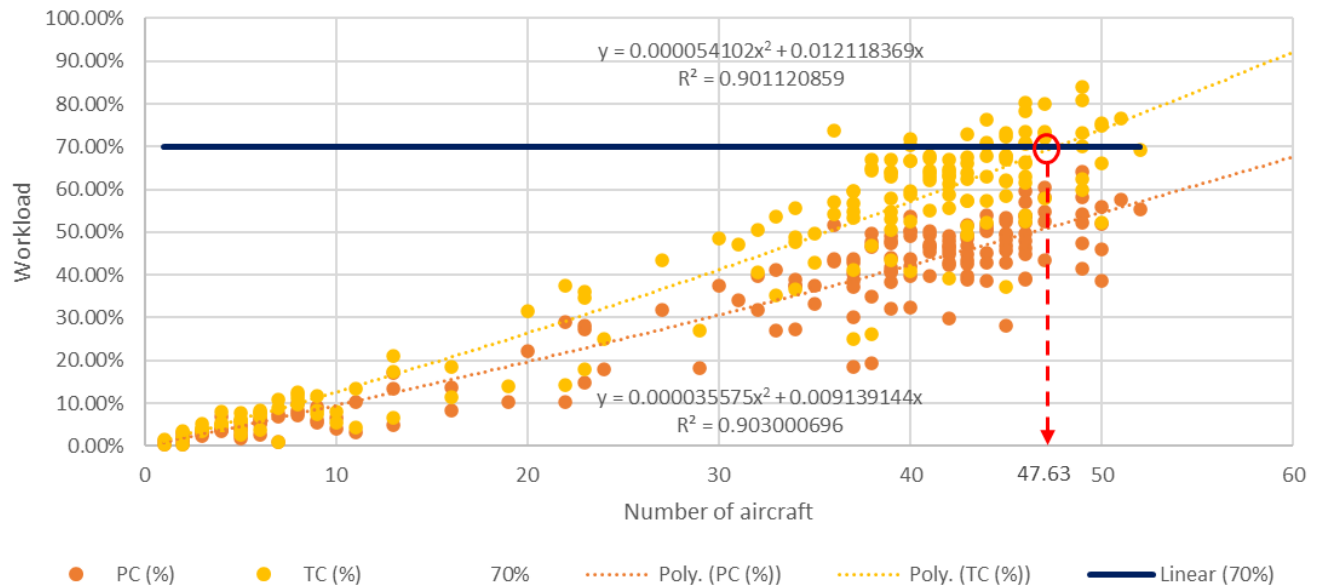


Figure 66. LECMDGU Capacity Ad Hoc Separation Scenario 2.

Table 20 presents the comparison of the capacity results obtained for the LECMDGU sector. It is observed that the increase in capacity is similar to that in LECMTLU, though slightly lower. In relative terms, once again, there is a shift from 46 aircraft/flight hour to 47 aircraft/flight hour. However, in absolute terms, the increase in the best-case scenario (Scenario 2) is 0.9 aircraft/flight hour, signifying an almost 2% capacity increase in the sector. It is important to note that a conservative approach has been adopted and separation minima determined for the LECMZMU sector have been applied.

Table 20. Capacity results in LECMDGU.

Scenario LECMDGU	Capacity (No. of aircraft / hour)	No of aircraft / hour	Difference	Percentage of capacity increase (%)
Baseline Scenario	46.74	46	-	-
Scenario 1 ASMT (no CD&R)	47.17	47	0.43	0.9%
Scenario 2 ASMT (CD&R)	47.63	47	0.89	1.9%

7.5.2. Environment and Airspace User Cost-Efficiency

As in the LECMZMU sector, the impact of the Ad Hoc separation concept application in the LECMTLU and LECMDGU sectors in the environment and airspace user cost-efficiency KPAs is analysed. The methodology followed and the indicators used are the same as for the LECMZMU sector.

- LECMTLU

Table 21 shows the results obtained for the LECMTLU sector. Positive results are obtained, although they are not as pronounced as those achieved in the LECMZMU sector. The most significant benefits are derived from resolving lateral LOS through horizontal manoeuvres (vectors).

These values should be placed in the context of the sector's characteristics. According to NEST data [118], [136], at LECMTLU, the average crossing distance is 115 NM and the average flight time in the sector is 15.5 minutes. Therefore, if the lateral LOS with horizontal resolution manoeuvre are analysed, it is obtained:

- Distance: reduction, on average, of 2.14NM per LOS saved, representing 1.86% of the total distance travelled in the sector.
- Delay: reduction, on average, of 0.13 minutes per LOS saved, representing 0.84% of the total flight time in the sector.
- Fuel and CO_2 : reduction, on average, of 10.76 kg of fuel and 33.88 kg of CO_2 emissions.

Benefits are also obtained for longitudinal LOS, although fewer than in lateral LOS. Horizontal resolution manoeuvres predominate for both types of LOS, longitudinal and lateral. Finally, in general terms, favourable average results are obtained for the indicators analysed, all of them being positive. That is, it is assumed that for each LOS saved, the flown distance, fuel consumption, CO_2 emissions and delay are reduced.

Table 21. Environmental and Cost-Efficiency results for the LECMTLU sector.**LECMTLU****Lateral LOS**

Resolution manoeuvre	Aircraft	Distance (NM)			Fuel (Kg)			CO2 (Kg)			Delay (min)		
		Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value
FL	3	0.00	0.00	0.00	15.32	25.00	0.00	48.25	78.75	0.00	0.00	0.00	0.00
Horizontal vector	19	2.14	12.68	-1.48	10.76	66.11	-7.06	33.88	208.25	-22.25	0.13	1.03	-0.42
Total	22	1.85	12.68	-1.48	11.38	66.11	-7.06	35.84	208.25	-22.25	0.11	1.03	-0.42

Longitudinal LOS

Resolution manoeuvre	Aircraft	Distance (NM)			Fuel (Kg)			CO2 (Kg)			Delay (min)		
		Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value
FL	2	0.00	0.00	0.00	0.95	1.90	0.00	2.99	5.99	0.00	0.07	0.14	0.00
Horizontal vector	11	0.74	1.38	-1.39	4.00	10.91	-7.00	12.61	34.38	-22.06	0.14	0.54	-0.55
Total	13	0.62	1.38	-1.39	3.53	10.91	-7.00	11.13	34.38	-22.06	0.13	0.54	-0.55

Lateral and Longitudinal LOS

Resolution manoeuvre	Aircraft	Distance (NM)			Fuel (Kg)			CO2 (Kg)			Delay (min)		
		Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value
FL	5	0.00	0.00	0.00	9.57	25.00	0.00	30.15	78.75	0.00	0.03	0.14	0.00
Horizontal vector	30	1.63	12.68	-1.48	8.28	66.11	-7.06	26.08	208.25	-22.25	0.13	1.03	-0.55
Total	35	1.39	12.68	-1.48	8.46	66.11	-7.06	26.66	208.25	-22.25	0.12	1.03	-0.55

- LECMDGU

Table 22 presents the results obtained for the LECMDGU sector. There are specific benefits in this sector, albeit not as substantial as those seen in the LECMZMU and LECMTLU sectors. In this sector, conflict resolution (CR) primarily involves level change manoeuvres. Consequently, the most significant benefits manifest in the metrics of fuel consumption and CO_2 emissions, while the improvements in flown distance and delay are practically negligible. Despite being small, these positive values contribute to the overall benefit of applying the Ad Hoc separation concept.

These values are contextualised in relation to the characteristics of the sector. In LECMDGU, the average flown distance is 94.2NM and the average flight time in the sector is 12.3 minutes (NEST data [118], [136]). Therefore, if the total LOS results (lateral and longitudinal) are analysed considering both manoeuvres together, the following results are obtained:

- Distance: reduction, on average, of 0.03NM per LOS saved, or 0.03% of the total distance travelled in the sector.
- Delay: reduction, on average, of 0.03 minutes per LOS saved, or 0.24% of the total flight time in the sector.
- Fuel and CO_2 : reduction, on average, of 20.11 kg of fuel and 63.35 kg of CO_2 .

Finally, it can be stated that, in general terms, favourable average results are obtained for the indicators analysed, all of which are positive. This means that for each LOS saved, the flown distance, fuel consumption, CO_2 emissions and delay are reduced.

Table 22. Environmental and Cost-Efficiency results for the LECMDGU sector.**LECMDGU****Lateral LOS**

Resolution manoeuvre	Aircraft	Distance (NM)			Fuel (Kg)			CO2 (Kg)			Delay (min)		
		Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value
FL	8	-0.11	0.00	-0.86	14.26	25.55	-4.32	44.90	80.48	-13.60	0.00	0.01	-0.02
Horizontal vector	5	0.43	2.68	-1.10	1.81	11.57	-5.36	5.69	36.45	-16.89	0.19	0.40	-0.19
Total	13	0.10	2.68	-1.10	9.47	25.55	-5.36	29.82	80.48	-16.89	0.08	0.40	-0.19

Longitudinal LOS

Resolution manoeuvre	Aircraft	Distance (NM)			Fuel (Kg)			CO2 (Kg)			Delay (min)		
		Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value
FL	13	0.00	0.00	0.00	44.83	237.67	11.84	141.21	748.66	37.30	0.01	0.08	0.00
Horizontal vector	9	-0.02	2.49	-2.17	-0.22	12.56	-10.94	-0.70	39.55	-34.46	-0.02	0.27	-0.59
Total	22	-0.01	2.49	-2.17	26.40	237.67	-10.94	83.16	748.66	-34.46	0.00	0.27	-0.59

Lateral and Longitudinal LOS

Resolution manoeuvre	Aircraft	Distance (NM)			Fuel (Kg)			CO2 (Kg)			Delay (min)		
		Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value	Average	Max value	Min value
FL	21	-0.04	0.00	-0.86	33.18	237.67	-4.32	104.52	748.66	-13.60	0.01	0.08	-0.02
Horizontal vector	14	0.14	2.68	-2.17	0.50	12.56	-10.94	1.58	39.55	-34.46	0.05	0.40	-0.59
Total	35	0.03	2.68	-2.17	20.11	237.67	-10.94	63.35	748.66	-34.46	0.03	0.40	-0.59

7.6. EASA validation

Part of this dissertation was presented at the first edition of the "European_Academia @EASA 2023" conference. This conference was held at the EASA headquarters in Cologne, Germany, from March 23-24, 2023. The congress was launched with the aim of fostering closer relations between EASA and the academic world, demonstrating a commitment to the next generation of European aeronautical scientists by promoting the connection between academia and industry.

During the conference, twenty doctoral theses (previously selected from over fifty European doctoral thesis applications) were presented to an audience of students, professors, aviation authorities, industry professionals and EASA staff. The conference focused on four topics reflecting challenges and emerging technologies in the aviation sector: "Artificial Intelligence in Aviation," "Impact of Climate Change on Aviation," "Environmental Sustainability," and "Risk Management in Air Safety." At the conclusion of the event, awards were given to the four best dissertations in these four areas among the participating doctoral students, acknowledging the quality, interest and relevance of both the submitted documentation and the conference presentations. This dissertation received the award in the category of new approaches and methods for risk management in safety.

The award included the opportunity to establish bilateral contacts with EASA for exchanging opinions on the doctoral dissertation. This resulted in a two-week stay at EASA in October 2023, during which this dissertation was evaluated by many experts.

On one hand, several documents (which constitute different chapters of this dissertation) were reviewed by EASA experts who provided feedback and comments. All these contributions were included into the dissertation. On the other hand, the doctoral thesis was presented during this stay to fourteen experts from the EASA Air Navigation department. Additionally, various interviews with experts allowed for an in-depth exploration of different aspects related to Ad Hoc separation (meteorological information, CNS, interviews with pilots and ATCOs, regulatory aspects of the concept, etc.).

While not constituting a validation process per se, it proved to be an insightful experience, enabling engagement with experts and facilitating discussions on various aspects of the dissertation.

7.7. Summary

In this chapter, a preliminary study of the impact of the Ad Hoc separation concept application in the reference scenario, the LECMZMU sector, has been conducted. Additionally, the study has been extended to the LECMTLU and LECMDGU sectors of the Madrid ACC to assess the benefits in other scenarios. The impact has been analysed in terms of capacity, environment and airspace user cost-efficiency KPAs. For this purpose, FTS have been performed in RAMS software. The most significant results are obtained for the reference scenario, the LECMZMU. For the LECMTLU and LECMDGU sectors, the outcomes are positive but less pronounced. This could be attributed to the fact that LECMZMU ADSM were conservatively applied in this sector (potential preliminary assessment), considering these sectors have similar operational characteristics. In conclusion, it can be said that the benefits vary according to the characteristics of the sector. In this case, as the three sectors have similar characteristics, the results obtained are not significantly different.

Regarding capacity, the application of the concept along with the ASMT tool allows for an increase of 1 aircraft per hour. These results demonstrate that the Ad Hoc separation concept has a positive impact on capacity. However, the current models used by ANSPs for capacity determination are based on the ATCOs WL. Therefore, improvements in ATC support systems will have a greater impact on capacity increase with less system complexity than a change in the separation mode.

Regarding the impact on environment and airspace user cost-efficiency KPAs, it is noteworthy that the benefits are per LOS saved. Although not highly noticeable, these are positive results. Future research should focus in implementing the concept in a larger-scale scenario (ACC) instead of a specific sector because the benefits could be more significant.

8. CONCLUSIONS AND FUTURE WORK

This chapter summarises the main contributions of this dissertation and presents the future research.

8.1. Research conclusions

In view of the expected growth in air traffic demand in the near future, one of the prevailing strategic objectives is to alleviate the current capacity constraints, ensuring the ability to manage the expected demand with a significant margin. Among various solutions, SESAR advocates for the exploration of research avenues aimed at the evolution of separation minima standards, such as dynamic separation, as a way to contribute to increasing airspace capacity. This dissertation has identified a novel line of research in the exploration of the Ad Hoc separation.

This new separation mode was developed in its first phase for an ENR scenario (at a basic level), to demonstrate its feasibility. That is, whether it is possible to reduce the separation minima (and if so, whether this reduction is absolute or partial depending on each situation) and if the application of the concept brings any benefits. Demonstrating the feasibility or non-feasibility of the concept implies whether further research and development can proceed to higher levels or, conversely, whether the idea is refuted.

The first Research Question posed at the beginning of this dissertation was: *"Under which situations is it possible to define new separation minima values lower than the current one?"* To address this issue, a two-stage process was followed. First, the Ad Hoc separation model was established (based on the IRP model and the Encounter Timeline concept principles). Subsequently, a CRM was developed to complement this model for defining Ad Hoc separation values, following the ICAO's absolute approach.

A new CRM was developed because of the limitations in existing CRMs identified after the state of the art review. These limitations rendered them inadequate for determining Ad Hoc separation. The newly developed CRM integrates the factors influencing Ad Hoc separation and is founded on key variables of the model developed (t_{nec} and $TCPA$).

New Ad Hoc separation values were defined through Montecarlo simulations from this CRM and after determining the TLS corresponding to the current 5NM separation. The obtained results demonstrate that for small encounter geometries (below 56°) it is feasible to apply separation values lower than 5NM. Specifically, for the reference scenario simulations (14°, 42°, 56°, 74° and 121°), the following outcomes were found. For the angle of 14°, it is deemed safe to implement a 4NM separation in 92% of the simulated encounters and a 3NM separation in 81%, considering a HF of 20s. When the angle is increased to 42°, a 4NM separation could be applied in 68% of the encounter situations and a 3NM in 11% of the situations without compromising safety levels. If the geometry is increased to 56°, a 4NM separation would be safe in 23% of the simulated encounter situations, while a separation minimum value of 3NM would not be safe in any situation. For 74° and 121° it would not be possible to reduce separation minima. Consequently, these results highlight various situations where it is possible to apply different separation minima, answering the first research question.

Having addressed Research Question 1, the subsequent inquiry emerged regarding how the operation would unfold with the application of different separation minima values within the same volume of airspace. Thus, Research Question 2 was formulated as follows: *What would be the mode of operation in a scenario where the Ad Hoc separation minima (ADSM) concept is applied?* This question refers to the CONOPS of the Ad Hoc separation, meaning the mode of operation in airspace where this concept is implemented. Although the definition of CONOPS is an ongoing process, updated as all components of the methodology are developed, an initial CONOPS proposal considering the application of this concept in ENR airspace was defined in Chapter 3.

One of the key elements and a prerequisite for the implementation of the Ad Hoc separation concept in a scenario is the ATC support tool ASMT. An initial prototype of this tool was developed and its architecture was described in Chapter 6. In addition, its application in the LECMZMU sector for a few hours traffic sample was included in Chapter 6. The primary goal of this practical exercise was to demonstrate the tool's behaviour, rather than creating a tool for real-world application. However, there is a need to enhance some modules for improved performance.

The consideration of the response to Research Question 2 raises the issue of determining whether the complexity involved in implementing such a significant system-wide change is justifiable. This is formulated in Research Question 3: *Which benefits does the Ad Hoc separation concept bring to a scenario?* To address this last research question, an analysis of the impact of this concept when applied in an ENR sector was conducted. The outcomes obtained are favourable:

Regarding safety, after determining the Ad Hoc separation between aircraft pairs, the concept was applied in the LECMZMU reference scenario to ascertain the requirement for maintaining safety levels at current ones. To achieve this objective without compromising safety, the simulations resulted in a requirement to halve the corresponding value for the number of LOS/flight hour.

Regarding capacity, environment and airspace user cost-efficiency KPAs, FTS were conducted in the reference sector for quantifying the benefits of the concept. Furthermore, to assess the potential benefits in other scenarios, this analysis was extended to LECMTLU and LECMDGU sectors.

The most significant outcomes were obtained in capacity KPA, with an increase of one aircraft per hour for the three scenarios studied. Although these results are positive, they highlight that the influence of the separation minima on the capacity KPA for an ENR scenario is minor. According to the current models used by ANSPs for capacity computation, an enhancement in ATC support tools would yield a greater increase in capacity with a lower degree of system complexity compared to a modification in the separation mode. Nevertheless, these results underscore the positive impact of the Ad Hoc separation concept on capacity.

Favourable outcomes were obtained for environment and airspace user cost-efficiency KPAs. The values obtained for Flown Distance, Fuel, CO_2 and Delay indicators were measured referred to each LOS saved by applying the Ad Hoc separation concept. The results were categorised based on the type of LOS (lateral, longitudinal) and the resolution manoeuvre applied (level change or horizontal vector).

The best results were obtained in the reference scenario LECMZMU, in which the favourable outcomes occurred when lateral LOS were resolved with horizontal manoeuvres. Some numerical values are highlighted. Considering both lateral and longitudinal LOS (total LOS) along with both resolution manoeuvres, there was an average reduction of 1.30NM/LOS in flown distance (1.6% of the

flown distance in the sector), of 0.09 min/LOS saved in delay (0.8% of the flight time in the sector), of 12 kg/LOS saved in fuel and of 37 kg/LOS saved in CO_2 .

In the LECMTLU and LECMDGU sectors there were also benefits, albeit smaller than in LECMZMU. Thus, if the concept was implemented in a larger scenario (e.g. ACC) rather than in a single sector, the obtained benefits would be more significant.

In conclusion, given the compelling findings outlined above, it is suggested to pursue further development and research into this innovative separation mode. This dissertation has demonstrated its feasibility in the initial stage and its application is proven to have a positive impact on the system.

8.2. Future work

Due to the novelty and promising results obtained, many activities have been identified as future work to develop and complete this research. Those that have been considered most relevant are presented below:

- 1) Wake vortex factor inclusion in the model. The ADSM values determined correspond to the minimum ATC separation (AMAS). The development of the AMWS is the main future work. Thus, the ADSM will be the largest between AMWS and AMAS.
- 2) Methodology generalisation. Generalising the methodology involves expanding the set of values associated with each factor (including a larger number of aircraft models, additional FL, encounter geometry at intervals of 5° , etc.). After conducting Montecarlo simulations for the combination of all these factors, Ad Hoc separation values could be obtained for a broader range of encounter situations.
- 3) Compatibility with TCAS system. Although a preliminary assessment has been made, an in-depth study should be performed to ensure the compatibility of the Ad Hoc separation concept with TCAS.
 - a. The TCAS RA manoeuvre should not be triggered before an Ad Hoc LOS in situations where the Ad Hoc separation of 4NM or 3NM is applied, since for a SL 7 the TCAS RA triggers at 35s and t_{nec} and $TCPA$ considered in the Ad Hoc separation model are higher than this value.

- b. The AMs associated with the ADSM should be the same as those of the TCAS RA. That is, if the AM is a climb and the TCAS RA would hypothetically trigger, the RA manoeuvre should be a climb.
- 4) Application to a Free Route scenario. The application to a Free Route scenario would be immediate after the generalisation of the model, given that the methodology is prepared for its development. A novel concept such as Ad Hoc separation should be implemented in future scenarios, where the elimination of predefined routes is sought.
- 5) Extension of the model to 3D. Expanding the model to 3D aims to incorporate evolving aircraft (climb, descent) and account for the complete aircraft population operating in a sector. This includes established aircraft, as well as those in the process of climbing and descending.
- 6) Study of the concept application in TMA airspace. It is considered that in such a scenario, the advantages could be significant, for two reasons.
 - a. In a TMA, aircraft are in evolution. Consequently, the mass is a key factor and more situations could be distinguished where different separation minima apply.
 - b. In a TMA, the capacity is calculated from the geometry and ATCO workload (WL). Therefore, a reduction in the separation minima would have a greater effect on the capacity estimate than in an ENR sector, where the capacity is calculated entirely from the ATCO WL.
- 7) Enhancement and development of the ASMT tool. In this dissertation a prototype of the ASMT tool has been presented. However, its constituent modules need to be improved. Specifically, the trajectory prediction and conflict detection modules are intended to be optimised using novel techniques such as Machine Learning (ML). Subsequently, more samples should be inserted in the tool. The tool will then undergo validation and verification processes.
- 8) Exploring the application of different separation minima beyond the two predefined values 4NM or 3NM can be meaningful. A future line of research involves analysing whether a broader range of separation minima such as 4.5NM, 4NM, 3.5NM, etc., would yield additional benefits.

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ANNEX A. CROSS-TRACK DEVIATION OF RADAR TRACKS

In this ANNEX A, two of the cases analysed in [11] are presented to demonstrate the cross-track deviation value of 0.4NM for aircraft flying with RNAV 5 specification and GNSS sensor.

For different segments of SID and ENR phases, actual radar trajectories were recorded (months of June, July and August 2019) and analysed to determine the cross-track deviation when aircraft fly with GNSS. Here, it is presented the study of PINAR 1R SID and R870 in the Spanish airspace.

A difficulty is that one of the most common clearances in a radar environment are the “directs” in order to save distance, time, fuel and CO₂. From an initial sample corresponding to trajectories of these months, a first filtering was performed to delete those trajectories in which the aircraft did not fly point to point but were given a "direct to" by ATCO after the pilot's request.

Figure A1a shows the cross-track deviation of aircraft flying PINAR 1R SID. The data analysed correspond to a segment of this SID located more than 30NM from the ARP, where en-route criteria apply. 10095 trajectories were analysed. It is observed that a large number of values accumulate in the range 0 - 0.2NM. A boxplot diagram (Figure A1b) was performed to know the limits from which the data are outliers. To obtain a conservative upper-bound value, the maximum deviation is set to 0.3NM.

