applied sciences

MDPI

Article

Preliminary Impact Assessment of the Ad Hoc Separation Minima: A New Separation Mode

Lidia Serrano-Mira [1,*], Luis Pérez Sanz [1], Javier A. Pérez-Castán [1], Adrián Casado López [1], Eduardo S. Ayra [1,2] and Marta Pérez Maroto [1,3]

[1] ETSI Aeronáutica y del Espacio. Plaza del Cardenal Cisneros, 3, Universidad Politécnica de Madrid, 28040 Madrid, Spain; l.perez@upm.es (L.P.S.); javier.perez.castan@upm.es (J.A.P.-C.); adrian.casadol@alumnos.upm.es (A.C.L.); eduardo.sanchez.ayra@upm.es (E.S.A.); marta.perez.maroto@alumnos.upm.es (M.P.M.)
[2] Iberia Airlines, Calle de Martínez Villergas, 49, 28027 Madrid, Spain
[3] AESA—Agencia Estatal de Seguridad Aérea en España, Paseo de la Castellana 112, 28046 Madrid, Spain
* Correspondence: lidia.serrano@upm.es

Abstract: A major challenge for the Air Traffic Management system is the need to boost airspace capacity, which is near saturation in some situations. Separation minima are one of the factors related to airspace capacity, and the SESAR program promotes research into advanced separation modes. Ad Hoc separation, a novel separation mode, involves applying different pairwise separation minima in the same volume of airspace depending on a set of factors, such as encounter geometry, aircraft models, and flight level, among others. This research examines the impact of implementing this concept in different en-route scenarios. The goal is to determine whether applying this concept proves advantageous or, conversely, results in an increase in the complexity of the system without significant benefits in the key performance areas of capacity, environment, and cost-efficiency. Fast Time Simulations are conducted in RAMS software, with the concept being implemented in the LECMZMU, LECMTLU, and LECMDGU sectors of the Madrid ACC. The results reveal favorable capacity outcomes with increases of around 2% and the LECMZMU sector exhibits the most significant environmental and cost-efficiency benefits. Furthermore, implementing the Ad Hoc concept in a larger scenario could yield even greater environmental and cost-efficiency benefits.

Keywords: separation minima; ad hoc separation minima; airspace capacity; environment; cost-efficiency

check for updates

Citation: Serrano-Mira, L.; Sanz, L.P.; Pérez-Castán, J.A.; López, A.C.; Ayra, E.S.; Maroto, M.P. Preliminary Impact Assessment of the Ad Hoc Separation Minima: A New Separation Mode. *Appl. Sci.* **2024**, *14*, 3824. https://doi.org/10.3390/app14093824

Academic Editor: Yutaka Ishibashi

Received: 8 March 2024
Revised: 17 April 2024
Accepted: 25 April 2024
Published: 30 April 2024

1. Introduction

The most reliable traffic forecasts anticipate 16 million Instrumental Flight Rules (IFR) movements by 2050 in the region of the European Civil Aviation Conference (ECAC) [1], which represents a 44% growth in air traffic compared to the levels of 2019. 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.

This strategic action requires a plan for research, development and implementation of new concepts and technologies. The SESAR program (Single European Sky ATM Research [2]) is an initiative aimed primarily at developing the future ATM system in Europe. This strategic program focuses on the definition, development, validation, and implementation of innovative technological and operational solutions to enhance various aspects of ATM [3]. These solutions are geared towards achieving benefits in four key performance areas (KPAs): capacity, safety, efficiency, and environment.

Given this expected growth in air traffic demand, within the SESAR framework, it is crucial to address the capacity challenge without neglecting environmental concerns or compromising safety levels. In pursuit of these goals, SESAR proposes research into various solutions, which address different KPAs.

Regarding the capacity KPA, several projects have been or are being performed to explore potential solutions. Among others, one of the investigated solutions is the dynamic configuration of airspace (DAC) [4], where the design/configuration of sectors adapts to traffic flows. Another solution developed [5] is based on Performance Based Navigation (PBN), specifically on the Required Navigation Performance (RNP) specifications of navigation. By meeting the required criteria (in terms of accuracy, continuity, etc.), it is possible to increase capacity through the reduction in spacing between routes and the incorporation of new ones. Additionally, improvements in ATC support systems contribute to capacity enhancement. The solution developed in [6] aims to decrease the frequency of tactical Air Traffic Control (ATC) interventions by equipping Air Traffic Control Officers (ATCOs) with ground conflict detection and resolution (CD&R) tools reliant on an enhanced ground trajectory prediction based on improved aircraft data. In [7], the SESAR solution provides the en-route ATCOs with two services to assist them in the separation provision. Firstly, the Monitoring of Aircraft Trajectories (MONA) service offers trajectory monitoring with newly included alerts. Secondly, the CD&R functionality provides improved conflict detection and resolution capabilities.