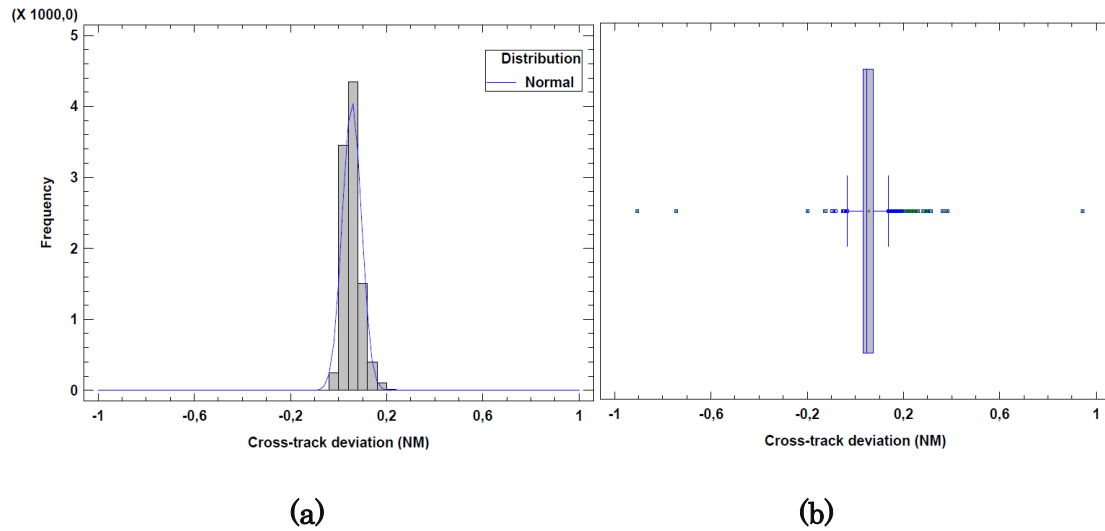


Figure A1. (a) PINAR 1R cross-track deviation distribution. (b) PINAR 1R Boxplot of cross-track deviation.

Table A1 shows the statistics of the data analysed corresponding to aircraft flying SID PINAR1R.

Table A1. Statistics of cross-track deviations in the PINAR 1R segment analysed.

Statistics	Lognormal
Average	0.0555282
Standard Deviation	0.0396557
Minimum	-0.905408
Maximum	0.943425
Range	1.84883
Lower quartile	0.031222
Upper quartile	0.0744073

Cross-track deviations were also analysed in several segments of R870 ENR airway. The sample studied was composed of 5972 trajectories. Figure A2a shows the histogram of the trajectories' lateral deviations values from the nominal trajectory. It is observed that a large number of values accumulate in the range 0-0.2NM. From these results, it is desired to know the cut-off value beyond which the data are considered outliers. Therefore, a boxplot diagram is shown in Figure A2b. From this diagram it is known that values below -0.064NM and above -0.029NM are outliers. In order to obtain a conservative upper-bound value, the maximum deviation is set to 0.3NM.

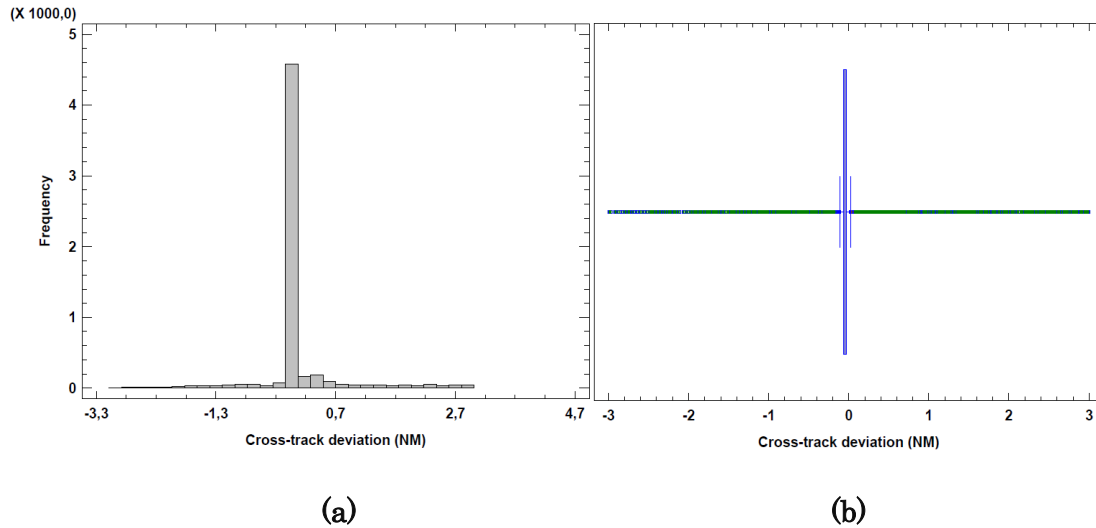


Figure A2. (a) R870 cross-track deviation histogram. (b) PINAR 1R Boxplot of cross-track deviation.

Table A2 shows the statistics of R870 cross-track deviation. The standard deviation value of 0.69NM refers to the dispersions of the histogram because of the ATCO clearance “direct to”. It is true that an initial filtering has been performed in order to remove these data (which implies a large deviation from the nominal trajectory but is an outlier). However, it was not possible to remove all of the “directs”. This is why the outlier criteria from the boxplot has been followed in order to establish the deviation of the nominal trajectory. The outliers of the boxplot correspond to direct manoeuvres.

Table A2. Statistics of cross-track deviations in the R870 segment analysed.

Statistics	Lognormal
Average	0.0379783
Standard Deviation	0.689364
Minimum	-2.99076
Maximum	2.99579
Range	5.98655
Lower quartile	-0.0640602
Upper quartile	-0.0293488

Many more segments have been analysed in the study [11] and, as a general result, it can be inferred that the actual aircraft deviation from the nominal trajectory flying with GNSS is contained within $\pm 0.4\text{NM}$. This deviation is modelled with a Gaussian distribution, according to the data and what is referred to in [13].

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ANNEX B. ATCO – PILOT COMMUNICATION ANALYSIS

The aim of this study is to model the ATCO-Pilot communications, in order to obtain time values that could be applied to the Ad Hoc separation concept. ENR communications during peak hours from August 22nd to August 31st, 2023, in the LECMZMU sector were analysed.

More than two hundred measures were studied. According to Equation (31) [137], for the mean estimation, 200 sample values are enough to obtain an error (E) of 0.1s, with a confidence level of 95%.

$$n = \frac{Z_{\alpha/2}^2 S^2}{E^2} \quad (31)$$

Where,

- n is the sample size.
- Z is the critical value of the standard normal distribution corresponding to confidence level $1 - \alpha$
- S standard deviation of the population.
- E error margin.

For the values of this study, α is 0.05, E is 0.1s and S is 0.713627.

The communications analysed correspond to FL change, direct to, heading or speed modifications clearances/instructions, either in English or Spanish. This study's outcome will contribute to the Ad Hoc separation concept, particularly in estimating times for urgent communications. Therefore, the analysed data are sourced from peak traffic hours, given that peak traffic hours are expected to prompt accelerated ATCO-Pilot communications, resembling urgency. The findings for both ATCO and pilot communications are outlined below.

B.1 ATCO communication analysis

A total of 220 communications were recorded for the ATCO. These communications were listened in real time in ENAIRE's PALESTRA application and subsequently analysed from their sound spectrum (Figure B1).

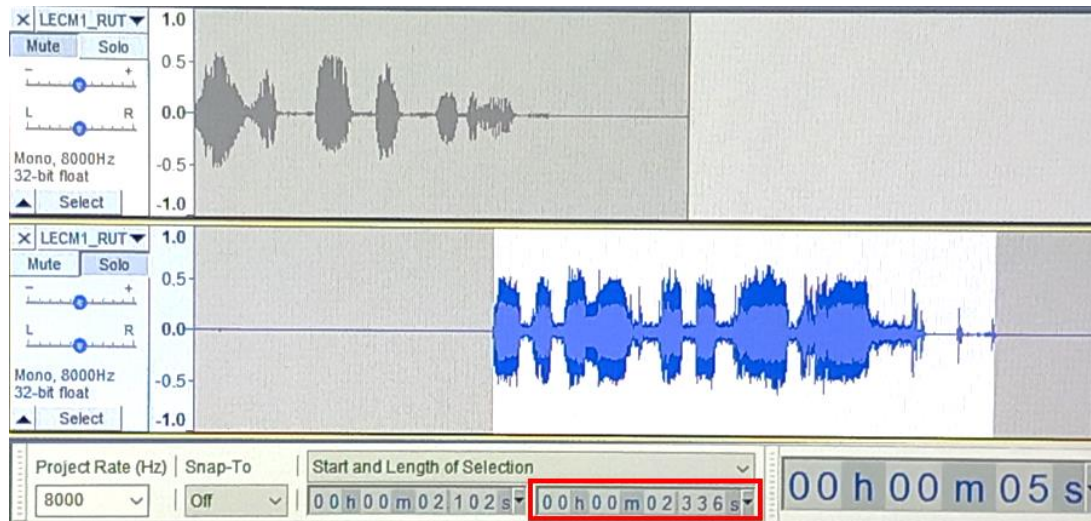


Figure B1. Example of sound spectrum analysis of ATCO communications.

Among the 220 communications analysed, 18% were in Spanish, compared to 82% in English. If a classification is made based on the type of manoeuvre instructed or cleared by the ATCO, it is observed that most communications in the LECMZMU sector involve direct manoeuvres (47%), followed by FL changes (44%) (Table B1).

Table B1. Distribution of ATCO communications instructions in LECMZMU.

Manoeuvre	Number	Percentage
Directs	104	47%
Climb	26	12%
Descent	70	32%
Heading	8	4%
Speed	12	5%

After analysing the data, the following results were obtained. Figure B2a shows the histogram. Figure B2b the boxplot. The data fit the Lognormal distribution, as the P-value is greater than 0.05 (Table B2), which means that the hypothesis

that these data are from a Lognormal distribution cannot be rejected with 95% confidence. This result is consistent with the nature of the data obtained. Generally, air-ground communications shall be made as fast as possible. Furthermore, there cannot be negative values (logarithmic nature). Consequently, most of the communications are concentrated around an average value that is small (distribution function shifted to the left). There is not much data below this average value, as in general, the communication process is trained by ATCOs in order to keep the communications short and clear (soon the distribution reaches its average value). Values located at the right side of the mean value correspond to longer communications or to communications made by an ATCO with a slightly slower speech rate. According to the boxplot information, values above 6.4s would be considered outliers.

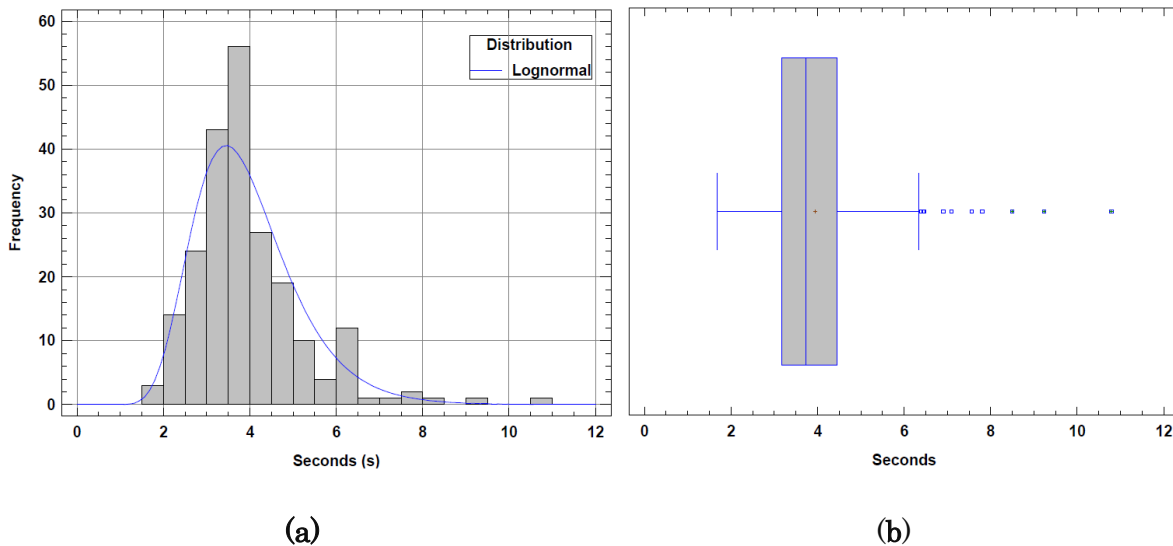


Figure B2. (a) Histogram and (b) boxplot of ATCO communications data.

The quantile plot is depicted in Figure B3. This is a tool used to assess the similarity between the distribution of the ATCO communications variable and the lognormal distribution. If the two distributions are identical, then the values of the communications variable will match the values of the lognormal cumulative distribution function. Most of the data are identical or very close. These data therefore follow a lognormal distribution.

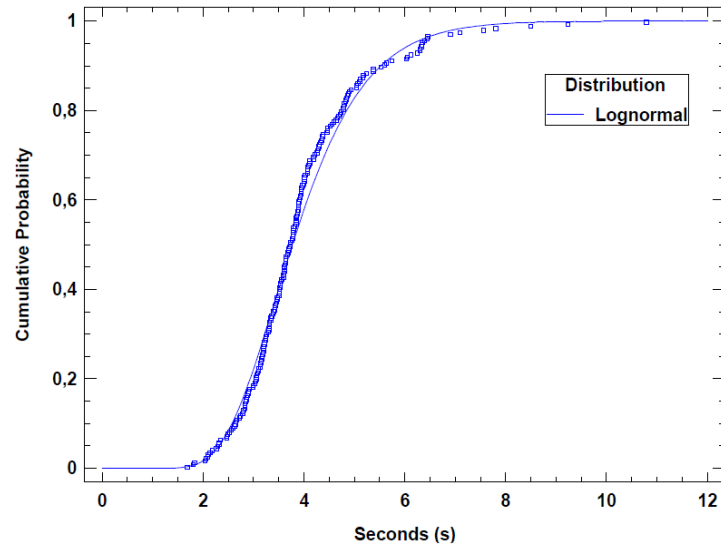


Figure B3. Quantile plot for ATCO communications data.

Table B2 shows the statistics for the variable analysed. The mean (μ) of the communications obtained is 3.9s, with a standard deviation (σ) of 1.2s. These data are consistent with those recorded by ENAIRE [138] as mean measures of ATCO communications.

Table B2. Statistics and Kolmogorov Smirnov test, ATCO communications data.

Statistics	Lognormal
Average	3.94188
Standard Deviation	1.20485
Log Scale. Median	1.327
Log Scale. Standard Deviation	0.298855
Kolmogorov-Smirnov	
DMAS	0.0732315
DMENOS	0.0466572
DN	0.0732315
P-value	0.191026

Nevertheless, it is noticeable that many of the communications in this sample analysed introduced additional information that would have no place in an urgent communication. For instance (invented callsigns):

“IBE123 MUY BUENAS, CONTACTO RADAR, ASCIENDA NIVEL DE VUELO 360”

or

“TAP123. MADRID BUENAS TARDES. I CONFIRM YOU ARE IDENTIFIED. 370. FLY DIRECT NUBLO”

The terms "Muy buenas", "Contacto radar", "Madrid buenas tardes", "I confirm you are identified", would not be used in an urgent avoidance manoeuvre communication. Therefore, the 220 ATCO communication data have been reprocessed to remove the time duration corresponding to these terms. The new results are presented below:

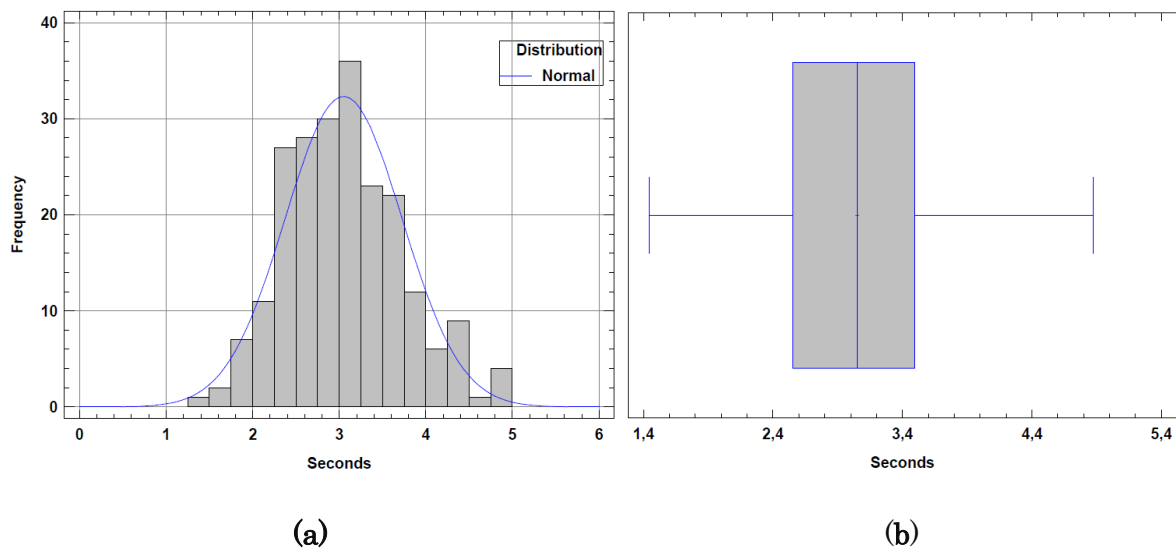


Figure B4. (a) Histogram and (b) boxplot of treated ATCO communications data.

After processing the ATCO data analysed, from its histogram and fitting distributions, it is observed that the data fit a normal distribution (Figure B4a). This outcome is consistent with the treatment performed, as most of the data have terms removed that, in theory, would not follow the standard

communication procedure. Consequently, these data would represent the behaviour of the communications variable when the standard procedure is followed, with the dispersion regarding the mean being smaller, as can be seen in the boxplot (Figure B4b).

The quantile plot is depicted in Figure B5. The similarity between the distribution of the treated ATCO communications variable and the normal cumulative distribution function is greater than in the previous case. Most of the data match or are very close. Therefore, it is shown that these data follow a normal distribution.

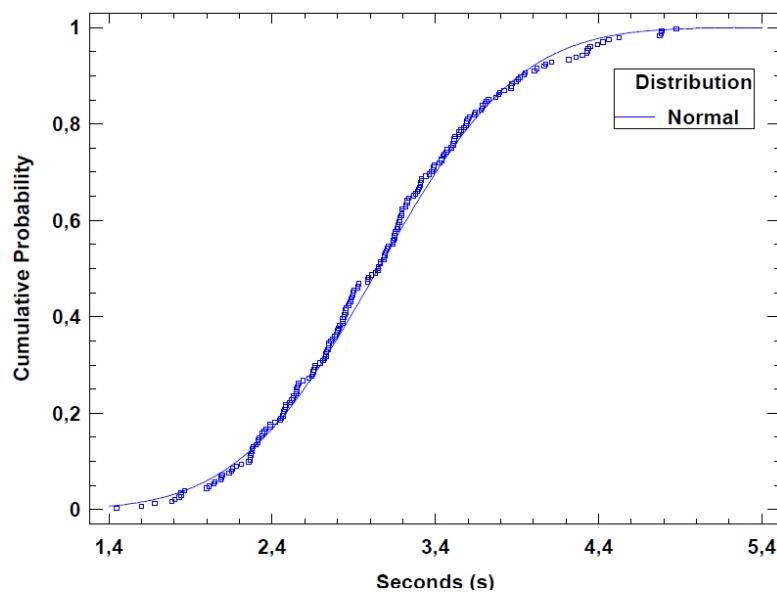


Figure B5. Quantile plot for treated ATCO communications data.

Table B3 presents the statistics for the treated ATCO communications variable. The data for the Kolmogorov Smirnov test confirm that it is not possible to reject the hypothesis that the data come from a normal distribution with 95% confidence. Table B3 also includes the values of the standardised skewness and standardised kurtosis, which can be used to determine whether the sample comes from a normal distribution. Values of these statistics outside the range -2 to +2 indicate significant deviations from normality. In this case, the values of both metrics are within the expected range of normal distribution data.

The μ value is 3.05s and σ is 0.68s. Therefore, 99.7% of the data ($\mu+3\sigma$) corresponds to a value of 5.1s. That is, 99.7% of the ATCO processed communications data variable is guaranteed to be less than 5.1s. This value, 5.1s,

will be the value used in the Ad Hoc separation concept for ATCO communication.

Table B3. Statistics and Kolmogorov Smirnov test treated ATCO communications data.

Statistics	Normal
Average	3.05022
Standard Deviation	0.675914
Standardised Skewness	1.84256
Standardised Kurtosis	-0.312817
Kolmogorov-Smirnov	
DMAS	0.0439887
DMENOS	0.0274243
DN	0.0439887
P-value	0.790504

B.2 Pilot communication analysis

A total of 222 communications were recorded from pilots. Of these, 220 correspond to the readback of the ATCO instructions studied in previous section B.1. The methodology followed for the data analysis is the same as for the ATCO communications. The outcomes are shown below.

Figure B6a shows the histogram while Figure B6b the boxplot. Data fit a lognormal distribution. As before, this result is consistent with the nature of ATCO - Pilot communications. Air-ground communications should be clear and short (to minimise frequency occupancy).

Pilot communications are shorter in duration and have less dispersion from the mean than those of the ATCO. This is because the measured pilot communications correspond to the readback procedure between pilot and ATCO. Therefore, the pilot does not have to think about the instruction first (which manoeuvre is better) and then communicate it. This is ATCO's responsibility.

The pilot simply repeats what the ATCO has told him/her (readback). Through this procedure, the ATCO ensures that the instruction has been correctly understood. Consequently, the times are shorter. According to the boxplot (Figure B6b), values from 3.1s onwards are considered outliers.

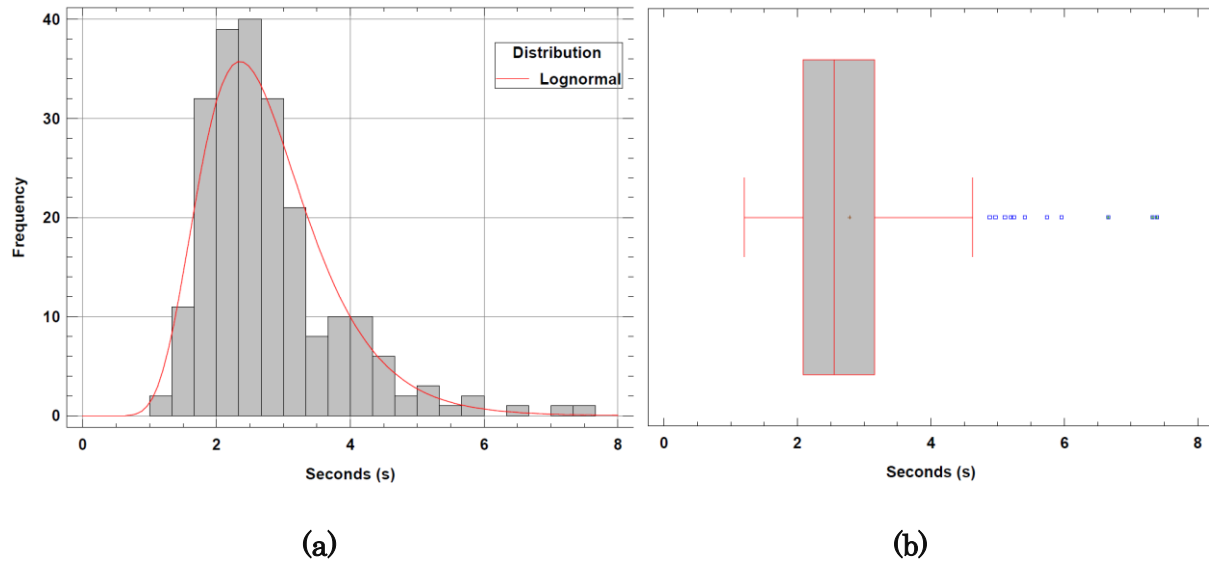


Figure B6. (a) Histogram and (b) boxplot of Pilot communication data.

Figure B7 presents the quantile plot of the pilot communications variable. There is similarity between the distribution of the pilot communications variable and the lognormal cumulative distribution function. Therefore, it is shown that these data follow a lognormal distribution.

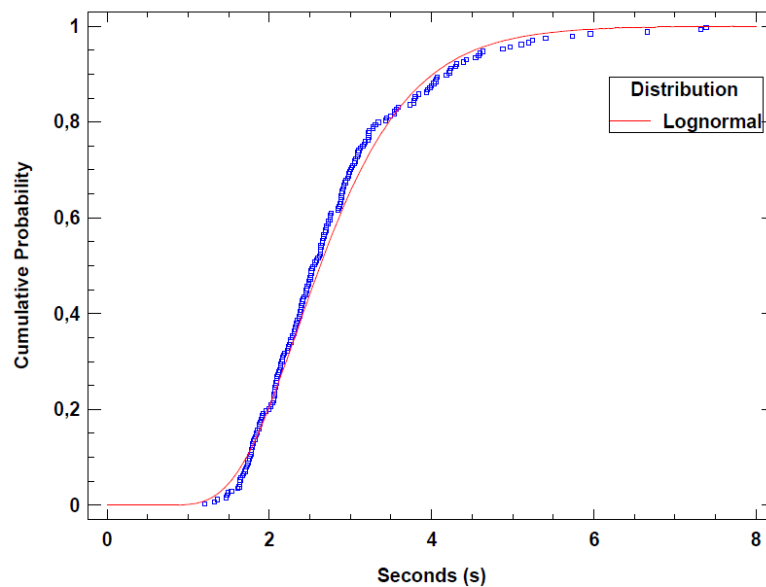


Figure B7. Quantile plot for Pilot communication data.

Table B4 presents the statistics for this variable. The μ value is 2.78s and the σ is 0.95s. These data agree with those recorded by ENAIRE [138]. The P-value from the Kolmogorov-Smirnov test is 0.57, which is greater than 0.05, meaning that the hypothesis that these data come from a Lognormal distribution cannot be rejected with 95% confidence.

Table B4. Statistics and Kolmogorov Smirnov test, Pilot communication data.

Statistics	Lognormal
Average	2.7755
Standard Deviation	0.94825
Log Scale. Median	0.965632
Log Scale. Standard Deviation	0.332265
Kolmogorov-Smirnov	
DMAS	0.0524191
DMENOS	0.0384523
DN	0.0524191
P-value	0.575298

Nevertheless, as with ATCO communications, data processing is performed to delete certain terms that would not exist in an urgent communication. For instance (invented callsigns):

“FLY TO ADINO, THANK YOU, TAP123”

o

“ASCENDEMOS A NIVEL DE VUELO 360, IBE123, ¿Y, ALGUNA POSIBILIDAD DE IR HACIA SIE?”

The terms "Thank you", “¿Y alguna posibilidad de ir hacia SIE?”, would not be used in an urgent avoidance manoeuvre communication. Therefore, the 222

Pilots' communication data have been reprocessed to remove the time duration corresponding to these terms. The new results are presented below.

Figure B8a shows the histogram and Figure B8b the boxplot of the treated pilot communications variable. As before, after fitting the distributions, the data fit the Lognormal distribution. This is consistent with the results due to the very nature of the readback procedure. Since the pilot merely repeats the ATCO instruction, he/she can hardly add much additional information beyond a "Thank you very much". Consequently, the variation of these processed data regarding those pilot data measured previously does not differ much. In fact, the biggest difference is in the tails of the distribution, with outliers being those above 3.9s.

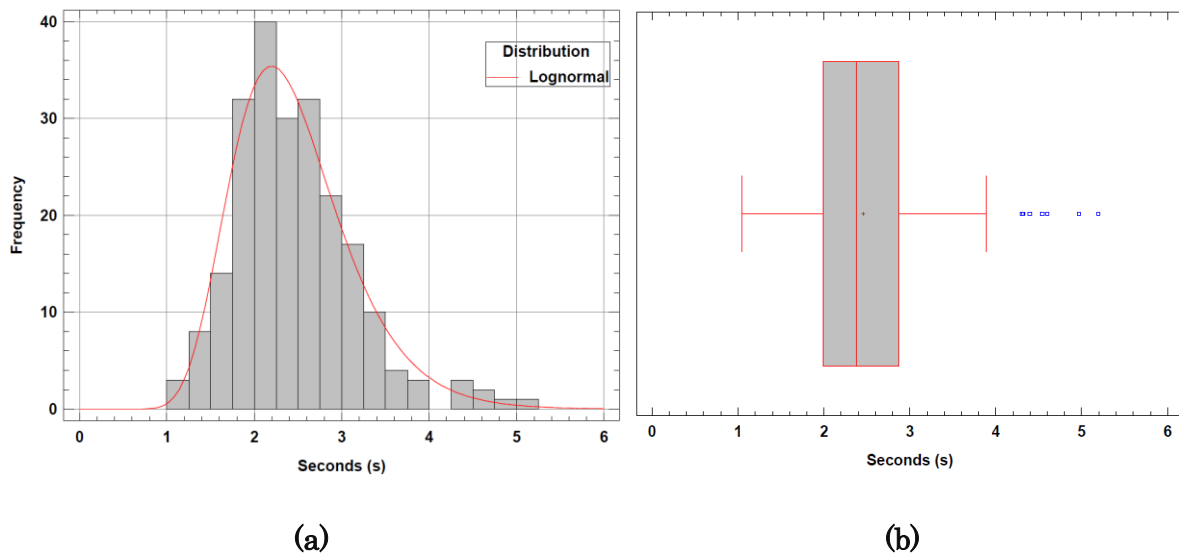


Figure B8. (a) Histogram and (b) boxplot of treated Pilot communications data.

Figure B9 shows the quantile plot in which the similarity between the distribution of the treated Pilot communications variable and the lognormal cumulative distribution function is presented. Both distributions are practically identical, as the values of the treated Pilot communications variable match with the values of the lognormal cumulative distribution function. Therefore, these data follow a lognormal distribution.

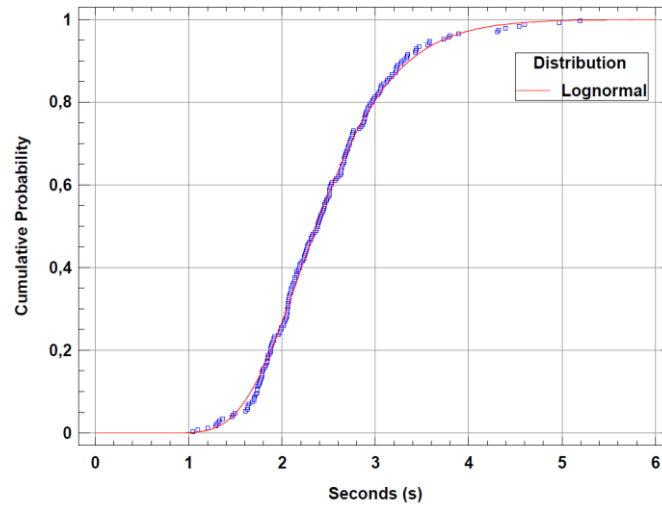


Figure B9. Quantile plot for treated Pilot communications data.

Finally, Table B5 shows the statistics of the distribution of the treated Pilot communications. The data corresponding to the Kolmogorov Smirnov test (P-value) confirm that it is not possible to reject the hypothesis that come from a lognormal distribution (95% confidence).

The μ is 2.46s and the σ is 0.69s. Therefore, 99.7% of the data ($\mu + 3\sigma$) corresponds to a value of 4.5s. It is guaranteed that 99.7% of the treated Pilot communications variable data will be less than 4.5s. This value shall be the one used in the Ad Hoc separation concept for the Pilot communication.

Table B5. Statistics and Kolmogorov Smirnov test treated Pilot communications data.

Statistics	Lognormal
Average	2.45997
Standard Deviation	0.686939
Log Scale. Median	0.862603
Log Scale. Standard Deviation	0.274022
Kolmogorov-Smirnov	
DMAS	0.0251495
DMENOS	0.0358661
DN	0.0358661
P-value	0.937618

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ANNEX C. ANALYSIS OF THE CONTRIBUTING FACTORS TO A LOS

This annex provides an analysis of the factors contributing to the separation minima. The ICAO defined this influence theoretically in [13]. Nevertheless, in this study the aim is to quantify this influence in order to build the ADSM model from these results. For this reason, a data-driven approach was followed together with expert judgement. Based on the Bayesian Network (BN) model, this influence is studied.

The work presented in this chapter is based on the following paper:

Lidia Serrano-Mira, Marta Pérez Maroto, Eduardo S. Ayra, Javier A. Pérez-Castán, Schon Z. Y., Víctor Gordo Arias, Luis Pérez Sanz. Identification and Quantification of Contributing Factors to the Criticality of Aircraft Loss of Separation. *Aerospace* 2022, 9, 513. <https://doi.org/10.3390/aerospace9090513>

C.1 Introduction

The ICAO [13] establishes in a theoretical way the factors to be considered for the determination of the separation minima. However, it does not propose any formula or model to determine the separation values in a radar scenario. Therefore, the following study analyses the influence on the separation minima of these factors defined theoretically.

The separation minima are a barrier to collision. Thus, a priori, there should be a relation between the factors contributing to the collision and the separation minima. However, since the occurrence of collisions is extremely rare (low-

frequency but high-consequence occurrences [139]), data are scarce. For this reason, it is decided to work with separation infringements, since, although infrequent as well, they occur more often than collisions.

A LOS is a situation in which prescribed separation minima is not maintained between aircraft [140]. It is considered by EUROCONTROL as one kind of incident, *inter alia* (Near CFIT, aborted take-off and so on). An incident is an occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operations [140]. Not all incidents are equally critical. The ICAO [141] and EUROCONTROL [142] established five categories of incidents depending on the severity of ATM related occurrences affecting the safety of the aircraft: serious incident (A), major incident (B), significant incident (C), not determined (D) and no safety effect (E). However, the criteria defining the severity of an incident seem to be unclear, as they encompass several aspects such as minimum separation achieved, ATCO or crew actions, kinematic factors and safety nets performance, among others.

An observation should be made regarding studies of contributing factors in ATM incidents/accidents. From data analysis, information about contributing factors may be available when the incident or accident has occurred, but situations where these factors have been present but have not triggered an incident/accident are not known. For this reason, the aim of this analysis is to identify those factors that contribute to the criticality of a LOS (how close the LOS has come to become a collision) based on BN. To this end, a new absolute metric called “LOS criticality” has been defined which is based solely on the minimum distance reached during the encounter between the pair of aircraft.

C.2 Methodology

The methodology followed for this analysis is reflected in the following flowchart (Figure C1). The first step is the collection and processing of data from official incident reports and the building of the database. In the second step, the definition of the study variables is performed. An exploratory data analysis (EDA) of these variables is conducted to get a better understanding of their behaviour. In the third step the network is constructed qualitatively (structure)

and quantitatively (conditional probabilities). Finally, the model is validated using the software's validation functionality and expert verification on the results obtained.

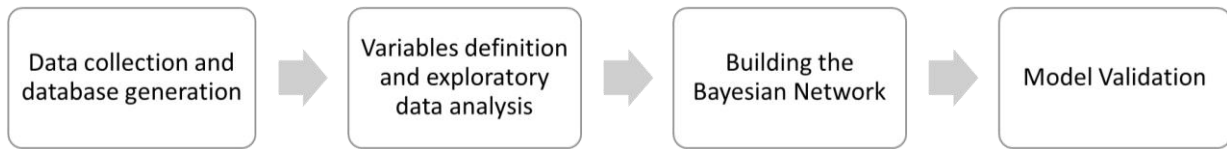


Figure C1. Methodology steps for the generation of the model.

C.2.1. Data collection and database generation

Reporting and investigation of aircraft incidents are relevant and essential elements in the Safety Management System of ATM. They provide fundamental information that allows the identification of risks and the detection of common patterns. In this way, it is possible to optimize efforts for safety improvements. For this dataset building, incidents published in the period 2012-2019 by the Spanish state commission were studied. Incident reports generally follow a publication pattern according to the ICAO's considerations [14], in which three different parts are distinguished:

- Scenario-related information (date and time, airspace where it occurred, meteorological conditions, aircraft models, etc.), communications (crew—ATCO) and radar traces.
- Extracts of the testimonial reports of the agents involved: crew and ATCO.
- Rating of the incident (severity and frequency), conclusions and recommendations.

The ATM incident investigation reports published within the study period were considered and classified according to three main categories specified by EUROCONTROL in ESARR 2 (EUROCONTROL Safety Regulatory Requirement) [143]: incident category (AIRPROX), type of flight (commercial traffic) and incident severity (A (serious) or B (major)), according to the classifications established in [142].

Since the scope of this study is restricted to the analysis of serious and major incidents between aircraft pairs in ENR airspace (only commercial traffic was considered, excluding Visual Flight Rules (VFR) traffic and military aviation), the first screening was filtered. The resulting incidents kept for study were only those involving just two aircraft and taking place in sectors corresponding to ENR airspaces, where the separation minima prescribed are 5NM in the horizontal dimension and 1000ft in the vertical dimension.

For the extraction, classification and temporal organization of the contributing factors, the Systemic Occurrence Analysis Methodology (SOAM) was used. According to [144], this is a common methodology for the identification of causal factors across the aviation industry. It is a modification from Reason's Model, studied by Licu et al. [145] and validated by EUROCONTROL, which allows human involvement to be considered in the analysis of accidents and to detect the deeper latent conditions of the organization that set the context for the event. Finally, the database was made up of 82 incidents (out of a total of 560 incidents, most of them involving VFR traffic), as these were the ones that fulfilled the established conditions.

C.2.2. Definition of the Research Variables and Exploratory Data Analysis

This section is divided into two subsections. First, a description is given of the variables considered in the research, which constitute the database. Subsequently, an exploratory analysis of these variables is performed.

C.2.2.1. Definition of the Research Variables

From the database generated, the following 14 variables were considered:

- ***Month***: in which the incident occurred.
- ***Year***: in which the incident occurred.
- ***Time slot***: time period during the day in which the incident occurred (Coordinated Universal Time, UTC time).
- ***Weather conditions***: existing when the incident occurred.

- ***Airspace***: ACC where the incident took place (ACC 1, ACC 2, ACC 3 and ACC 4). The name of the ACC is ordered from 1 to 4 according to the traffic volume in each ACC, with ACC 1 being the one with the highest traffic and ACC 4 the one with the lowest traffic during the study period.
- ***Communication issues***: technical failure or error related to the communication system, such as frequency failure (connection of Push to Talk pedal, PTT), poor transmission/reception quality, congestion, etc.
- ***ATCS ergonomics***: Automated ATC System ergonomics. This software is used by ANSP for ATM through the provision of ATS. This factor refers to the range of colours in which information is presented by Automated ATC System in the screen of the ATCO work position. It is considered because it has been proven during the incident analysis that the ergonomic configuration of the system sometimes leads to confusion for the ATCO (e.g., the colour of the labels for aircraft assumed, not assumed, transferred, etc.). This is mentioned several times by ATCOs in the testimonial part of the incident reports. Therefore, no value judgments have been made for the recording of this variable.
- ***STCA***: Short Term Conflict Alert Tool for CD by ATCO. It is a system which supports ATCO to detect conflicts (a situation in which separation minima could be compromised) and separation infringements. The system issues a conflict alert (PAC) based on predictions and a violation LOS alarm (Conflict Alert: Violation, VAC) when the separation infringement has taken place.
- ***TCAS***: On-board system which issues a TA alert and a RA alarm.
- ***ATC error***: it refers to an error made by ATC that contributed to the occurrence of the LOS. It has been extracted from the analysis and investigation of the reports applying the SOAM methodology.
- ***Crew error***: it refers to an error made by the crew that contributed to the occurrence of the LOS. It has been extracted from the analysis and investigation of the reports applying the SOAM methodology.
- ***Encounter geometry***: as a function of the angle between tracks. There are three possible geometries, according to the ICAO PANS-ATM document [14]: same tracks ($-45^\circ < \alpha < 45^\circ$), opposite tracks ($135^\circ < \alpha < 225^\circ$) or convergent tracks ($45^\circ < \alpha < 135^\circ$). Since this information is vague in the

reports and the geometry between aircraft is only mentioned theoretically as “crossing, same or reciprocal track”, the angle between tracks has been studied to validate the classification, based on the trajectories simulated by RAMS Plus software [119].

- ***Sector overload:*** situation in which the number of aircraft in the sector, at the time of the incident, exceeded the declared capacity of the sector. This information has been extracted from the ATCOs’ testimonial extracts from the incident reports analysed. To make this variable more objective, this information has been contrasted with that obtained in NEST tool [118], a simulation software developed by EUROCONTROL, on the state of the sector at the time of the incident. Only those cases in which NEST showed that the sector was overloaded were recorded in the dataset.
- ***LOS Criticality:*** metric related to the severity of the LOS. This variable refers to how close the LOS has come to being a collision. It is an indicator associated with the minimum horizontal and vertical separation reached in the LOS, with values ranging from 0 to 1. The steps followed for the definition of this metric are:
 1. Definition of ten equal length intervals in the ranges 0–5NM and 0–1000ft. The lower limit of the range refers to the distance of 0 (NM or ft) between aircraft (collision) while the upper limit corresponds to the separation minima values in the horizontal (5NM) and vertical (1000ft) dimensions for ENR airspace. In the horizontal dimension the intervals are in 0.5NM increments, while in the vertical dimension they are 100ft.
 2. Normalisation (scale of 0–1) of the horizontal intervals (Sep_{NormH}) and vertical intervals (Sep_{NormV}) (Equation (32)).

$$Sep_{NormH} = \frac{Sep\ Int_H}{Sep\ min_H}, \quad Sep_{NormV} = \frac{Sep\ Int_V}{Sep\ min_V} \quad (32)$$

where:

$Sep Int_H$ = upper limit value of the interval (first column of the array in Figure C2) in the horizontal dimension.

$Sep Int_V$ = upper limit value of the interval (first row of the array in Figure C2) in the vertical dimension.

$Sep min_H$ = Separation minima in the horizontal dimension (5NM).

$Sep min_V$ = Separation minima in the vertical dimension (1000ft).

3. Calculation of the oblique distance, from Equation (33), between the values obtained in the previous step. These values are shown in Figure C2.

$$Oblique\ distance = \sqrt{(Sep_{NormH})^2 + (Sep_{NormV})^2} \quad (33)$$

Sep Int # (NM)	Sep Int v (ft)	0	100	200	300	400	500	600	700	800	900	1000
	Sep Norm V Sep Norm H	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0	0	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
0.5	0.1	0.1	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1	0.2	0.2	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.9	1.0
1.5	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.7	0.8	0.9	0.9	1.0
2	0.4	0.4	0.4	0.4	0.5	0.6	0.6	0.7	0.8	0.9	1.0	1.1
2.5	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.8	0.9	0.9	1.0	1.1
3	0.6	0.6	0.6	0.6	0.7	0.7	0.8	0.8	0.9	1.0	1.1	1.2
3.5	0.7	0.7	0.7	0.7	0.8	0.8	0.9	0.9	1.0	1.1	1.1	1.2
4	0.8	0.8	0.8	0.8	0.9	0.9	0.9	1.0	1.1	1.1	1.2	1.3
4.5	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.1	1.1	1.2	1.3	1.3
5	1	1	1.0	1.0	1.0	1.1	1.1	1.2	1.2	1.3	1.3	1.4

Figure C2. Oblique distance between interval ranges.

4. The criticality array is obtained by normalising the array obtained in step 3 (since the highest value is $1.4 \approx (\sqrt{2})$, this is the one used for normalisation) and subtracting unity from all values, according to Equation (34).

$$LOS\ Criticality = 1 - \left(\frac{Oblique\ distance}{\sqrt{2}} \right) \quad (34)$$

where:

Oblique distance = obtained in the previous step

$$\sqrt{2} \approx 1.4 = \text{value used to normalise the array, because of}$$

$$\sqrt{\left(\frac{5NM}{5NM}\right)^2 + \left(\frac{1000ft}{1000ft}\right)^2}$$

Figure C3 shows the criticality array obtained, in which a heat map has been generated, which is similar to a risk matrix for this indicator. Values closer to 1 indicate that the separation minima reached in the encounter between aircraft pair was very small and a near-collision occurred. Values close to 0 indicate that the separation minima between the aircraft were practically not violated. Thus, the LOS criticality is classified as:

Minor – [0.01, 0.29] Hazardous – [0.50, 0.69]

Major – [0.30, 0.49] Catastrophic – [0.70, 1.00]

Vert Sep (ft) Horiz Sep (NM)	0	100	200	300	400	500	600	700	800	900	1000
0	1,0	0,9	0,9	0,8	0,7	0,6	0,6	0,5	0,4	0,4	0,3
0,5	0,9	0,9	0,8	0,8	0,7	0,6	0,6	0,5	0,4	0,4	0,3
1	0,9	0,8	0,8	0,7	0,7	0,6	0,5	0,5	0,4	0,3	0,3
1,5	0,8	0,8	0,7	0,7	0,6	0,6	0,5	0,5	0,4	0,3	0,3
2	0,7	0,7	0,7	0,6	0,6	0,5	0,5	0,4	0,4	0,3	0,2
2,5	0,6	0,6	0,6	0,6	0,5	0,5	0,4	0,4	0,3	0,3	0,2
3	0,6	0,6	0,5	0,5	0,5	0,4	0,4	0,3	0,3	0,2	0,2
3,5	0,5	0,5	0,5	0,5	0,4	0,4	0,3	0,3	0,2	0,2	0,1
4	0,4	0,4	0,4	0,4	0,4	0,3	0,3	0,2	0,2	0,1	0,1
4,5	0,4	0,4	0,3	0,3	0,3	0,3	0,2	0,2	0,1	0,1	0,0
5	0,3	0,3	0,3	0,3	0,2	0,2	0,2	0,1	0,1	0,0	0,0

Figure C3. Risk array for LOS criticality.

Therefore, the criticality of the incidents analysed is obtained from the minimum separation reached in each LOS (Equation (35)) and the categories defined from the risk array (Figure C3).

$$LOS\ Criticality = 1 - \left(\frac{\sqrt{\left(\frac{Sep\ LOS_H}{Sep\ min_H}\right)^2 + \left(\frac{Sep\ LOS_V}{Sep\ min_V}\right)^2}}{\sqrt{\left(\frac{Sep\ min_H}{5NM}\right)^2 + \left(\frac{Sep\ min_V}{1000ft}\right)^2}} \right) \quad (35)$$

where:

$Sep\ LOS_H$ = horizontal separation reached in the LOS between aircraft pair.

$Sep\ LOS_V$ = vertical separation reached in the LOS between aircraft pair.

$Sep\ min_H$ = Separation minima in the horizontal dimension, 5NM.

$Sep\ min_V$ = Separation minima in the vertical dimension, 1000ft.

For instance, for the case of a separation infringement in which the minimum separation between aircraft was 3NM and 600ft the criticality would be, according to Figure C3 and Equation (35).

$$LOS\ Criticality = 1 - \left(\frac{\sqrt{\left(\frac{3\ NM}{5\ NM}\right)^2 + \left(\frac{600\ ft}{1000\ ft}\right)^2}}{\sqrt{\left(\frac{5\ NM}{5\ NM}\right)^2 + \left(\frac{1000\ ft}{1000\ ft}\right)^2}} \right) = 0.4 \quad \text{MAJOR Criticality}$$

Other factors do not constitute the current database (such as surveillance or navigation errors) as no cases were found in the analysis of incidents where these appear as contributing elements to a LOS.

C.2.2.2. Exploratory Data Analysis (EDA)

The purpose of exploratory data analysis is to obtain information about the data and to extract knowledge from an initial analysis of the sample using statistical methods and graphical tools. As this database consists of discrete variables, the exploratory analysis of the data is limited only to the frequency of the different states of the variables. In this part of the study, first an analysis of the frequency of the different states of each variable is presented. Afterwards, other analyses were performed (analysis of the time distribution, spatial distribution, geometry of the encounter, etc.) which were important to understand certain results of the BN model.

- Study of the frequency of the states of some variables.

Table C1 lists the frequency distributions of the variables describing the characteristics of the LOS scenario: airspace, encounter geometry, weather conditions and sector overload. This analysis was useful to contextualize the incidents. It can be seen from Table C1 that the number of incidents in ACC 1 (highest traffic volume) is almost double that of ACC 2. Moreover, it is observed that most incidents occurred in good weather and when sectors were not overloaded. In addition, in most of the incidents the aircraft were on reciprocal (opposite) tracks.

Table C1. Frequency distributions for qualitative variables which describe scenario characteristics.

Airspace	Frequency	%
<i>ACC 1</i>	45	54.8
<i>ACC 2</i>	26	31.7
<i>ACC 3</i>	8	9.8
<i>ACC 4</i>	3	3.6
Encounter Geometry	Frequency	%
<i>Convergent tracks</i>	27	32.9
<i>Reciprocal tracks</i>	41	50.0
<i>Same tracks</i>	14	17.1
Weather Conditions	Frequency	%
<i>Thunderstorm</i>	9	11.0
<i>Turbulence</i>	3	3.7
<i>Non-Relevant</i>	70	85.3
Sector Overload	Frequency	%
<i>Yes</i>	5	6.1
<i>No</i>	77	93.9

Table C2 lists the frequency distributions of the variables describing the safety nets behaviour. Since ENR incidents were analysed, the safety nets considered were the STCA system and the TCAS system. The objective of these systems is to prevent a precursor from becoming a collision. For this reason, it is important to know how they have performed. Regarding the TCAS system, the total number of triggered Traffic Alerts (TA), Resolution Alerts (RA) and when the system has not been activated is considered. About STCA, which is the system that supports the ATCO task for conflict detection, the parameters considered concern the triggered Conflict Alert (PAC), LOS Alarm (VAC), alerts triggered but ignored by ATCO, if the system was inhibited in the airspace, failures of the system and alert omissions.

Table C2. Frequency distributions for qualitative variables which describe the safety nets behaviour.

TCAS	Frequency	%
<i>TA</i>	16	19.5
<i>RA</i>	61	74.4
<i>Non TCAS</i>	5	6.1
STCA	Frequency	%
<i>PAC</i>	8	9.8
<i>VAC</i>	60	73.1
<i>Ignored</i>	3	3.7
<i>Inhibited</i>	1	1.2
<i>System Failure</i>	5	6.1
<i>Non STCA</i>	5	6.1

Table C3 lists the frequency distributions of the variables associated with the HF and the technical systems. On the one hand, the frequency of crew and ATCO errors is studied. The ATC error is greater than the crew error. This is because the responsibility for the exercise of separation lies on the ATCO, while the crew generally follows the instructions issued by the

ATCO. On the other hand, the variables associated with the technical systems are related to the communication issue and the Automated Air Traffic Management System. The latter variable is not so much related to software errors as to the ergonomics of the system, which misleads the ATCO on some occasions.

Table C3. Frequency distribution of the node states representing the causal factors of the incidents.

Crew Error	Frequency	%
<i>Yes</i>	15	18.3
<i>No</i>	67	81.7
ATC Error	Frequency	%
<i>Yes</i>	80	97.6
<i>No</i>	2	2.4
Communication Issues	Frequency	%
<i>Contributing Factor</i>	4	4.9
<i>Non-Contributing Factor</i>	78	95.1
ATCS Ergonomics	Frequency	%
<i>Contributing Factor</i>	8	9.8
<i>Non-Contributing Factor</i>	74	90.2

Finally, Table C4 lists the frequency distributions of the target variable, which is LOS criticality. From the values of the minimum horizontal and vertical separation of each LOS, the four criticality states of the variable have been obtained. It is noteworthy that the criticality of the majority of incidents corresponds to the Minor and Major categories.

Table C4. Frequency distribution of the target node LOS Criticality variables.

LOS Criticality	Frequency	%
<i>Minor</i>	22	26.8
<i>Major</i>	35	42.7
<i>Hazardous</i>	19	23.2
<i>Catastrophic</i>	6	7.3

- Temporal and spatial distribution of incidents

Data analysis by month, season, time slot and ACC are shown in Figure C4. The temporal distribution of incidents by month does not demonstrate a clear relation between the number of incidents and the amount of traffic. However, this relation is clearer if the analysis is performed by season. It is shown that during the winter season (November–March) the number of LOS is lower than in the summer season (April–October). Moreover, it is observed that the occurrence of incidents during the morning and midday is higher than during the rest of the day, in line with the fact that the peak traffic hours in the sectors are during the morning period. At night, there are clearly fewer problems, as there is almost no traffic. Finally, in line with Table C1 it can be seen that the highest number of incidents corresponds to the ACC with the most traffic. A preliminary hypothesis, to be confirmed by the model, yields that the number of incidents is proportional to the volume of traffic, as expected.

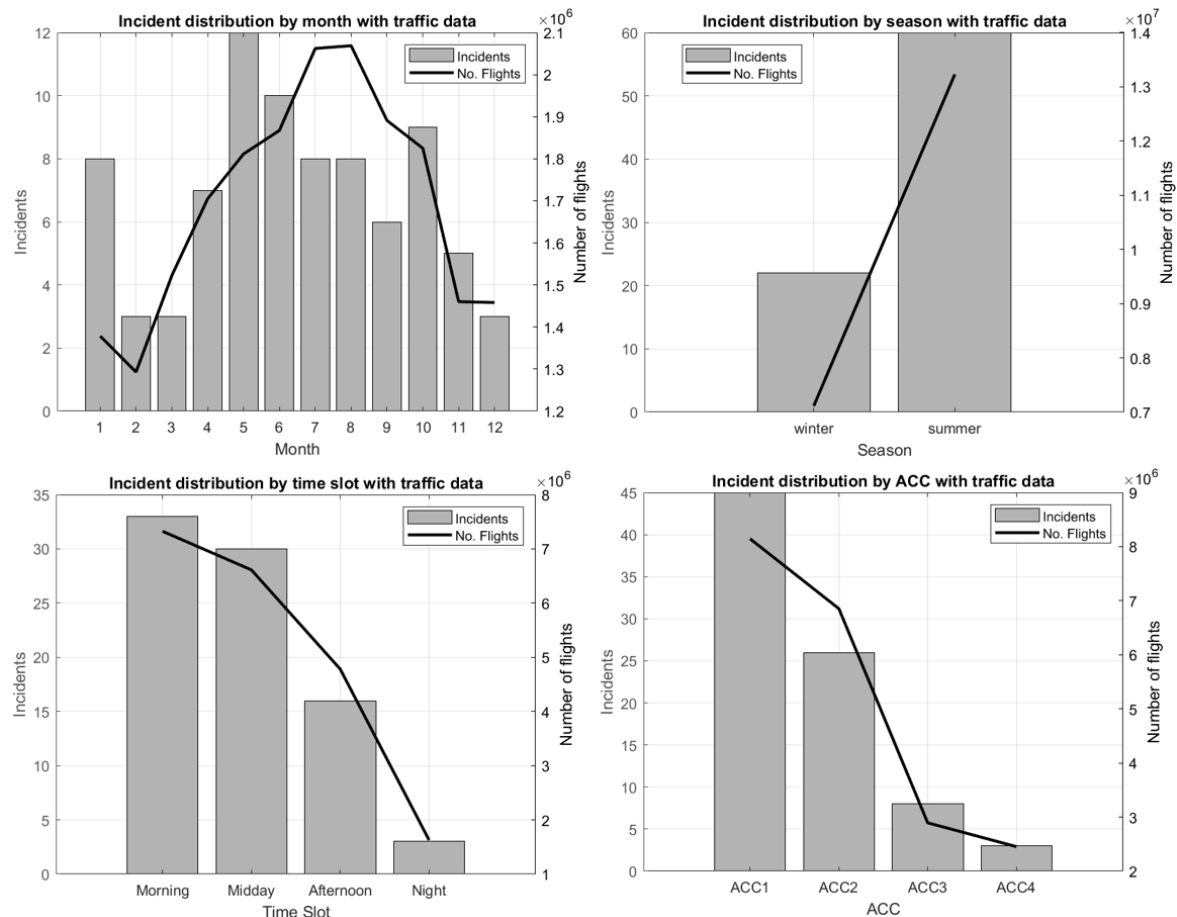


Figure C4. Distribution of incidents by month, season, time slot and ACC.

- Incident analysis by sector in the studied ACCs

Table C5 shows the results obtained from the characterisation of incidents according to where they occurred, that is, whether in a single control sector or they occurred in different sectors as a result of poor coordination. In this second category, poor coordination may have occurred between two sectors of the same ACC (also within this category it has been differentiated whether these sectors were upper - lower), or between sectors of different ACCs. This analysed information is relevant. It is possible to know from this point of view about the behaviour of the different ACCs and to detect possible hot spots.

Table C5. Incident characterisation according to where it occurred (single control sector/more than one sector involved).

ACC 1	Frequency	%
<i>LOS within the same sector</i>	33	71.7
<i>LOS between different sectors</i>	13	28.3
Coordination		
<i>Upper sector - Lower sector</i>	2	15.4
<i>Both sectors of ACC 1</i>	7	53.8
<i>ACC 1 - and other ACC</i>	4	30.8
ACC 2	Frequency	%
<i>LOS within the same sector</i>	25	78.2
<i>LOS between different sectors</i>	6	18.8
Coordination		
<i>Upper sector - Lower sector</i>	1	16.7
<i>Both sectors of ACC 2</i>	1	16.7
<i>ACC 2 – and other ACC</i>	4	66.6
ACC 3	Frequency	%
<i>LOS within the same sector</i>	8	88.9
<i>LOS between different sectors</i>	1	11.1
Coordination		
<i>ACC 3 - and other ACC</i>	1	100.0
ACC 4	Frequency	%
<i>LOS within the same sector</i>	3	100.0

- Analysis of incident encounter geometry

For each incident included in the dataset, the angular difference between the tracks of the pair of aircraft was analysed from the trajectories in RAMS Plus. It is observed (Figure C5) that in most of the incidents the angle between tracks is 180°. In the case of reciprocal tracks, angular differences between 135° and 149° are also frequent. The most frequent range of angles when the tracks are convergent is 105°–120°, while for same tracks it is 0°. From the model it will be possible to deduce how the geometry of the encounter affects the criticality of the incident. Likewise,

this information is beneficial to be able to establish future mitigation measures in order to reduce the probability of occurrence of an incident.

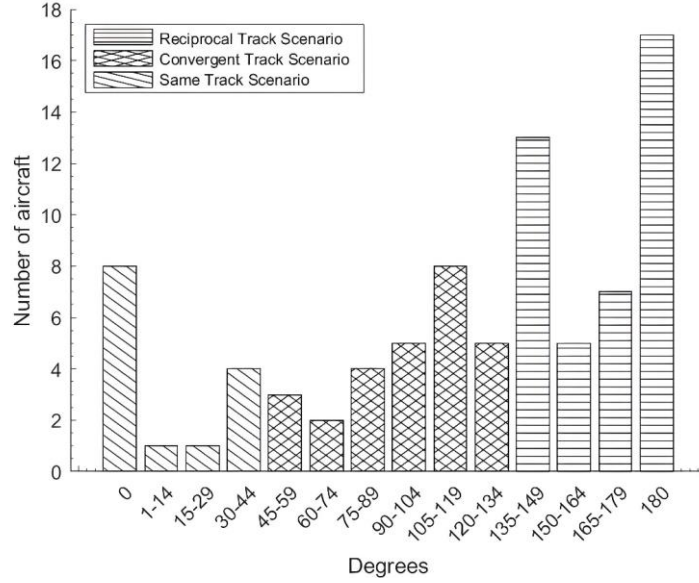


Figure C5. Angles between tracks for the different encounter geometries.

C.2.3. Building the BN

A probabilistic causal model was used to study the problem: BN. A BN can be described, qualitatively, as a Directed Acyclic Graph (DAG). A DAG is a pair $G=(V,E)$, where V is a set of nodes and E is a set of arcs defined over the nodes. The nodes represent variables and are connected to each other by directed arcs. They start at the parent node and are directed to the child node. From a quantitative viewpoint (Equation (36)), in a BN the probabilistic relationships between nodes are determined by a joint probability density function $F(V)$. This joint probability density function is visualised by the Conditional Probability Tables (CPT) that constitute the probabilistic structure of the network. An edge in a BN shows a probabilistic dependency between two nodes; however, it does not imply a causality relation between them because causality is a relation, which cannot be defined only from the joint distribution [146].

$$F(V_1, \dots, V_N) = \prod_{i=1}^N F(V_i | \text{Parent}(V_i)) \quad (36)$$

There are three main approaches to build a BN. The first approach is solely on the basis of expert judgment in which the network is constructed from human knowledge. The second is based on some learning algorithm which, applied on a database, establishes the relationships between the nodes. Finally, the third approach consists of merging the first and the second approaches. Increasingly, this last approach is being used especially for modelling very low frequency problems and it is the one used in this study. Thus, the model has been built from the data (incidents database) and the experts' judgment (aerospace engineers, flight crews and ATCOs).

Having briefly referred to the BN methodology, the building of the BN is now explained. For the BN model constitution, a process called Expert-based Knowledge Engineering of BN (EKEBN) [147] was followed; this technique has been employed in other projects to detect the ATC complexity metrics [148]. It consists of two main steps: (1) expert-based structure building and (2) incidents database feeding uncertainty quantification.

1. Expert-based structure building provides the identification of all variables and causal correlations between them, as well as their states, that can be taken. Based on the identification of the variables by the experts, the list of research variables defined in the previous section is generated. This means that a part of the research variables has been obtained directly from the incident reports and other variables, such as those related to Human Errors or LOS Criticality, have been identified or generated by expert knowledge. The identification of the causal correlation by expert knowledge among defined research variables has been considered a fundamental step for posterior BN building in GeNIe software [149], particularly in definition of the BN architecture. This identification process has been repeated several times until the experts removed the inconsistencies and discrepancies, as explained in [147], [148]. From this step, 14 variables have been considered relevant for the model building. Table C6 shows, in summary form, for each variable chosen as a node in the model, the number of states and their descriptions. As a result, the BN structure was built as shown in Figure C6.
2. Incidents database feeding uncertainty quantification basically deals with the CPT estimation combining incidents database with expert-based BN architecture approach. In contrast to other similar research works like

[150], [151], [152], this CPT estimation has proceeded directly with the incidents database applying the Bayesian Search algorithm provided in GeNIe. The algorithm follows essentially a hill climbing procedure (guided by a scoring heuristic, which in GeNIe is the log likelihood function) with random restarts [153]. The estimated BN, which depicts the nodes, their levels and probabilities, is shown in Figure C7.

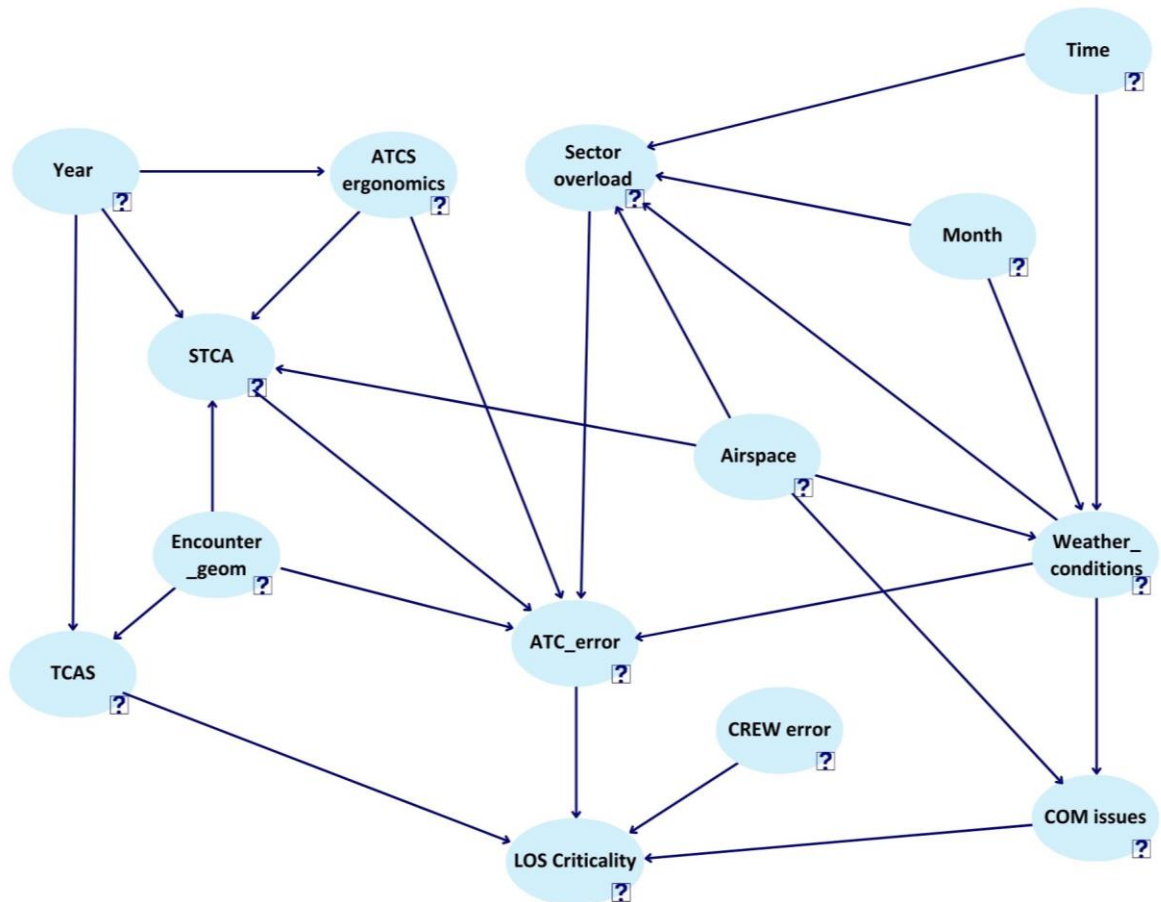


Figure C6. Expert-based BN architecture.

Table C6. Nodes and associated states for incident analysis.

	Node	No. of States	Description of States
1	Month	12	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12
2	Year	8	2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019
3	Time	4	Morning, Midday, Afternoon, Night
4	Weather_ conditions	3	Thunderstorm, Turbulence, Non-Relevant
5	Airspace	4	ACC_1, ACC_2, ACC_3, ACC_4
6	Encounter geometry	3	Reciprocal Track Scenario, Crossing Track Scenario, Same Track Scenario
7	Sector_overload	2	LOS contributing factor, Non-Contributing factor
8	CREW_error	2	LOS contributing factor, Non-Contributing factor
9	ATC_error	2	LOS contributing factor, Non-Contributing factor
10	COM_issues	2	LOS contributing factor, Non-Contributing factor
11	ATCS_ergonomics	2	LOS contributing factor, Non-Contributing factor
12	TCAS	3	TA, RA, No TCAS
13	STCA	6	PAC, VAC, System Failure, Ignored, Inhibited, No STCA
14	LOS Criticality	4	Minor, Major, HAZ, CAT

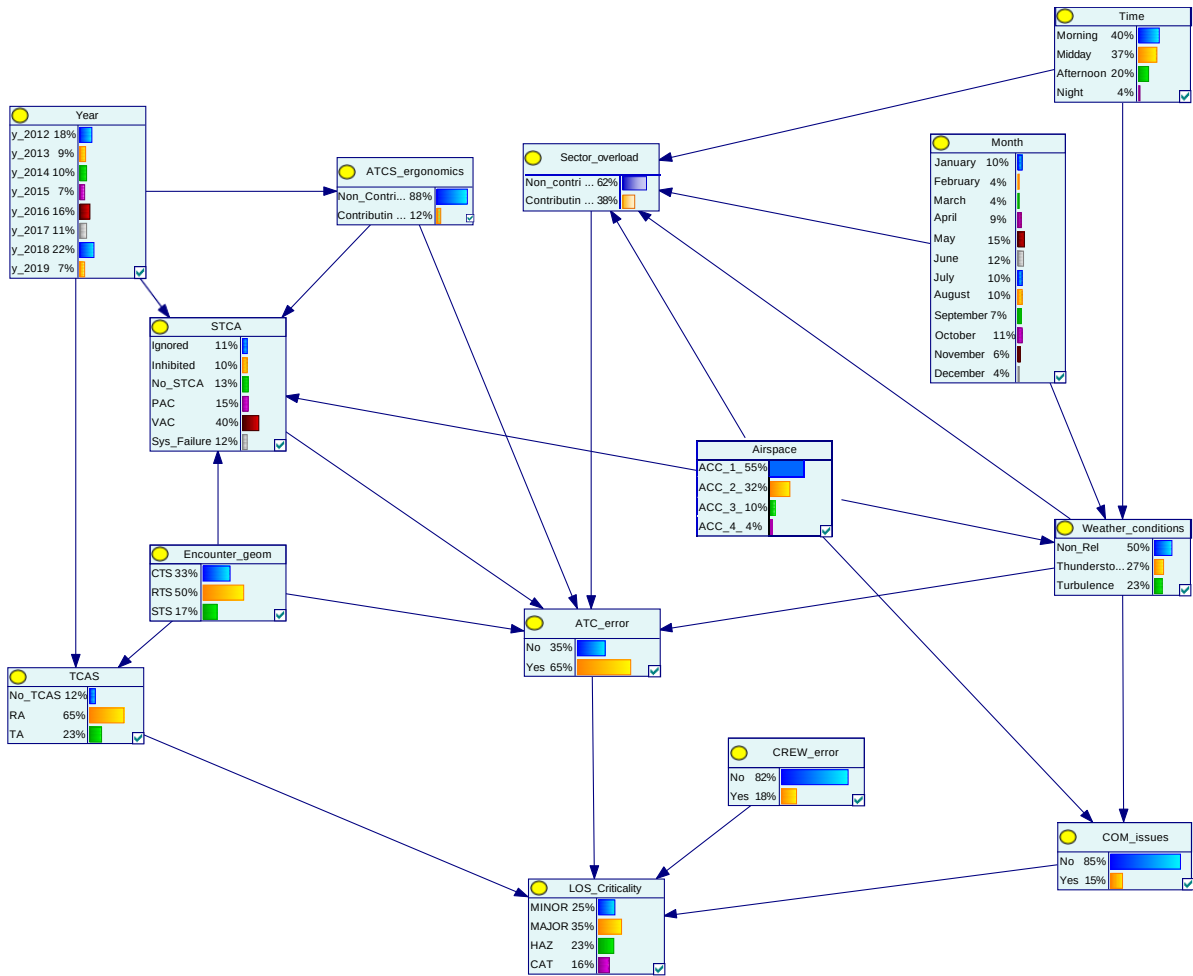


Figure C7. Graphical representation of the BN considered.

In summary, this technique is especially used to model very low frequency problems. In this study the database contains only 82 incident records, so this technique is applicable in this case. Consequently, as a hybrid model, it has been built from data (incident database) and expert judgement (aerospace engineers, flight crews and ATCOs). Therefore, a different model validation process is also required.

C.2.4. Model Validation

In this research, the validation of this hybrid BN model has been divided into two parts:

- 1) Test only validation for expert-based and data-driven consistency in the BN model.
 - 2) Expert-based final validation.
1. Test only validation is a GeNIe software algorithm used specifically to validate expert-based BN models [149], [153]. Particularly, this method has been applied to the BN model to check the consistency between expert-based architecture and data-driven modelling results. Receiver Operating Characteristic curve (ROC Curve) and the Area Under the ROC Curve (AUC) in the target variable (LOS_Criticality) have been calculated to assess the accuracy of this consistency.

In BN, the ROC curves are generally used to depict the model performance [154]. A ROC curve is a graphical tool defined by True Positive Rate (TPR, also called sensitivity) on the vertical axis and the False Positive Rate (FPR, also called specificity) on the horizontal axis. The TPR is defined as the ratio between the total number of correctly identified positive cases (True Positive (TP)) and the total number of positive cases (TP + False Negative (FN)), while the FPR is defined as the ratio of the total number of negative cases incorrectly identified as positive cases (False Positive (FP)) and the total number of negative cases (FP + True Negatives (TN)). The results obtained from validating the model are shown in Figure C8.

It is observed that the highest AUC value is obtained for the CAT state of the target variable. This state is the critical one (representing the transition from a LOS scenario to a MAC scenario); its value is close to 0.85, while for the rest of the states the AUC value is greater than 0.75. According to [155], these scores are high (around 70~80 %). This check result shows the high consistency between expert knowledge and data-driven for the CAT state, which allows us to better understand which factors contribute to a more critical incident (near-collision).

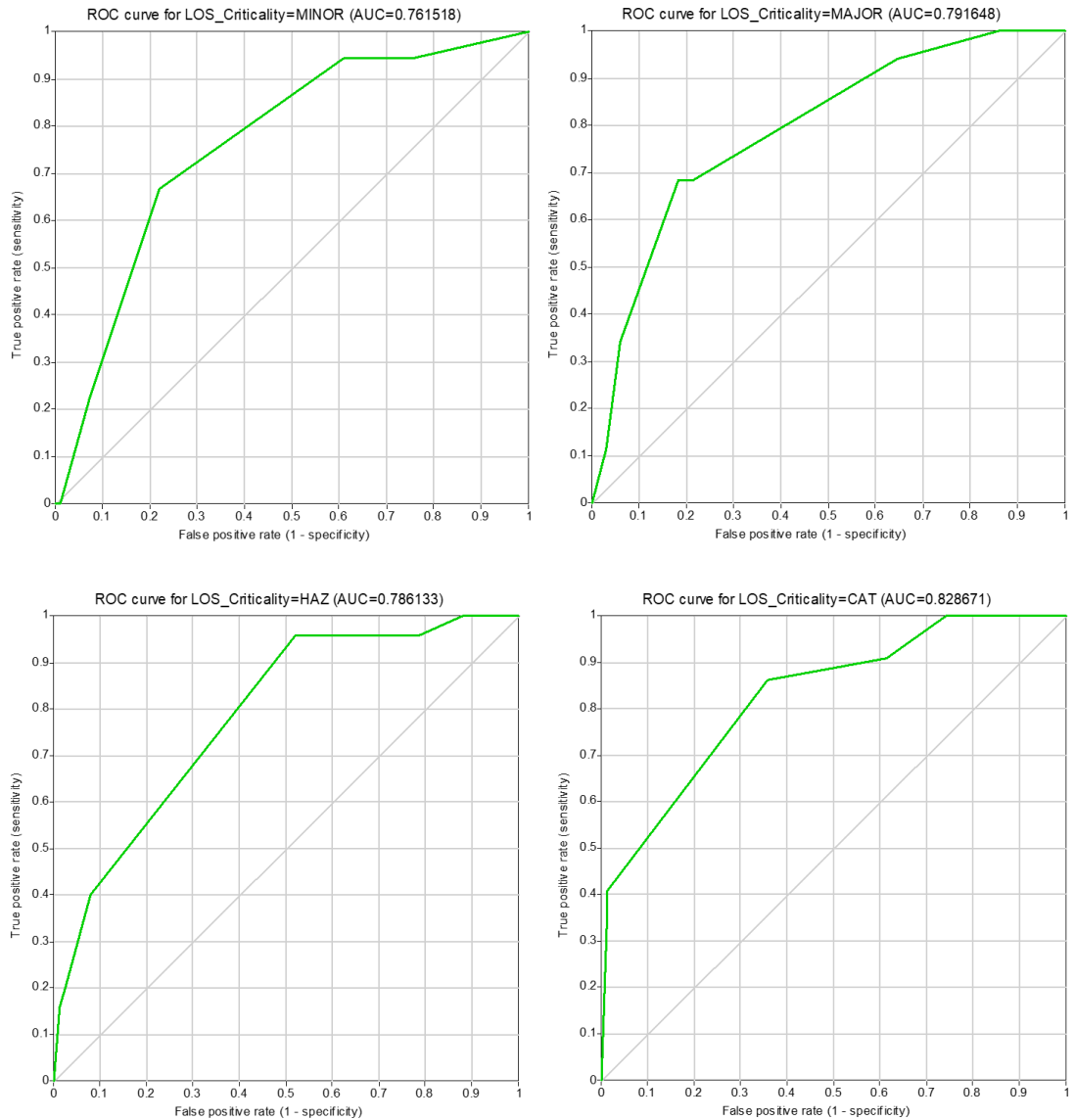


Figure C8. ROC curves of the target variables states for the validation of the model.

2. Expert-based final validation consists of the validation of BN architecture (before applying the incidents database for CPT estimation) and the verification of the BN model once the Test only validation is concluded.

The validation of BN architecture has been concluded as the last step of expert-based structure building described previously. Rather than an isolated validation process, it has been performed as part of the BN structure building process. The experiences of aeronautical engineers, pilots and ATCOs aided in achieving this definitive BN architecture.

In addition to the validation of the model with the specific functionality of the software, expert verification has been applied to the results obtained,

which will be presented in the following section. Since the results obtained from the model are consistent with the expectations of the experts, it is possible to validate the model based on these results.

C.3 Model Results

This section provides the results obtained from the proposed model based on BN and the analysis of the generated database. Regarding the degree of influence of the network nodes on the target variable, the system confirms that the variables with the highest influence on the LOS Criticality target node, as expected, are ATC error, crew error, communications issues and TCAS (Figure C9). Strength of influence is calculated from the CPT of the child node and essentially expresses the distance between various conditional probability distributions over the child node conditional on the states of the parent node [153]. The measure of distance between distributions used has been the Euclidean one.

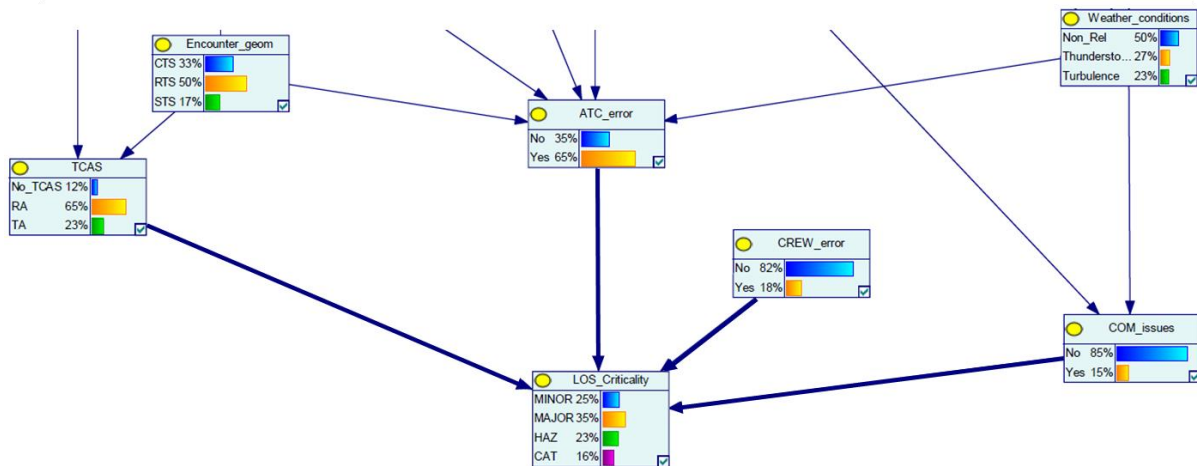


Figure C9. Strength of influence on the node of the target variable.

In BN, after propagating the evidence through the network, conditional probabilities for the levels of any node can be obtained. The probabilities of the different states of the nodes are a consequence of the sample, here 82 incidents. Therefore, the results obtained by fixing evidence (setting probability of 1 to a state of a variable) and as a consequence of the network, must be interpreted, not so much in their numerical value but in the trend or variation that they

experience. On account of this, the following most relevant results can be seen from the model:

- Regarding the target node, by setting the evidence in each of its states it is possible to know the contributing factors to minor, major, HAZ and CAT LOS criticality. It can be shown that the probability of an incident occurring as a result of ATC error is much higher than due to crew error or communications issues in each scenario (Minor, Major, HAZ and CAT), as indicated in Table C7. Due to the BN characteristics and properties, these results must be interpreted independently for each scenario. Results obtained are in accordance with the roles established in a scenario with surveillance: the separation responsibility lies with the ATCO, while the crew is limited to executing the clearances/instructions issued by the ATCO. The probability of a LOS as a result of crew error or due to a communications issue is roughly similar, with the communications issues being slightly lower. However, these results need to be contextualised as they are events with a low probability of occurrence. The current ATM system architecture is configured in a way that minimizes system/technical errors: redundancy of equipment, mandatory and recommended required performances, certification of equipment, certification of manufacturing companies, etc. Furthermore, it is worth considering that in this study, after analysing the incidents that constitute the database, no variables relating to surveillance or navigation have been established because no technical errors in these systems have been found to have given rise to a LOS.

Table C7. HF and COM issues contributing factors' probability for LOS criticality.

LOS Criticality	ATC_Error	CREW_Error	COM_Issues
Minor $P(\text{Minor}) = 1$	66%	20%	14%
Major $P(\text{Major}) = 1$	74%	13%	14%
Hazardous $P(\text{HAZ}) = 1$	64%	25%	14%
Catastrophic $P(\text{CAT}) = 1$	49%	18%	18%

- Focusing on the above contributing factors (setting evidence on ATC_error, CREW_error and COM_issues), it is possible to know the probability of different LOS Criticality scenarios as a consequence of them and the rest of the network. As can be seen (Table C8), when an ATC error takes place, the LOS criticality generally has a low probability of being CAT. However, when a crew error or communication failure takes place, the LOS criticality is slightly more severe (HAZ and CAT). Therefore, it can be stated that the probability of ATC error is more frequent, but its criticality is generally less severe in comparison with other contributing factors. From all these probabilistic results (Table C7 and Table C8) it can be concluded that the influence of technical means is negligible. Therefore, mitigating measures to reduce the risk of a MAC should focus on the HF and particularly on ATC. Thus, the model for the determination of Ad Hoc separation should be based in operational error but not on technical failures.

Table C8. LOS Criticality probabilities related to HF and COM_issues.

	LOS Criticality			
	Minor	Major	HAZ	CAT
ATC_error $P(ATC\_error) = 1$	25%	40%	23%	12%
CREW_error $P(CREW\_error) = 1$	27%	25%	32%	16%
COM_issues $P(COM\_issues) = 1$	23%	35%	22%	20%

- The BN model shows the relation between weather conditions, communication issues and sector overload and the influence on ATC performance. When there are storms or turbulence phenomena, there are, generally, congestion problems; aircraft deviate from their planned routes, producing an overload in certain areas of the sector. Therefore, there is an overload of communications. In these situations, it is observed that while the probability of communications issues increases considerably (compared to when there are no relevant weather phenomena) and the probability of sector overload increases considerably, ATC error decreases moderately (Table C9). This contrast occurs especially with the occurrence of

turbulence. Contrary to what might be expected regarding the ATC error, the model shows that it seems that ATCOs perform better when the situation is more adverse, with the probability of a LOS as a result of the ATC error being lower than in ordinary situations, where overconfidence may occur. Expert opinion (ATCOs and flight crews) confirmed that the most demanding scenarios require maximum concentration, thus reducing the probability of error. Therefore, based on these model results, possible safety-enhancing measures should be aimed at encouraging the HF during the working period and during normal situations to try to pay more attention and to maintain it during the working time.

Regarding the Ad Hoc separation concept, although it is a more demanding concept from the ATC point of view, if the ATCO is provided with a support tool that allows it not to exceed the WL (workload) values, its performance can be satisfactory, since in the light of these results it is observed that in more demanding scenarios the probability of error of the ATC and the crew is lower.

Table C9. Probability relation between nodes Weather_conditions and ATC_error, Sector_overload and COM_issues.

		Weather_Conditions		
		Non_Relevant $P(Non\_rel) = 1$	Thunderstorm $P(Thunderstorm) = 1$	Turbulence $P(Turbulence) = 1$
ATC_error	Yes	72%	62%	54%
Sector_overload	Yes	30%	45%	53%
COM_issues	Yes	4%	20%	31%

It is relevant to know the contribution of the performance of the existing barriers (safety nets: STCA and TCAS) in the defined LOS categories. As stated by ICAO [22] safety nets existence should not be considered when separation minima are being determined. Nevertheless, the results obtained are useful for the validation of the BN and justify the inclusion of the CD&R functionality in the ASMT.

- Regarding the STCA, it is observed that when the system issues the VAC alarm on the ATCO display the probability of a CAT criticality LOS is

lower than when this alarm is not issued. Moreover, the probability of failure of STCA alerting a LOS increases considerably (more than 20%) when the factor of the ergonomics of the ATCS is present. As explained above, the ergonomics factor refers to the range of colours in which information is presented in the ATCS. However, indirectly this factor refers to the transfer of aircraft between sectors. Therefore, what is highlighted in the relationship between these two nodes is that, on the basis of the STCA functionality, it seems that when aircraft are transferred to other sectors, the STCA does not always detect that a LOS may occur between an assumed aircraft and a transferred aircraft (which is still flying within the boundaries of the sector under consideration). Therefore, the system does not alert controllers of the conflict. This result is consistent with the development of the STCA that, in some versions, it does not detect LOS between aircraft assumed by nearby control sectors. Not all ANSPs have the same support systems or the same degree of evolution in them. Therefore, this STCA limitation is a hot spot for the occurrence of aircraft separation losses in inter-sector coordination situations and may be considered by those ANSPs that do not have this system functionality as a mitigating measure for LOS occurrence. Technical reports from the ANSP managing the airspace where the incidents analysed occurred have been investigated. These reports indicate that there was a system upgrade in 2020 by which this gap has been resolved. Therefore, this output validates the results emerging from the network for this node.

- Concerning the other safety net considered in this study and from the BN, it is observed (Table C10) that when the TCAS system issues a RA, the probability of occurrence of a CAT incident decreases considerably, by more than half, in comparison to when this anti-collision system does not issue any alert. The higher probabilities correspond to a lower criticality, which means that when the TCAS RA is activated, the separation breach is resolved correctly and promptly (without escalating to a more critical category). As expected, this result demonstrates that the TCAS system reduces the risk of MAC occurrence and demonstrates the effectiveness of this barrier. The activation of this system, in particular the resolution warning, implies a low probability that the LOS will be of CAT criticality.

Table C10. LOS Criticality probabilities related to TCAS behaviour.

	LOS Criticality			
	Minor	Major	HAZ	CAT
Non_TCAS $P(Non\_TCAS) = 1$	15%	18%	23%	44%
TCAS_TA $P(TCAS\_TA) = 1$	15%	44%	26%	15%
TCAS_RA $P(TCAS\_RA) = 1$	30%	36%	23%	12%

Finally, from the results obtained from the BN model, it can be inferred that from the different factors theoretically defined by ICAO for the definition of the separation minima, the most influential factor in a scenario with surveillance is the HF. This is consistent with Brooker [63] and Mehadhebi [90] statement. They pointed out that in scenarios with surveillance the risk should be modelled from operational errors, but not from navigation errors or radar inaccuracies. Moreover, they noted that separation minima are seen as “time buffers”. Technical means are indispensable but should be considered as requirements. The model for the development of the Ad Hoc separation will therefore be based on this principle.

ANNEX D. RESULTS OF THE COMPARISON BETWEEN *tnec* AND *TCPA*

This annex provides the results of the theoretical analysis approach for the preliminary feasibility study of the ADSM (section 4.3 in Chapter 4). The application of the Ad Hoc separation is potentially feasible whenever $t_{nec} < TCPA$. From the results of worst-case simulations with BADA model the following outcomes were obtained.

The results are categorised based on the three different AM (climb, unlimited descent, descent_UNL and limited descent, descent_LIM) the different manoeuvring aircraft masses, different FL and different HF values (40s, 30s or 20s). The maximum intersection angle between tracks (encounter geometry) required to ensure that the necessary time t_{nec} never exceeds the *TCPA*, calculated for separation minima of 5NM, 4NM and 3NM, is presented. Different geometries have been considered (angles between tracks from 15° to 175°), obtaining in each case the highest angle value in order to meet the condition ($t_{nec} < TCPA$). A more detailed explanation is provided in section 4.3 of Chapter 4.

- *TCPA* for a separation minimum of 5NM

Figure D1 shows the results for the climb AM obtained for the *TCPA* calculated for a separation minimum value of 5NM.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	NA	NA	15	15	15	NA	NA	15	15	25	NA	NA	15	25	25
	390	NA	15	15	15	25	NA	15	15	25	25	NA	15	25	25	35
	380	NA	15	15	25	25	NA	15	25	25	25	15	15	25	35	35
	370	15	15	25	25	25	15	15	25	25	35	15	25	25	35	45
	360	15	25	25	25	25	15	25	25	35	35	25	25	35	45	45
	350	15	25	25	25	35	25	25	25	35	35	25	35	35	45	45
	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC2	400	15	15	25	25	25	15	25	25	35	35	15	25	35	35	45
	390	15	25	25	25	35	25	25	25	35	35	25	35	35	45	45
	380	25	25	25	25	35	25	25	35	35	35	35	35	45	45	45
	370	25	25	25	35	35	25	35	35	35	45	35	35	45	45	55
	360	25	25	35	35	35	35	35	35	45	45	45	45	45	55	55
	350	25	35	35	35	35	35	35	45	45	45	45	45	55	55	65
	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC3	400	25	25	25	25	25	25	25	25	35	35	25	35	35	45	45
	390	25	25	25	25	35	25	25	35	35	35	35	35	35	45	45
	380	25	25	25	25	35	25	35	35	35	35	35	35	45	45	45
	370	25	25	25	35	35	25	35	35	35	35	35	35	45	45	55
	360	25	25	35	35	35	35	35	35	35	45	45	45	45	55	55
	350	25	35	35	35	35	35	35	35	45	45	45	45	45	55	55
	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC4	400	NA	15	15	25	25	NA	15	15	25	25	NA	15	25	25	35
	390	15	15	15	25	25	15	15	25	25	35	15	25	25	35	35
	380	15	15	25	25	25	15	25	25	25	35	25	25	35	35	45
	370	15	25	25	25	25	25	25	25	35	35	25	35	35	35	45
	360	25	25	25	25	35	25	25	35	35	35	35	35	45	45	55
	350	25	25	25	35	35	25	35	35	35	45	35	35	45	45	55
HF 40						HF 30						HF 20				

Figure D1. Climb AM results. *TCPA* 5NM.

Figure D2 shows the results for the descent_LIM AM obtained with an ROD limited to 1500ft/min for the *TCPA* calculated for a separation minimum value of 5NM.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	390	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	380	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	370	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	360	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	350	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC2	400	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	390	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	380	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	370	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	360	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	350	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC3	400	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	390	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	380	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	370	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	360	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	350	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC4	400	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	390	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	380	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	370	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	360	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
	350	35	35	35	35	35	45	45	45	45	45	55	55	55	55	55
HF 40						HF 30						HF 20				

Figure D2. Descent_LIM AM results, ROD limited to 1500ft/min. *TCPA* 5NM.

Figure D3 shows the results for the descent_UNL AM obtained for the *TCPA* calculated for a separation minimum value of 5NM.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	35	35	35	35	35	45	45	55	55	55	65	65	65	65	65
	390	35	35	35	35	35	55	55	55	55	55	65	65	65	65	65
	380	35	35	35	35	35	55	55	55	55	55	65	65	65	65	65
	370	35	35	35	35	35	55	55	55	55	55	65	65	65	65	65
	360	35	45	45	45	45	55	55	55	55	55	75	75	75	75	75
	350	45	45	45	45	45	55	55	55	55	55	75	75	75	75	75
AC2	400	35	35	35	45	45	55	55	55	55	55	65	65	65	75	75
	390	35	35	45	45	45	55	55	55	55	55	65	65	75	75	75
	380	35	45	45	45	45	55	55	55	55	55	65	75	75	75	75
	370	45	45	45	45	45	55	55	55	55	55	75	75	75	75	75
	360	45	45	45	45	45	55	55	55	55	55	75	75	75	75	75
	350	45	45	45	45	45	55	55	55	55	55	75	75	75	75	75
AC3	400	35	35	35	35	35	45	45	45	45	45	65	65	65	65	65
	390	35	35	35	35	35	45	45	45	55	55	65	65	65	65	65
	380	35	35	35	35	45	45	45	55	55	55	65	65	65	65	75
	370	35	35	35	35	45	45	55	55	55	55	65	65	65	65	75
	360	35	45	45	45	45	55	55	55	55	55	75	75	75	75	75
	350	45	45	45	45	45	55	55	55	55	55	75	75	75	75	75
AC4	400	35	35	35	35	35	45	45	45	45	45	65	65	65	65	65
	390	35	35	35	35	35	45	45	45	45	45	65	65	65	65	65
	380	35	35	35	35	35	45	45	45	45	45	65	65	65	65	65
	370	35	35	35	35	35	45	45	45	45	45	65	65	65	65	65
	360	35	35	35	35	35	45	45	45	45	55	65	65	65	65	75
	350	35	35	35	35	35	45	45	45	45	55	65	65	65	65	75
HF 40						HF 30						HF 20				

Figure D3. Descent_UNL AM results, unconstrained ROD. *TCPA* 5NM.

- *TCPA* for a separation minimum of 4NM

Figure D4 shows the results for the climb AM obtained for the *TCPA* calculated for a separation minimum value of 4NM.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	NA	NA	NA	15	15	NA	NA	NA	15	15	NA	NA	15	15	25
	390	NA	NA	15	15	15	NA	NA	15	15	15	NA	NA	15	25	25
	380	NA	15	15	15	15	NA	15	15	15	25	NA	15	15	25	25
	370	NA	15	15	15	25	15	15	15	25	25	15	15	25	25	35
	360	15	15	15	25	25	15	15	25	25	25	15	25	25	35	35
	350	15	15	15	25	25	15	25	25	25	25	25	25	25	35	35
AC2	400	15	15	15	15	25	15	15	25	25	25	15	15	25	25	35
	390	15	15	15	25	25	15	15	25	25	25	15	25	25	35	35
	380	15	15	25	25	25	15	25	25	25	25	25	25	25	35	35
	370	15	25	25	25	25	25	25	25	25	35	25	25	35	35	35
	360	25	25	25	25	25	25	25	25	35	35	35	35	35	45	45
	350	25	25	25	25	25	25	25	35	35	35	35	35	35	45	45
AC3	400	15	15	15	25	25	15	15	25	25	25	25	25	25	35	35
	390	15	15	15	25	25	15	25	25	25	25	25	25	25	35	35
	380	15	15	25	25	25	25	25	25	25	25	25	25	35	35	35
	370	15	25	25	25	25	25	25	25	25	25	25	25	35	35	35
	360	25	25	25	25	25	25	25	25	25	35	35	35	35	45	45
	350	25	25	25	25	25	25	25	25	35	35	35	35	35	45	45
AC4	400	NA	NA	15	15	15	NA	15	15	15	25	NA	15	15	25	25
	390	NA	15	15	15	15	15	15	15	25	25	15	15	25	25	25
	380	15	15	15	15	25	15	15	15	25	25	25	25	25	35	35
	370	15	15	15	25	25	15	15	25	25	25	25	25	25	35	35
	360	15	15	25	25	25	15	25	25	25	35	25	25	35	35	35
	350	15	15	25	25	25	25	25	25	25	35	25	35	35	35	35
HF 40						HF 30						HF 20				

Figure D4. Climb AM results. *TCPA* 4NM.

Figure D5 shows the results for the descent_LIM AM obtained with an ROD limited to 1500ft/min for the *TCPA* calculated for a separation minimum value of 4NM.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	390	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	380	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	370	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	360	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	350	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
AC2	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	390	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	380	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	370	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	360	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
AC3	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	390	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	380	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	370	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	360	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
AC4	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	390	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	380	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	370	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
	360	25	25	25	25	25	35	35	35	35	35	45	45	45	45	45
HF 40						HF 30						HF 20				

Figure D5. Descent_LIM AM results, ROD limited to 1500ft/min. *TCPA* 4NM.

Figure D6 shows the results for the descent_UNL AM obtained for the *TCPA* calculated for a separation minimum value of 4NM.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	25	25	25	25	25	35	35	35	35	35	55	55	55	55	55
	390	25	25	25	25	25	35	35	35	35	35	55	55	55	55	55
	380	25	25	25	25	25	35	35	35	35	35	55	55	55	55	55
	370	25	25	25	25	35	35	35	35	35	35	55	55	55	55	55
	360	35	35	35	35	35	35	35	35	35	45	55	55	55	55	55
	350	35	35	35	35	35	35	35	45	45	45	55	55	55	55	55
AC2	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	25	25	25	35	35	35	35	35	35	35	55	55	55	55	55
	390	25	25	35	35	35	35	35	35	35	35	55	55	55	55	55
	380	25	35	35	35	35	35	35	35	35	35	55	55	55	55	55
	370	35	35	35	35	35	35	35	35	35	45	55	55	55	55	55
	360	35	35	35	35	35	35	45	45	45	45	55	55	55	55	55
AC3	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	25	25	25	25	25	35	35	35	35	35	55	55	55	55	55
	390	25	25	25	25	25	35	35	35	35	35	55	55	55	55	55
	380	25	25	25	25	35	35	35	35	35	35	55	55	55	55	55
	370	25	25	25	25	35	35	35	35	35	35	55	55	55	55	55
	360	25	35	35	35	35	35	35	35	45	45	55	55	55	55	55
AC4	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	25	25	25	25	25	35	35	35	35	35	45	45	45	55	55
	390	25	25	25	25	25	35	35	35	35	35	45	45	55	55	55
	380	25	25	25	25	25	35	35	35	35	35	45	55	55	55	55
	370	25	25	25	25	25	35	35	35	35	35	55	55	55	55	55
	360	25	25	25	25	35	35	35	35	35	35	55	55	55	55	55
HF 40						HF 30						HF 20				

Figure D6. Descent_UNL AM results, unconstrained ROD. *TCPA* 4NM.

- *TCPA* for a separation minimum of 3NM

Figure D7 shows the results for the climb AM obtained for the *TCPA* calculated for a separation minimum value of 3NM.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	NA	NA	NA	NA	15	NA	NA	NA	NA	15	NA	NA	15	15	15
	390	NA	NA	NA	NA	15	NA	NA	NA	15	15	NA	15	15	15	15
	380	NA	NA	NA	15	15	NA	NA	15	15	15	NA	15	15	15	15
	370	NA	NA	15	15	15	NA	NA	15	15	15	NA	15	15	15	25
	360	NA	15	15	15	15	NA	15	15	15	15	15	15	15	25	25
	350	NA	15	15	15	15	15	15	15	15	25	15	15	25	25	25
AC2	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	NA	NA	15	15	15	NA	15	15	15	15	NA	15	15	15	25
	390	NA	15	15	15	15	15	15	15	15	15	15	15	15	25	25
	380	15	15	15	15	15	15	15	15	15	25	15	15	25	25	25
	370	15	15	15	15	15	15	15	15	15	25	15	25	25	25	25
	360	15	15	15	15	15	15	15	25	25	25	25	25	25	25	35
AC3	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	NA	15	15	15	15	15	15	15	15	15	15	15	15	25	25
	390	15	15	15	15	15	15	15	15	15	15	15	15	25	25	25
	380	15	15	15	15	15	15	15	15	15	25	15	15	25	25	25
	370	15	15	15	15	15	15	15	15	15	25	15	25	25	25	25
	360	15	15	15	15	15	15	15	25	25	25	25	25	25	25	25
AC4	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	NA	NA	NA	NA	15	NA	NA	NA	15	15	NA	NA	15	15	15
	390	NA	NA	NA	15	15	NA	NA	15	15	15	NA	15	15	15	15
	380	NA	NA	15	15	15	NA	15	15	15	15	15	15	15	15	25
	370	NA	15	15	15	15	15	15	15	15	15	15	15	15	25	25
	360	15	15	15	15	15	15	15	15	15	25	15	15	25	25	25
HF 40						HF 30						HF 20				

Figure D7. Climb AM results. *TCPA* 3NM.

Figure D8 shows the results for the descent LIM AM obtained with an ROD limited to 1500ft/min for the *TCPA* calculated for a separation minimum value of 3NM.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	390	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	380	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	370	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	360	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	350	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
AC2	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	390	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	380	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	370	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	360	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
AC3	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	390	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	380	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	370	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	360	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
AC4	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	390	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	380	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	370	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
	360	15	15	15	15	15	25	25	25	25	25	25	25	25	25	25
HF 40						HF 30						HF 20				

Figure D8. Descent LIM AM results, ROD limited to 1500 ft/min. *TCPA* 3NM.

Figure D9 shows the results for the descent_UNL AM obtained for the *TCPA* calculated for a separation minimum value of 3NM.

	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
AC1	400	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	390	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	380	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	370	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	360	25	25	25	25	25	25	25	25	25	25	35	35	35	35	45
	350	25	25	25	25	25	25	25	25	25	25	35	35	45	45	45
AC2	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	390	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	380	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	370	25	25	25	25	25	25	25	25	25	25	35	35	35	35	45
	360	25	25	25	25	25	25	25	25	25	25	45	45	45	45	45
AC3	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	390	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	380	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	370	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	360	25	25	25	25	25	25	25	25	25	25	35	35	35	45	45
AC4	FL	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW	90% MTOW	85% MTOW	80% MTOW	75% MTOW	70% MTOW
	400	15	15	15	25	25	25	25	25	25	25	35	35	35	35	35
	390	15	15	25	25	25	25	25	25	25	25	35	35	35	35	35
	380	15	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	370	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
	360	25	25	25	25	25	25	25	25	25	25	35	35	35	35	35
HF 40							HF 30					HF 20				

Figure D9. Descent_UNL AM results, unconstrained ROD. *TCPA* 3NM.

ANNEX E. DESCRIPTION OF THE LECMZMU, LECMTLU AND LECMDGU ENR SECTORS

This annex provides information on the scenarios in which the Ad Hoc separation (LECMZMU, LECMTLU and LECMDGU) has been applied. The results obtained from the analysis conducted in this annex justify the values used in the simulations presented in Chapter 4 and Chapter 5.

Spain has three Flight Information Regions (FIRs): Madrid (LECM), Barcelona (LECB) and the Canary Islands (GCCC). The vertical limits for these FIRs are from SFC until FL195. From FL195 until FL660, three upper information regions (UIRs) exist. At the same time, Spanish airspace has 5 ACC which are Madrid, Sevilla, Barcelona, Palma and Canarias (Figure E1). Spanish airspace is composed of 43 ENR sectors, 16 of which are located in LECM. Three of LECM's ENR sectors have been used in this study for the application of Ad Hoc separation. These are Zamora upper (LECMZMU), Domingo upper (LECMDGU) and Toledo upper (LECMTLU) sectors. The operational characteristics of these sectors are described in this annex based on information analysed from NEST [118].

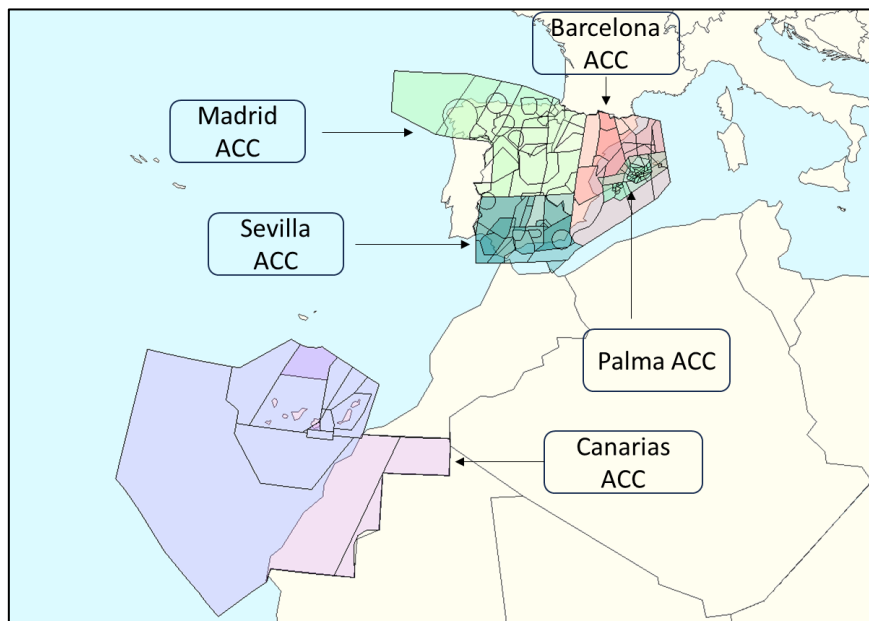


Figure E1. Madrid, Barcelona, Palma, Sevilla and Canarias ACC.

E.1 LECMZMU Sector

LECMZMU is the reference scenario used in this research for the application of the Ad Hoc separation concept. For this reason, a more in-depth analysis is performed based on the physical, operational and demand characteristics of the sector.

- **Busy day**

For the study and characterisation of the scenario the Busy day criterion has been used. IATA defines a typical busy day as the second busiest day in an average week during the peak month [156]. Pre-pandemic traffic levels (2019 year) have been considered as data in this dissertation. Peak month of traffic in LECMZMU during the year 2019 was July, being the busy day the 13th of July. AIRAC 1907 data has been used, obtained from EUROCONTROL DDR2 [136] .

- **Scenario analysis**

LECMZMU sector is located in the west part of the Madrid ACC (Figure E2). The LECMZMU sector is located on the border between UIR Madrid and UIR LISBON. Demand in this sector is influenced by the proximity to Madrid-Barajas Adolfo Suárez (LEMD) and Lisbon Humberto Delgado (LPPT) airports. Regarding the vertical limits, the lower and upper vertical limits for LECMZMU are FL345 and FL660, respectively.

The declared capacity of the LECMZMU sector is 45 aircraft/hour.

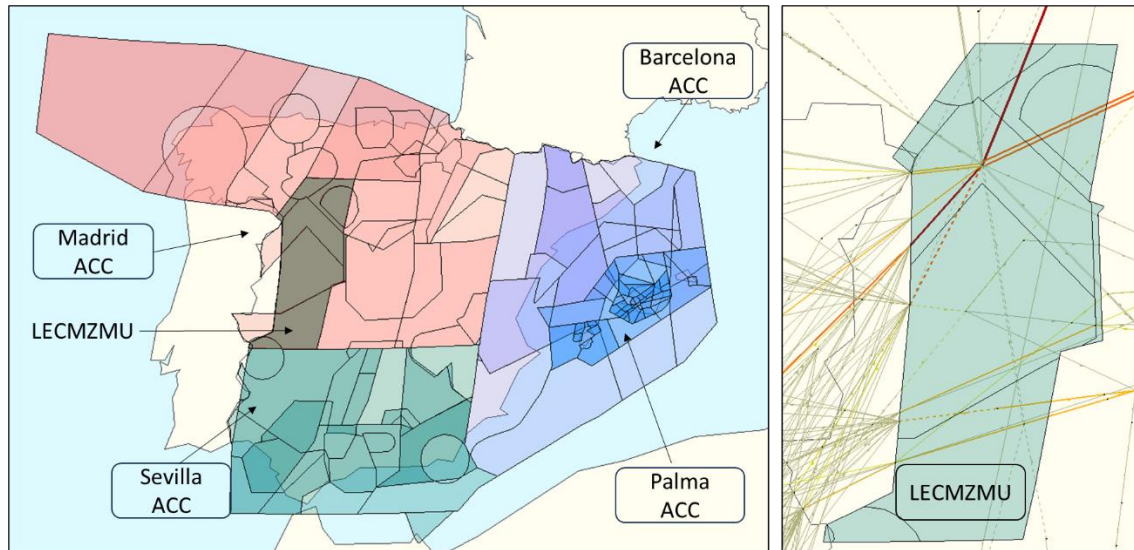


Figure E2. LECMZMU sector (Zamora-Upper sector), NEST.

• Traffic demand analysis

○ Main traffic flows

The majority of traffic in the LECMZMU sector is concentrated in the northern part of the sector, where most of the airways converge at the ZMR WP. Two predominant traffic flows are clearly distinguishable.

- East-West flow: usually flights from Portugal to Italy (or vice versa) or flights from Spain to North America (or vice versa).
- North-South flow: usually these are flights from Portugal to Europe (or vice versa), from Europe to Africa (or vice versa), or flights from the Canary Islands to Europe (or vice versa).

○ City Pairs

A city pair is defined as a pair of origin/destination flight itinerary. Generally, it refers to the pair of origin/destination airports of the flight. However, in this research, the study has focused on the countries of origin/destination of the flights, so they are not strictly city pairs, but it allows studying the configuration of traffic flows. Table E1 shows this information for LECMZMU sector. The majority of traffic correspond to Portugal – Europe flows. The row labelled “others” corresponds with origin-destination flights involving less than ten aircraft for that city pair; therefore, it has been classified as “others”.

Table E1. LECMZMU City pairs.

CITY PAIRS		FLOW	PERCENTAGE (%)
France	Portugal	88	14
Italy	Portugal	50	8
Canary Island	Spain	42	7
Germany	Portugal	45	7
Portugal	Switzerland	45	7
United Kingdom	Portugal	36	6
Spain	Portugal	30	5
United Kingdom	Spain	27	4
Spain	Spain	22	3
Germany	Canary Island	21	3
Morocco	France	16	3
Netherlands	Portugal	19	3
Portugal	Belgium	11	2
Belgium	Canary Island	10	2
Canary Island	France	12	2
Canary Island	United Kingdom	15	2
Others		128	20

○ Airways

Table E2 lists the airways of the sector with their segments and direction. Depending on the track of the airways, odd or even FLs are used. Thus, according to [19], tracks between 090° to 269° use odd FL, while tracks between 270° and 089° use even FL.

ANNEX E. DESCRIPTION OF THE LECMZMU, LECMTLU AND LECMDGU ENR SECTORS

Table E2. Segments of airways in LECMZMU.

	Airway	SEGMENT 1			SEGMENT 2			Directionality (unidirectional / bidirectional)
		Previous WP	Next WP	Track Mag	Previous WP	Next WP	Track Mag	
65 % traffic	UN873	BARDI	ZMR	029°	ZMR	NUBLO	024°	-
	UN745	TOSDI	ZMR	043°	-	-	-	-
	UL155	ADORO	ZMR	086° 266°	ZMR	AVILA	139° 319°	Bidirectional
	UM30	OMESI	ZMR	174° 354°	ZMR	MELON	173° 353°	Bidirectional
	UN976	NEA	ZMR	248° 067°	ZMR	ARDID	235°	NEA-ZMR segment Bidirectional
	UN733	UNSOL	ZMR	297°	ZMR	DESAT	306° 126°	ZMR-DESAT segment Bidirectional
35 % traffic	UZ405	TLD	BARDI	293°	-	-	-	-
	UZ406	GODIV	ZMR	112°	-	-	-	-
	UZ409	OGERO	TLD	085°	-	-	-	-
	UZ180	MELON	USIBA	197°	-	-	-	-
	UZ436	AVILA	CCS	234°	-	-	-	-
	UL14	NEA	ZANKO	222°	RIDAV	ADINO	221°	-
	UL185	LUPES	CCS	244°	-	-	-	-
	UM191	BARDI	RIDAV	098° 278°	RIDAV	DIPOL	099° 279°	Bidirectional
	UN870	URED	DIPOL	068°	-	-	-	-
	UN975	TLD	CCS	256°	-	-	-	-

In LECMZMU sector, 65% of the traffic flies in the northern part through the ZMR WP (Table E2). This is also shown in Figure E3, where the airways with the highest traffic loads are highlighted in red and orange. To determine the Ad Hoc separation, the traffic on these airways is simulated, to represent the majority of the traffic in the sector and to have different values of the most common encounter geometries. This allows to check in which situations it would be possible to define a separation value different from the current one.

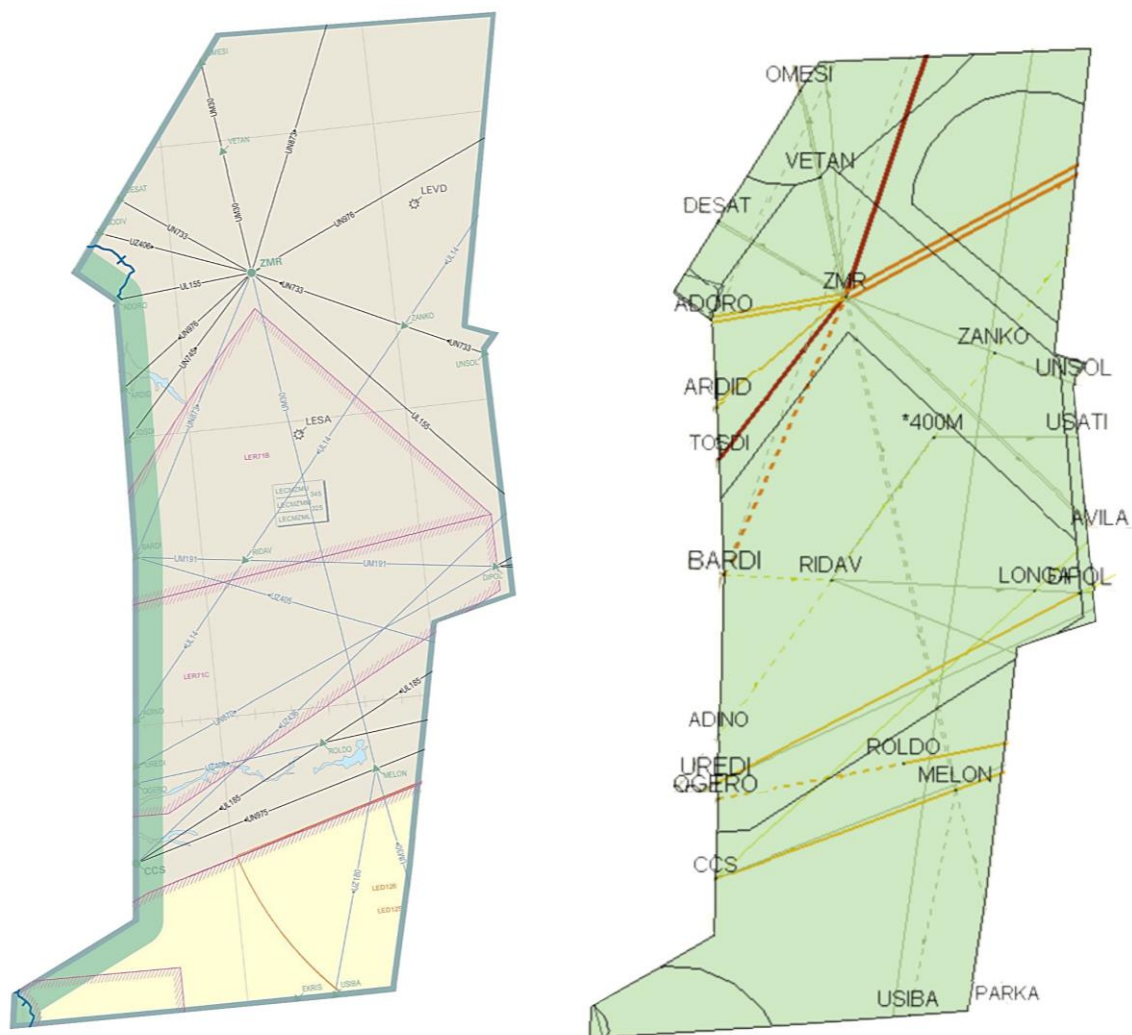


Figure E3. LECMZMU airways and traffic load.

Table E3 presents information regarding the amount of traffic flying on the segments in the northern part of the LECMZMU sector and the encounter geometry (angle between tracks) of these segments. These have been the geometries used for the determination of the Ad Hoc separation. Moreover, some of these segments have a relevant traffic load (TOSDI-ZMR, BARDI-ZMR).

Table E3. Encounter geometry data used for the ADSM computation.

Segment 1	No. of aircraft Segment 1	Segment 2	No. of aircraft Segment 2	Difference between tracks
NEA-ZMR	78	OMESI - ZMR	3	74°
DESAT_ZMR	5	NEA - ZMR	78	121°
BARDI_ZMR	87	TOSDI - ZMR	169	14°
ADORO_ZMR	38	TOSDI - ZMR	169	42°
TOSDI_ZMR	169	BARDI - ZMR	87	56°

○ Aircraft distribution per FL

As the LECMZMU sector is located close to two major airports (Madrid-Barajas Adolfo Suárez (LEMD) and Lisbon Humberto Delgado (LPPT)), the traffic operating in the sector is not only cruising traffic, but a significant percentage of it corresponds to evolving aircraft. In particular, 45% of the traffic is evolving (17% descending traffic and 28% ascending traffic) compared to 55% of the cruising traffic.

From the analysis performed in the busy day, 86% of the aircraft that cross the sector is concentrated between FL360 and FL400, being FL380 the one where the greatest number of aircraft operate (33%). To determine the ADSM FL360, FL370, FL380, FL390 and FL400 have been considered in order to account for the majority of stabilised traffic (Figure E4).

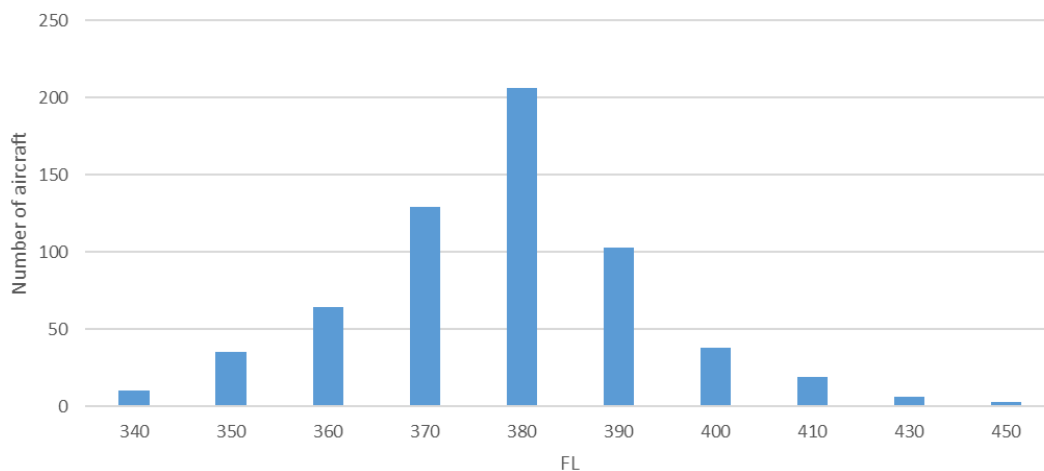


Figure E4. Traffic distribution per FL in LECMZMU.

○ Aircraft and propulsive model classification

In LECMZMU 90% of the aircraft flying are classified as M according to the wake vortex categorisation, with the remaining 10% being H. The predominant aircraft models are B738 (30%), A320 (24%) and A319 (15%). For the determination of ADSM, consideration is given to the aircraft models that operate most frequently in the sector. Thus, the simulations involve B738, A320 and A319 models (M), as well as A332 and B778 models (H).

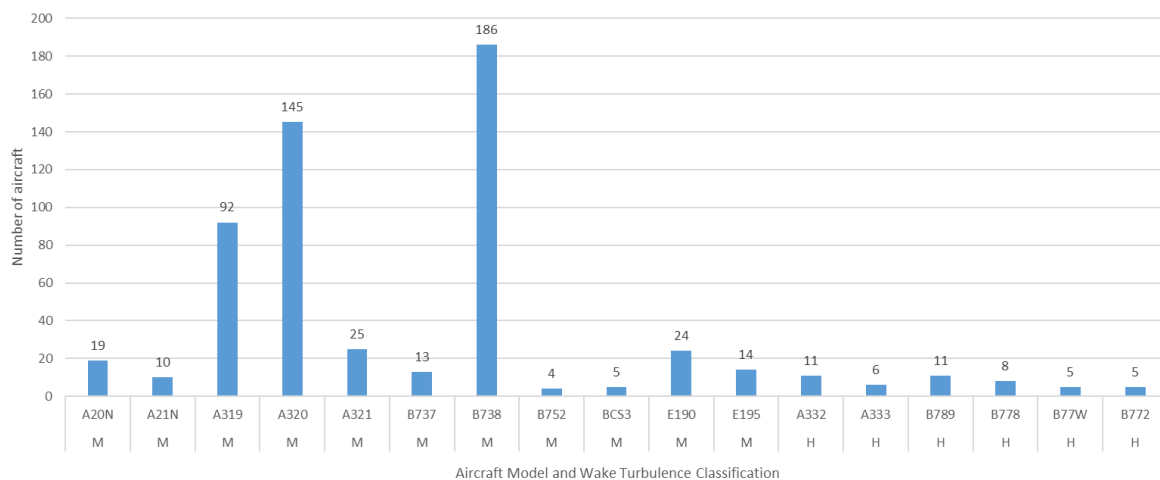


Figure E5. Aircraft and propulsive model classification in LECMZMU.

● Overload

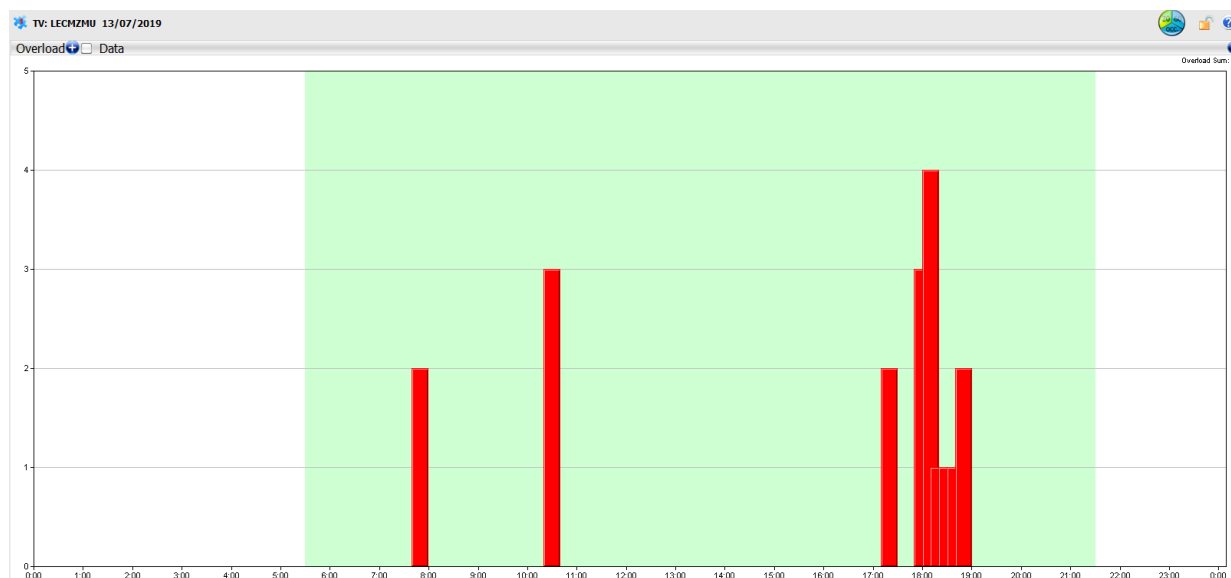


Figure E6. LECMZMU overload for the busy day.

Regarding sector saturation and overload, for the busy day there are certain periods in which the number of aircraft slightly exceeds the declared capacity (red bars), with a maximum of 4 simultaneous aircraft. While this quantity is manageable by the ATCO, this could indicate potential capacity issues during certain periods in LECMZMU sector.

E.2 LECMTLU Sector

The LECMTLU sector is one of the sectors used for the preliminary impact assessment of the Ad Hoc separation concept. For this reason, its physical, operational and sector demand characteristics are analysed below. As the LECMZMU sector, the LECMTLU sector is located in the Madrid ACC.

- **Busy day**

For the study and characterisation of the scenario the Busy day criterion has been used. Peak month of traffic in LECMTLU during the year 2019 was July, being the busy day the 6th of July. AIRAC 1907 data has been used, obtained from EUROCONTROL DDR2 [136] .

- **Scenario analysis**

The LECMTLU sector is located in the southern part of the Madrid ACC (Figure E7). As observed, the LECMTLU sector is situated on the border between the Madrid ACC and the Sevilla ACC and over the Madrid TMA. Regarding the vertical limits, the lower and upper vertical limits for LECMTLU are FL345 and FL660, respectively.

The declared capacity of the LECMTLU sector is 45 aircraft per hour.

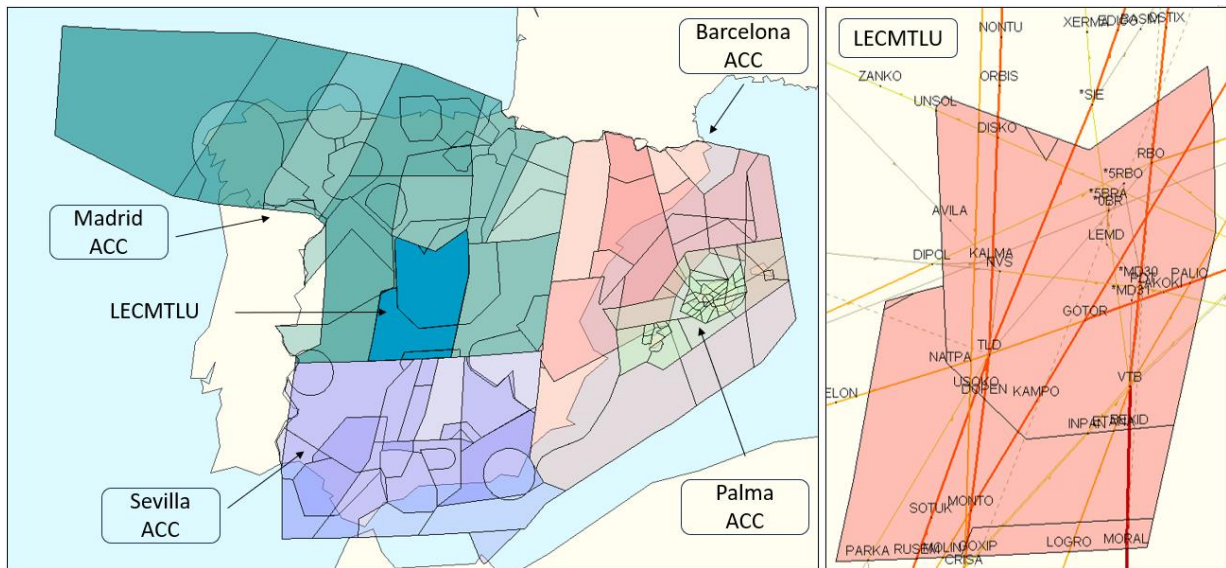


Figure E7. LECMTLU sector (Toledo-Upper sector), NEST.

• Traffic demand analysis

○ Main traffic flows

The traffic is distributed across the sector, predominantly crossing it in the North-South direction. There are five relevant WPs serving as intersections of airways: NVS, RBO, TLD, VTB and PDT. Two traffic flows are clearly distinguished:

- South-North flow: predominant in the sector, consists mainly of flights from Spain to the United Kingdom (or vice versa).
- East-West flow: generally consisting of flights from Portugal to Italy (or vice versa) or flights between Spain and America.

○ City Pairs¹⁶

Table E4 shows this information for LECMTLU sector. The majority of traffic correspond to Spain – United Kingdom and Morocco – France city pairs. This is the reason why the south-north traffic flow is the predominant. The row labelled “others” corresponds with origin-

¹⁶ It is reminded that this analysis has focused on the countries of origin/destination of flights. Consequently, what is shown does not strictly correspond to city pairs but to countries. However, this allows to study the configuration of traffic flows.

destination flights involving less than ten aircraft for that city pair; therefore, it has been classified as “others”.

Table E4. LECMTLU City pairs.

CITY PAIRS		FLOW	PERCENTAGE (%)
United Kingdom	Spain	133	20
Morocco	France	62	9
Italy	Portugal	38	6
Germany	Spain	23	4
Belgium	Morocco	24	4
Spain	Portugal	27	4
Netherlands	Spain	26	4
France	Spain	18	3
Germany	Canary Island	18	3
Ireland	Spain	21	3
Spain	Spain	20	3
Belgium	Spain	14	2
Canary Island	Spain	12	2
Denmark	Spain	13	2
Finland	Spain	15	2
France	Portugal	13	2
Morocco	Germany	14	2
Norway	Spain	16	2
Sweden	Spain	13	2
United Kingdom	Gibraltar	12	2
Others	Others	122	19

○ Airways

Table E5 lists the airways of the sector and their segments and directionality. Depending on the track of the airways, odd or even FLs are used. Thus, according to [19], tracks between 090° to 269° use odd FL, while tracks between 270° and 089° use even FL.

Table E5. Segments of airways in LECMTLU.

	Airway	SEGMENT 1			SEGMENT 2			Directionality (unidirectional / bidirectional)
		Previous WP	Next WP	Track Mag	Previous WP	Next WP	Track Mag	
55 % traffic	UN865	MORAL	VTB	005° 185°	VTB	SIE	359°	MORAL – VTB Bidirectional
	UZ230	RUSEM	TLD	023°	TLD	NVS	010° 190°	TLD – NVS Bidirectional
	UN857	BAN	GOTOR	215°	GOTOR	MONTO	214°	-
	UN864	DISKO	TLD	185°	TLD	CRISA	190°	-
45 % traffic	UL185	NVS	ROLDO	244°	-	-	-	-
	UM871	DIPOL	NVS	099° 279°	NVS	PDT	100°	DIPOL-NVS Bidirectional
	UM191	DIPOL	KALMA	092°	-	-	-	-
	UL155	VTB	NVS	315°	NVS	AVILA	139° 319°	NVS-AVILA segment Bidirectional
	UZ409	ROLDO	TLD	085°	-	-	-	-
	UN733	CJN	DISKO	297°	DISKO	UNSOL	297°	-
	UN870	DIPOL	RBO	069°	RBO	PINAR	076°	-
	UL184	TLD	RBO	044°	RBO	BAN	045°	-
	UN867	VTB	ANZAN	167°	VTB	RBO	009°	-
	UL150	CJN	RBO	312°	-	-	-	-
	UN871	LOGRO	VTB	024°	VTB	PALIO	034°	-
	UN975	PALIO	TLD	254° 074°	TLD	MELON	256°	PALIO – TLD Bidirectional
	UN10	CJN	VTB	230° 050°	VTB	CRISA	226° 046°	-
	UN858	PARKA	TLD	034°	TLD	SIE	026°	-
	UZ165	PARKA	SOTUC	059°	-	-	-	-

The majority of the traffic in the LECMTLU sector is distributed in North-South flows. Airways UN865, UZ230 and UN857 handle approximately 50% of the traffic. In Figure E8 the airways with the highest traffic load are highlighted in red and orange.

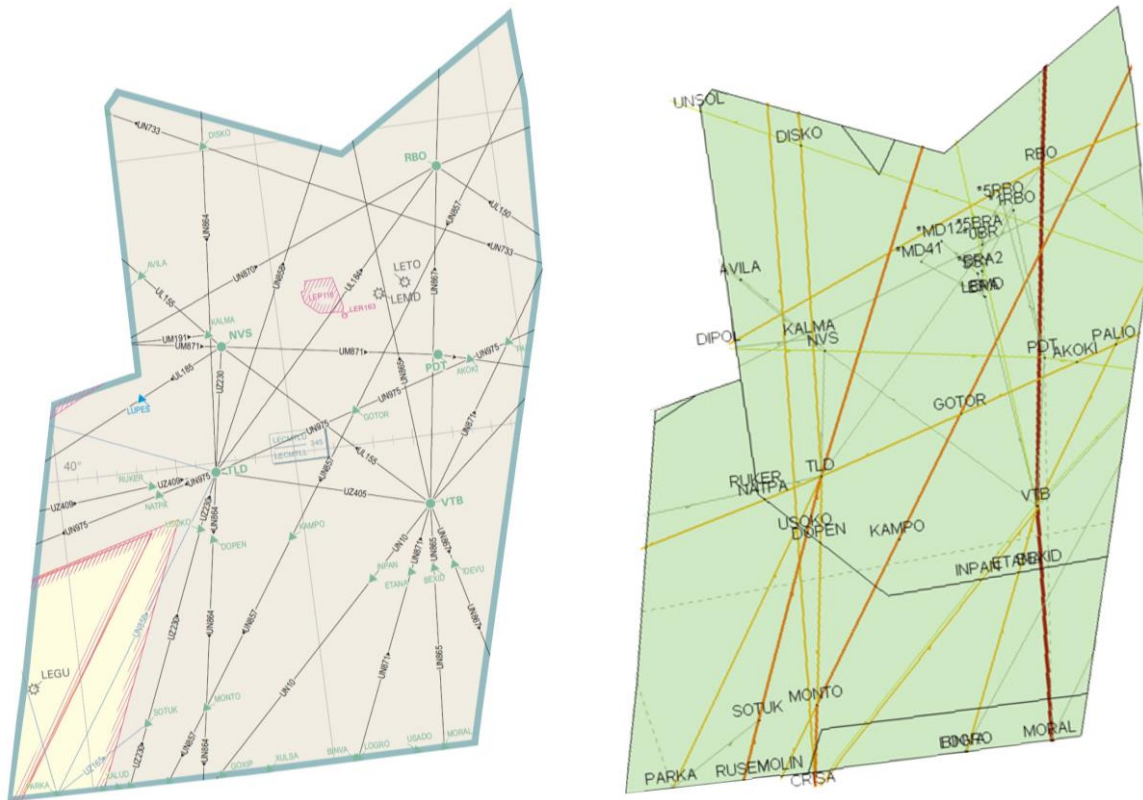


Figure E8. LECMTLU airways and traffic load.

○ Aircraft distribution per FL

In the LECMTLU sector, traffic is predominantly cruising. Only 22% of the traffic is in evolution (5% in descent and 17% in ascent), while 78% of the traffic is in cruise. This is due to the fact that this sector is traversed by aircraft travelling to or from the Canary Islands to Europe (mainly to the United Kingdom or vice versa) and from Morocco to France.

From the analysis of busy day, Figure E9 shows that 91% of the cruise traffic is concentrated between FL360 and FL400, with FL380 having the highest number of aircraft operations (32%). The distribution is similar to that of the LECMZMU sector.

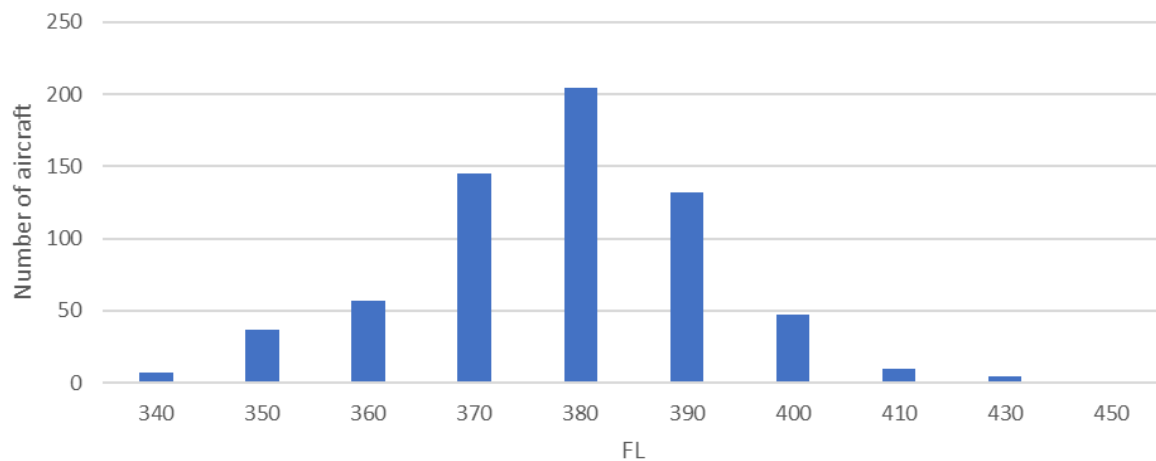


Figure E9. Traffic distribution per FL in LECMTLU.

○ Aircraft and propulsive model classification

Figure E10 shows the aircraft and propulsive model classification for the LECMTLU sector. The 96% of the aircraft flying in the sector are classified as M according to the wake vortex categorisation, with the remaining 4% classified as H. The most common aircraft models are B738 (40%), A320 (24%) and A319 (10%). As observed, these distributions are similar to those of the LECMZMU sector.

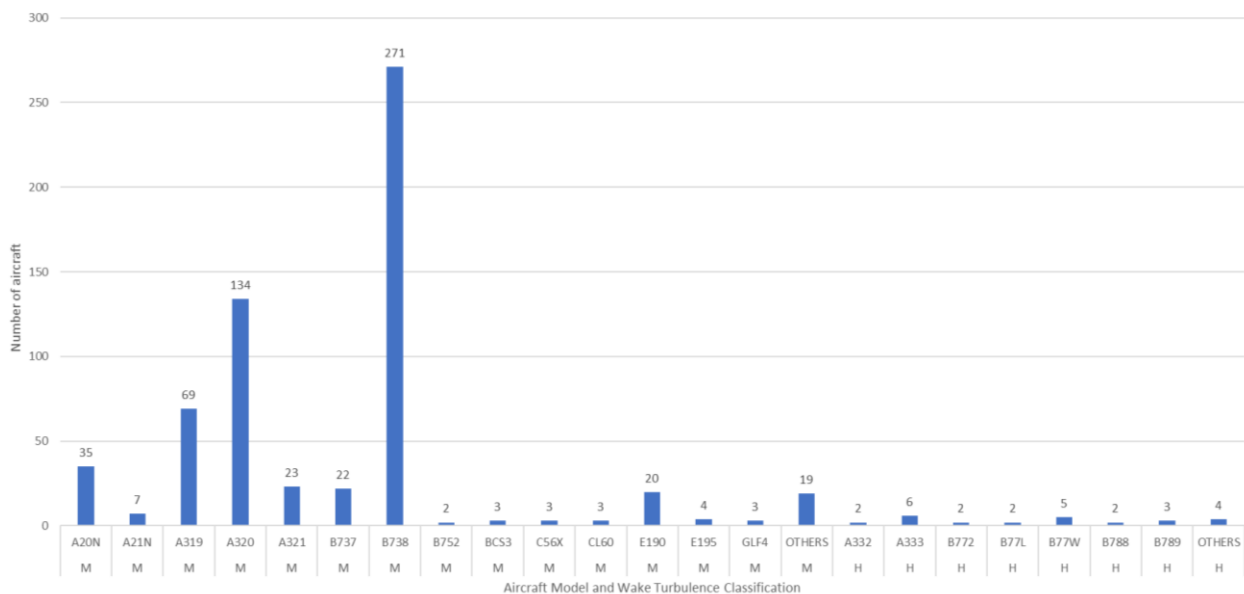


Figure E10. Aircraft and propulsive model classification in LECMTLU.

• Overload

Regarding to sector saturation and overload, Figure E11 shows that there are certain periods in which the number of aircraft slightly exceeds the declared capacity (red bar), with a maximum of 3 simultaneous aircraft. Although this quantity is manageable by the ATCO, it is true that it could indicate potential capacity issues during certain periods in the LECMTLU sector.

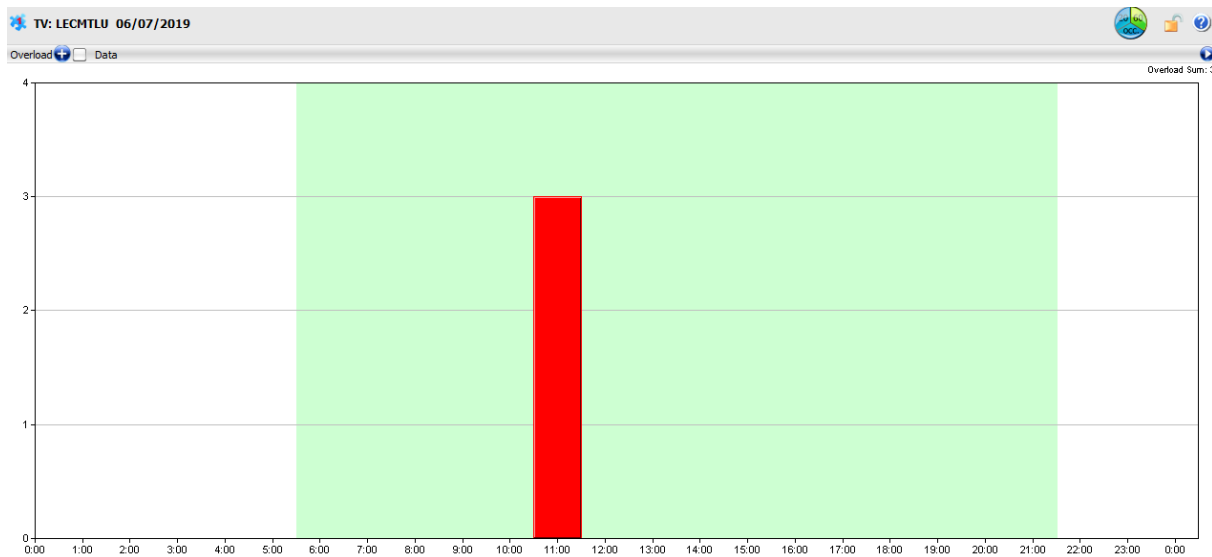


Figure E11. LECMTLU overload for the busy day.

E.3 LECMDGU Sector

The LECMDGU sector, as LECMZMU and LECMTLU, has served as the backdrop for the preliminary assessment of the Ad Hoc separation. Its physical, operational and sector demand characteristics are analysed below. The LECMDGU sector belongs to the Madrid ACC.

• Busy day

For the study and characterisation of the scenario the Busy day criterion has been used. Peak month of traffic in LECMDGU during the year 2019 was July, being the busy day the 7th of July. AIRAC 1907 data has been used, obtained from EUROCONTROL DDR2 [136] .

• Scenario analysis

The LECMDGU sector is located in the centre of the Madrid ACC. As observed in Figure E12, the LECMDGU sector is bordered by the LECMZMU sector to its left, the LECMTLU sector to the south, the LECMPAU sector to the east and the LECMBLU sector to the north, all belonging to the Madrid ACC. Regarding the vertical limits, the lower and upper boundaries for LECMDGU are FL345 and FL660, respectively.

The declared capacity of the LECMDGU sector is 44 aircraft per hour.

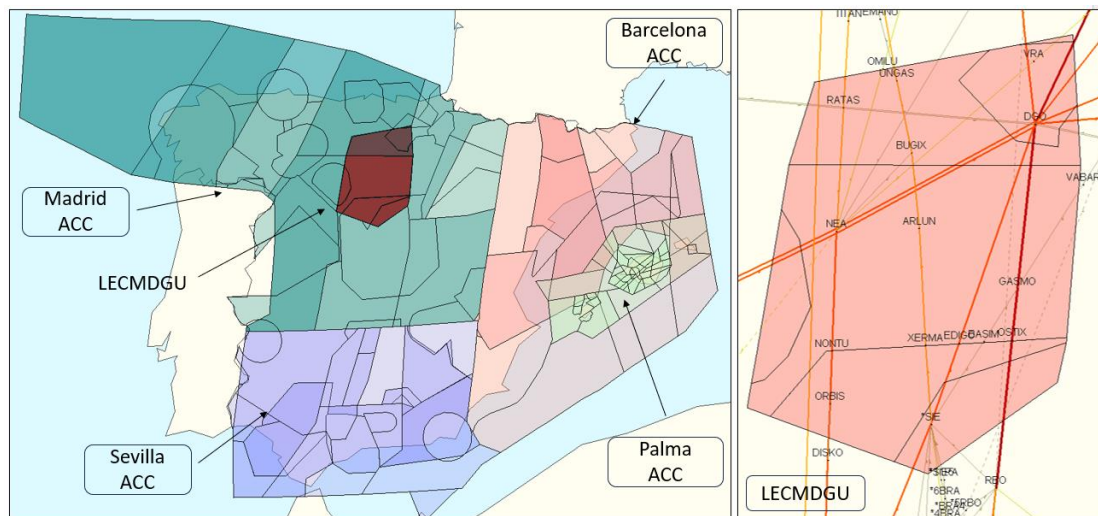


Figure E12. LECMDGU sector (Domingo-Upper sector), NEST.

• Traffic demand analysis

○ Main traffic flows

The traffic is distributed across the sector, with the majority crossing in the north-south direction. This makes sense as the LECMTLU sector borders to the south and the predominant flows of LECMTLU are in this direction. In LECMDGU, there is also a significant flow of aircraft crossing the sector in the west-northeast direction. There are four relevant WPs that serve as intersections of airways: SIE, DGO, VRA and NEA. Two distinct traffic flows can be clearly distinguished:

- South-North flow: predominant in the sector, involving flights from the Canary Islands or the Iberian Peninsula to England (or vice versa), from North Africa to France (or vice versa) and from the Canary Islands to Central Europe (or vice versa).

- West-Northeast flow: generally consisting of flights from Portugal to Central Europe (or vice versa) and some from the Canary Islands to Central Europe (or vice versa).

○ **City Pairs**¹⁷

Table E6 shows this information for the LECMDGU sector. The majority of the traffic corresponds to the Spain – United Kingdom, Morocco – France and Portugal-Central Europe city pairs. Therefore, south-north traffic flow is important, but also west-northeast. The row labelled “others” corresponds with origin-destination flights involving less than ten aircraft for that city pair; therefore, it has been classified as “others”.

Table E6. LECMDGU City pairs.

CITY PAIRS		FLOW	PERCENTAGE (%)
United Kingdom	Spain	157	25
France	Portugal	66	10
Morocco	France	57	9
Portugal	Switzerland	46	7
Italy	Portugal	23	4
Spain	France	24	4
Germany	Spain	17	3
Germany	Portugal	20	3
Ireland	Spain	21	3
Morocco	Belgium	15	2
Netherlands	Spain	14	2
Norway	Spain	10	2
Sweden	Spain	11	2
United Kingdom	Gibraltar	13	2
Belgium	Spain	11	2
Others		128	20

¹⁷ See footnote 16.

○ Airways

The following Table E7 details the airways crossing the sector, their segments and directions. It is important to note that, depending on the airway's tracks, either even or odd flight levels are used. According to [4], tracks between 090° and 269° use odd flight levels, while tracks between 270° and 089° use even flight levels. 44% percent of the traffic is concentrated on the main airways with north-south direction (or vice versa), which corresponds to the traffic coming from or going to the LECMTLU sector. The 30% of the traffic is concentrated in UN976 airway crossing the sector in the west-northeast direction (or vice versa). In Figure E13 the airways with the highest traffic load are highlighted in red and orange.

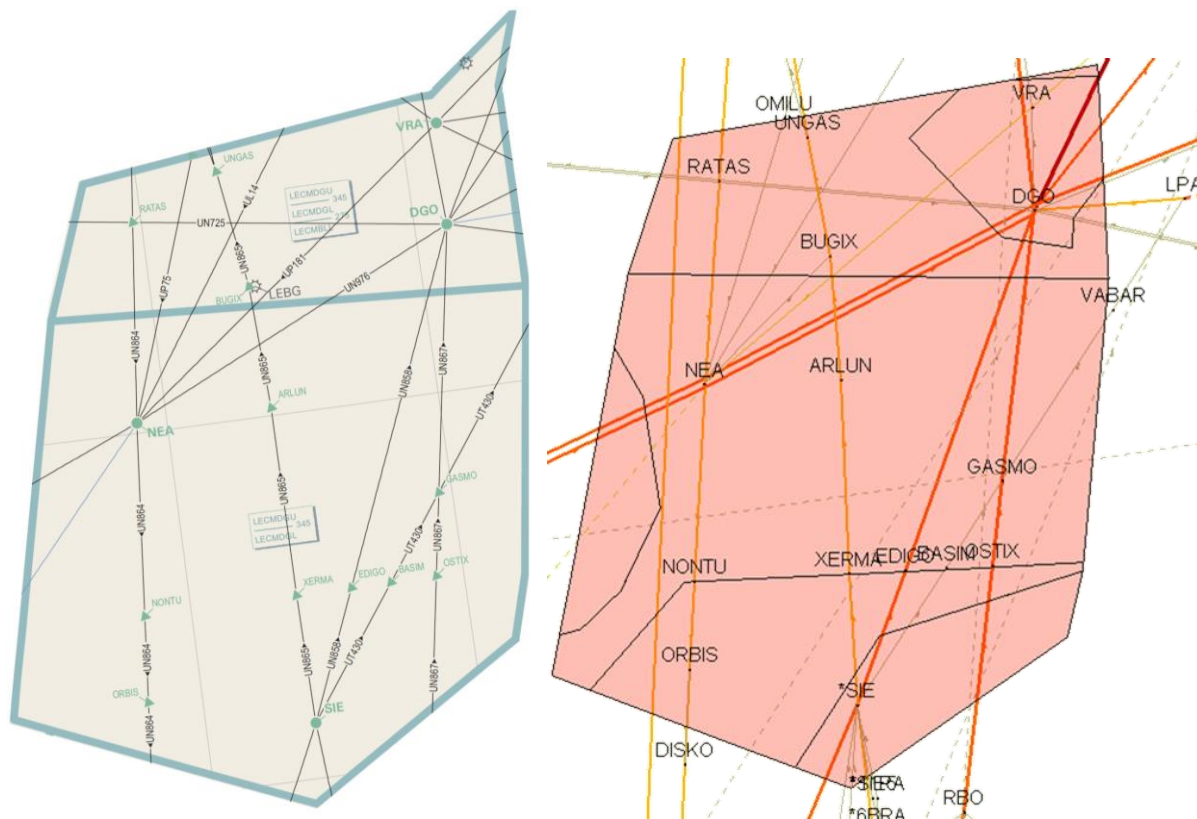


Figure E13. LECMDGU airways and traffic load.

ANNEX E. DESCRIPTION OF THE LECMZMU, LECMTLU AND LECMDGU ENR SECTORS

Table E7. Segments of airways in LECMTLU.

	Airway	SEGMENT 1			SEGMENT 2			Directionality (unidirectional / bidirectional)
		Previous WP	Next WP	Track	Previous WP	Next WP	Track	
44 % traffic	UN865	SIE	ARLUN	359°	BUGIX	UNGAS	352°	-
	UN867	RBO	DGO	010°	DGO	BLV	358°	-
	UN858	SIE	DGO	023°	DGO	ABRIX	030°	-
30 % traffic	UN976	MIRPO	DGO	252° 072°	DGO	NEA	245° 065°	Bidirectional
29 % traffic	UL176	DGO	CEGAM	042°	-	-	-	-
	UL14	AMTOS	NEA	215°	NEA	ZANKO	222°	-
	UN725	RATAS	DGO	099° 279°	DGO	VASUM	106° 286°	Bidirectional
	UP181	SSN	VRA	233°	VRA	NEA	233°	-
	UN864	TITAN	NEA	167°	NEA	DISKO	185°	-
	UP75	OMILU	NEA	200°	-	-	-	-
	UT430	SIE	GASMO	036°	GASMO	VABAR	036°	-
	UQ210	ROLES	VRA	134° 314°	VRA	LPA	124° 304°	Bidirectional
	UM299	VRA	PPN	090° 270°	-	-	-	Bidirectional

○ Aircraft distribution per FL

For LECMDGU, 17% of the traffic is in evolution (4% in descent and 13% in ascent), while 83% of the traffic is cruising. From the analysis of the busy day, Figure E14 shows that 94% of the cruising traffic is concentrated between FL360 and FL400, with FL380 having the highest number of aircraft operations (36%). For the determination of the ADSM, FL360, FL370, FL380, FL390 and FL400 have been considered to encompass the majority of the stabilised traffic. The distribution is similar to that of the LECMZMU and LECMTLU sectors.

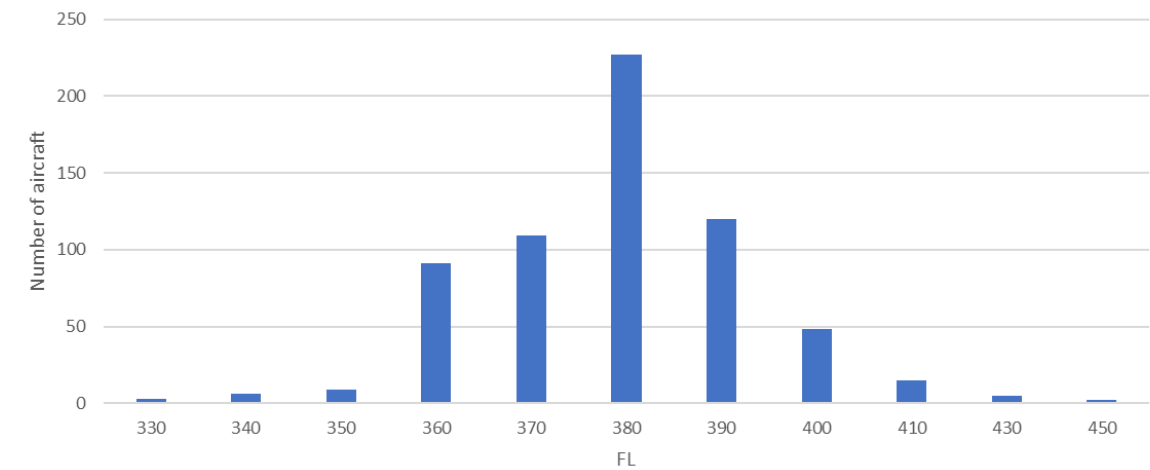


Figure E14. Traffic distribution per FL in LECMDGU.

○ Aircraft and propulsive model classification

Figure E15 shows the aircraft and propulsive model classification for the LECMTLU sector. The 94% of the aircraft flying in the LECMDGU sector are classified as M according to the wake vortex classification, with the remaining 6% classified as H. The predominant aircraft models are B738 (42%), A320 (23%) and A319 (13%), as in LECMZMU and LECMTLU.

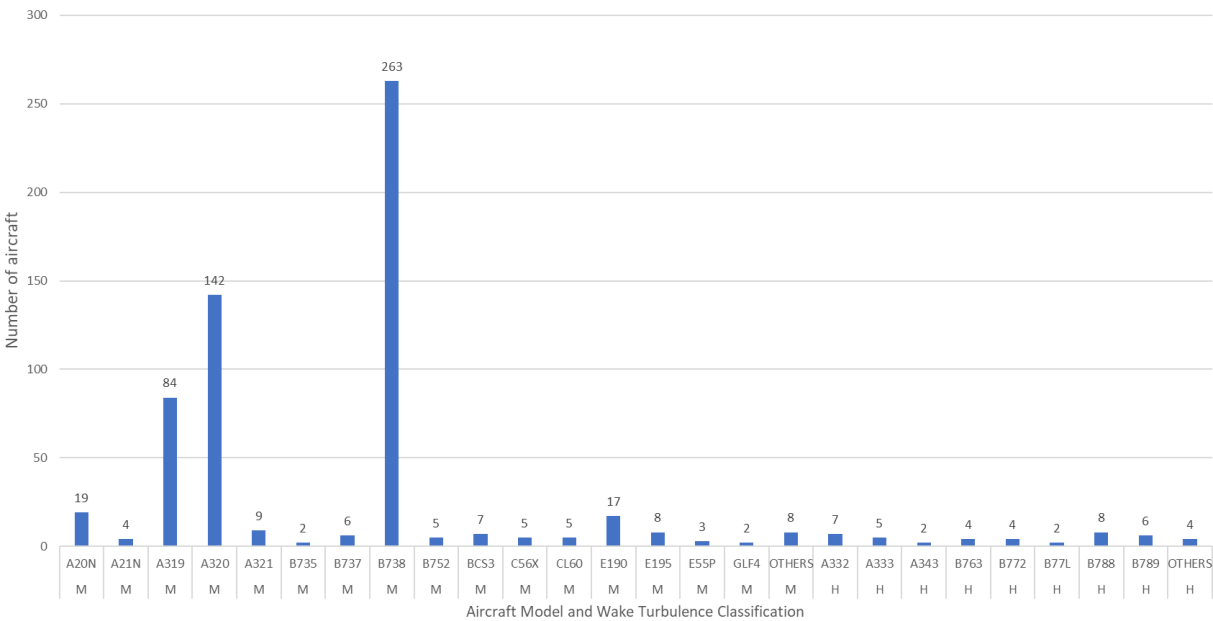


Figure E15. Aircraft and propulsive model classification in LECMDGU.

- **Overload**

Regarding sector saturation and overload, certain periods are observed (Figure E16) where the number of aircraft slightly exceeds the declared capacity, with a maximum of 2 aircraft. Although this quantity is manageable by the ATCO, it is true that it could indicate potential capacity problems during certain periods.

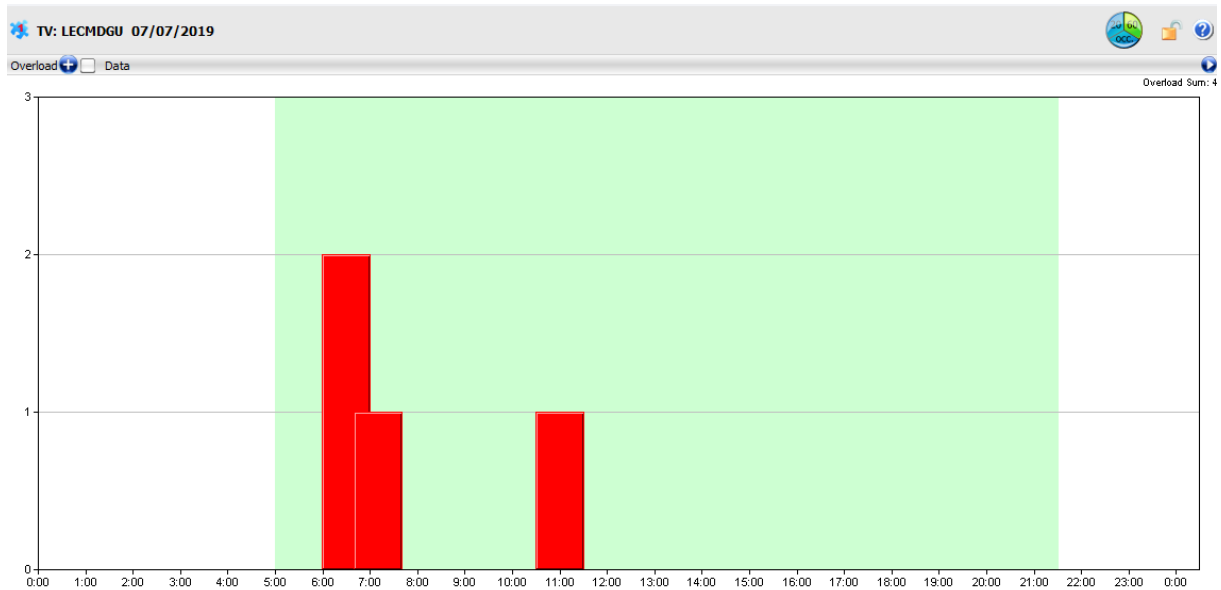


Figure E16. LECMDGU overload for the busy day.

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ANNEX F. ATCO – PILOT SURVEYS

F.1. ATCO survey

SURVEY TO AIR TRAFFIC CONTROL OFFICER (ATCO): TIME ESTIMATION

Related to the ATCO who completes the survey:

1.- Please, indicate the ANSP (s) you work/have worked with: _____ (Optional)

2.- Please, indicate in which airspace you have provided ATC service:

☐ En – route (ACC)

☐ TMA (APP)

☐ AD (TWR)

SURVEY

Scenario description

En-route sector. Published ATS routes. Traffic is close to the declared capacity without exceeding it.

ATC tools available

Modern ATC equipment in a surveillance environment (the one used in countries such as France, Italy, Germany, Spain, England, etc.).

Objective

Estimation of the time necessary to resolve a loss of separation between an aircraft pair once it has taken place, **considering that TCAS system has not triggered and it is not going to trigger (hypothesis of the survey).**

That is, just consider resolving the loss of separation by the ATCO observing the loss of separation late and issuing an avoiding action instruction to the Pilot, (TCAS is hypothetically OFF).

Background to the situation

Two aircraft flying in an en-route sector **lose separation one from each other**. That is, **in this instant of time they fly below the separation minima**. The ATCO notices this (once the separation has been lost) and reacts by issuing a resolution manoeuvre between them. It is considered that the TCAS is not working and it is not going to work in the next minutes (hypothesis of the survey).

ATCO Task	Time (s)
1. Detection <i>It is considered that the ATCO has a <u>Short-Term Conflict Alert (STCA) system</u> that issues a conflict prediction <u>alert</u> (before the loss of separation takes place) and a loss of separation <u>alarm</u> (once the loss of separation has taken place)</i> The task of the ATCO is to prevent a LOS from occurring. If the separation between a pair of aircraft is lost and the ATCO has not detected it in advance (<i>he/she has ignored or has not realised about the conflict prediction <u>alert</u></i>), How long, from the time the separation is lost (and the loss of separation <u>alarm</u> triggers), do you think it would take for the ATCO to <u>detect</u> it? <i>Comments. Please leave your comments if you wish:</i>	

2. Avoidance manoeuvre communication If the system (future system) would present (show) you with the solution (no decision process) on the manoeuvre to be performed by the aircraft to regain separation between them (above the separation minima) How long do you think it would take to communicate the solution to the pilot ? (Oral communication in VHF) <i>(Time to communicate the instruction ATCO – Pilot and the corresponding readback by the pilot)</i> Consider, if necessary, that the pilot may need to have the instructions repeated by the ATCO. <i>Comments. Please leave your comments if you wish:</i>	
3. Resolution implementation Once the pilot has readback, the aircraft begins to follow the instruction and the ATCO monitors that the instruction is being properly executed. How long does it take for the ATCO, once the instructions are communicated to the pilot (and the pilot has readback), to confirm that the aircraft is executing the manoeuvre? <i>Comments. Please leave your comments if you wish:</i>	

Now, these times want to be estimated for a Free Route scenario (FRA). Could you estimate these “new” times for FRA?

ATCO Task	Time (s)
1. Detection <i>It is considered that the ATCO has a Short-Term Conflict Alert (STCA) system that issues a conflict prediction alert (before the loss of separation takes place) and a loss of separation alarm (once the loss of separation has taken place)</i> The task of the ATCO is to prevent a LOS from occurring. If the separation between a pair of aircraft is lost and the ATCO has not detected it in advance (<i>he/she has ignored or has not realised about the conflict prediction alert</i>), How long, from the time the separation is lost (and the loss of separation alarm triggers), do you think it would take for the ATCO to <u>detect</u> it? <i>Comments. Please leave your comments if you wish:</i>	
2. Avoidance manoeuvre communication If the system (future system) would present (show) you with the solution (no decision process) on the manoeuvre to be performed by the aircraft to regain separation between them (above the separation minima) How long do you think it would take to communicate the solution to the pilot ? (Oral communication in VHF) <i>(Time to communicate the instruction ATCO – Pilot and the corresponding readback by the pilot)</i> Consider, if necessary, that the pilot may need to have the instructions repeated by the ATCO. <i>Comments. Please leave your comments if you wish</i>	

3. Resolution implementation Once the pilot has readback, the aircraft begins to follow the instruction and the ATCO monitors that the instruction is being properly executed. How long does it take for the ATCO, once the instructions are communicated to the pilot (and the pilot has readback), to confirm that the aircraft is executing the manoeuvre? <i>Comments. Please leave your comments if you wish:</i>	

Please answer the following question:

From your ATCO personal experience, have you been trained (as pilots do with TCAS RA alarm) in order to respond in a short period of time when the loss of separation alarm from STCA triggers?

F.2. Pilot survey

SURVEY TO PILOT: TIME ESTIMATION

Related to the pilot who completes the survey:

Please, indicate the airline(s) you work/have worked with: _____ (Optional)

Please, indicate the aircraft models you fly/have flown, either as captain or first officer: _____

Survey

Scenario description

En-route sector. Published ATS routes.

Objective

Estimation of the time necessary to resolve a loss of separation between an aircraft pair once it has taken place, **considering that TCAS system has not triggered and it is not going to trigger (hypothesis of the survey).**

That is, just consider the resolution of the loss of separation from the ATCO instruction (who was late in detecting the loss of separation and issues an avoiding action instruction to the Pilot), i.e., no TCAS alert.

Background to the situation

Two aircraft flying in an en-route sector lose separation one from each other. That is, in this instant of time they fly below the separation minima. The ATCO notices this (once the separation has been lost) and reacts by issuing a resolution manoeuvre between them. It is considered that the TCAS system has not yet been triggered and it is not going to trigger in the next minutes (hypothesis of the survey).

Pilot Task	Time (s)
1. Avoidance manoeuvre communication How long do you estimate it takes to communicate the solution? (Oral communication in VHF) (Time to communicate the instruction ATCO – Pilot and the corresponding readback by the pilot) i.e. ATCO-. IBE 123 climb 1000 ft Immediately Pilot .- Climb 1000 ft Immediately IBE 123 Consider, if necessary, that the pilot may need to have the instructions repeated by the ATCO. Comments. Please leave your comments if you wish:	

2. Pilot reaction time How much time is needed from the end of the communication with the ATCO (after the readback of the pilot) until the manoeuvre is initiated by the aircraft? That is: 2.1 Does the pilot need a reaction time? If yes, please indicate the pilot's reaction time (i.e. human reaction time). 2.2 For a climb manoeuvre of 1000 ft or a descent manoeuvre of 1000 ft.... 1) If the manoeuvre is performed by the <u>automatic pilot (autopilot)</u>, how much time the pilot needs to transmit or configure this manoeuvre in the autopilot? 2) If the manoeuvre is performed <u>manual by the pilot</u>, how much time it is required by the pilot? 2.3 For a climb manoeuvre of 500 ft or a descent manoeuvre of 500 ft.... 1) If the manoeuvre is performed by the <u>automatic pilot (autopilot)</u>, how much time the pilot needs to transmit or configure this manoeuvre in the autopilot? 2) If the manoeuvre is performed <u>manual by the pilot</u>, how much time it is required by the pilot?	Answer to Q 2.1 Answer to Q 2.2.1) Answer to Q 2.2.2) Answer to Q 2.3.1) Answer to Q 2.3.2)
3. Aircraft response time How much time is required from the time the pilot executes an avoidance manoeuvre until the aircraft begins to execute this avoidance manoeuvre (response time of the aircraft)? Do you think there is a difference in response time for different aircraft models (A320, A350, B737, B777....)? If so, based on your experience, please indicate the aircraft models and its associated response time.	

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ANNEX G. ATC TASKS SPECIFICATIONS

This annex provides the tasks and their associated times defined in RAMS for the computation of the ATCO WL, which have been extracted from [134].

Table G1. RAMS tasks and times for the simulation of ATCO WL.

Conflict Search

Task id	Task description	Execution Time (seconds)	
		Planning Controller	Tactical (Executive) Controller
CFSch1	Conflict search to establish an initial clearance for a flight entering a sector in climb or descent	9	4
CFSch2	Conflict search by a controlling sector to establish a sector planning clearance	9	2
CFSch3	Conflict search to establish a sector exit clearance	3	3
CFSch4	Conflict search to establish a new sector planning clearance	8	3
CFSch5	Updating of flight information and notification of planning re-clearance to the tactical controller	4	4
CFSch6	Receipt and acknowledgement by the tactical controller of a planning reclearance	2	2

Flight Data Management

Task id	Task description	Execution Time (seconds)	
		Planning Controller	Tactical (Executive) Controller
FltDataMgt1	Loading and distribution of flight progress strips (without conflict search)	-	6
FltDataMgt2	Removal of flight progress strips and associated tasks	10	5

R/T Task

Task id	Task description	Execution Time (seconds)	
		Planning Controller	Tactical (Executive) Controller
RTComm1	First call from an aircraft entering the first sector of an ACC	5	10
RTComm2	First call from an aircraft entering another sector of the same ACC	5	10
RTComm3	Instruction to aircraft to avoid a military area	5	10
RTComm4	Report from an aircraft on passing or reaching a specified level	3	6
RTComm5	Instruction to aircraft to comply with a new planning clearance (level change, start of climb or descent, or reallocation of stack level to inbound aircraft)	5	10
RTComm6	Last message to an aircraft leaving an ATC sector	2	8

Co-ordination

Task id	Task description	Execution Time (seconds)	
		Planning Controller	Tactical (Executive) Controller
Coord1	Inter sector co-ordination (N/A)	15	-
Coord2	Inter centre co-ordination (N/A)	20	-
Coord3	Co-ordination(s) required for aircraft departing from a “local” airport	20	-
Coord4	Co-ordination(s) required for a flight arriving to a “local” airport	15	-
Coord5	Special co-ordination (e.g. with a military unit...)	25	-

Radar Task

Task id	Task description	Execution Time (seconds)	
		Planning Controller	Tactical (Executive) Controller
Radar1	Radar conflict search at sector entry	-	3
Radar2	Conflict resolution by radar intervention: 2 aircraft, same direction, stable	5	65
Radar3	Conflict resolution by radar intervention: 2 aircraft, same direction, at least one climbing or descending (unstable)	5	65
Radar4	Conflict resolution by radar intervention: 2 aircraft, on crossing tracks, stable	5	66
Radar5	Conflict resolution by radar intervention: 2 aircraft, on crossing tracks, at least one climbing or descending	5	66
Radar6	Conflict resolution by radar intervention: 2 aircraft, opposite direction, stable	5	72
Radar7	Conflict resolution by radar intervention: 2 aircraft, opposite direction, at least one climbing or descending	5	72