Regarding the environmental and cost-efficiency KPAs, some of the extensively studied solutions include the Continuous Descent Operations (CDO) [8–10] and Continuous Climb Operations (CCO) [11–13]. The impact of these ecofriendly trajectories (optimized descents and climbs) on emissions, fuel consumption, and noise is analyzed in [14,15] (CDOs) and in [16,17] (CCOs). Conversely, in general, the other concepts' main goal is not to achieve an environmental improvement. That is, in other concepts, the environmental benefits are generally achieved indirectly, as a consequence of improvements in other aspects. Examples of this include concepts such as Free Route or AMAN/DMAN. In the Free Route concept [18], aircraft are allowed to fly their chosen trajectories between entry and exit points in an airspace, without the need to follow published routes along conventional airways. As a result, the flown routes are generally shorter, leading to savings in flown distance, flight time, fuel, and emissions. The AMAN/DMAN solution [19] provides automated support for aircraft sequencing, assisting ATCOs in managing traffic arriving and departing from an airport. Because of sequence optimization, waiting times, the associated flown distances, fuel consumption, and emissions are reduced. An analysis of the impact of these concepts on the environment and cost-efficiency was conducted for Free Route airspace in [20,21], and for AMAN/DMAN in [22–24].

In the last SESAR call [25], a proposed research line related to airspace capacity is the evolution of separation minima. Separation minima values were determined decades ago. SESAR encourages research into advanced separation modes (e.g., dynamic separation) because new horizons are opening in the ATM system. This is due to recent and expected future technological developments (European ATM Masterplan, Level 4 and Level 5 of Automation [26]) and their impact on the area of separation minima and separation modes. Ad Hoc or Variable separation minima (ADSM) concept is one of these new topics, among others, such as Time-Based Separation (TBS), Airborne Separation Assurance Systems (ASAS), or European Recategorization Pairwise (RECAT-EU PWS). This last solution [27] was recently developed and is based on the definition of different Minimum Wake Vortex Separation (MWS) values, depending on the aircraft models (considering over a hundred) and according to their individual characteristics.

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 model, aircraft mass, FL, and encounter geometry, among others. These pairwise separation minima (Ad Hoc separation) also imply a reduction in separation values in those situations in which this is safe. On the one hand, this new separation mode is expected, to some extent, to increase airspace capacity. On the other hand, the effort to reduce separation minima values aims, among other objectives, to minimize the necessity for frequent tactical interventions by ATCOs during in-flight operations. Consequently, the reduction in ATCO interventions holds the potential to decrease aircraft deviations from their intended trajectories, resulting in savings in fuel, carbon dioxide emissions (CO_2), and mitigating delays.

In this research, an analysis is presented of the impact of this novel concept in various en-route scenarios. The objective of this analysis is to assess whether applying this concept to a scenario is beneficial. It is considered non-beneficial if the application of this concept increases system complexity without yielding any benefits in terms of capacity, environment, and airspace user cost-efficiency. This analysis serves as a Go/No-Go test for the next stages of development.

This study is structured as follows: Section 2 provides a brief description of the Ad Hoc separation operational concept (CONOPS), while Section 3 outlines the methodology that is employed to assess the impact of implementing this concept on the capacity, environmental, and cost-efficiency KPAs. The results of the analysis of different scenarios are presented in Section 4. Section 5 includes a discussion of the results. Finally, Section 6 provides conclusions drawn from the findings and outlines potential avenues for future research.

2. Ad Hoc Separation CONOPS

The concept of the ADSM refers to the application of a variable separation value for each aircraft pair within the same volume of airspace, depending on a set of factors, namely: aircraft models, aircraft masses, aircraft speed, encounter geometry (intersection angle), avoidance maneuver (AM), FL, Human Factor (HF), and wind conditions. These separation minima values must always be greater than the corresponding en-route minimum wake vortex separation obtained as an input from [28]. The CONOPS of Ad Hoc separation was developed in previous work. For a better understanding of this, readers are referred to [29]. This section provides a brief explanation of the Ad Hoc CONOPS.

In the first stage of the development of this concept, ADSM are only determined for the horizontal dimension. The main feature of this new mode of operation is that there is a set of possible separation minima values within the range of 3 Nautical Miles (NM)–5 NM. Therefore, this concept not only implies applying different separation minima values depending on the situation, but also reducing the separation minima wherever possible. The possible Ad Hoc separation values within the defined range are 3 NM, 4 NM, or 5 NM. At further stages of the concept's development, other separation values could be applied with a higher resolution (i.e., 3.5 NM). These extreme values (3 NM–5 NM) are considered for the following reasons:

- Upper limit value (5 NM): currently, in en-route scenarios with surveillance, the defined horizontal separation minimum is 5 NM.
- Lower limit value (3 NM): in en-route phase when the preceding aircraft belongs to an equal or lower category than the succeeding one, the MWS separation may be smaller than 5 NM [28]. There are several projects which have studied or are studying the reduction of MWS and proposing new en-route MWS values: [28,30,31]. Therefore, it was decided to take the value of 3 NM as the lower limit of the range of variable separations.

2.1. Operational Scenario

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

- En-route airspace, sectors of medium–high complexity and traffic density.
- Upper en-route FLs are considered (FL 340–FL 660).
- Aircraft flying at the same FL. These are the majority of aircraft in the cruise segment. This means that it is just considered horizontal separation minima.
- A scenario of predefined routes.

Nevertheless, once the feasibility of this novel concept is demonstrated, its application will be extended to 3D (aircraft in evolution) and to Free Route Airspace.

2.2. Mode of Operation: ATCO—Ad Hoc Separation Minima Tool (ASMT) Interaction

The application of different separation minima values in the same volume of airspace means that the ATCO is unable to mentally calculate the variable separation that must be applied between a specific aircraft pair, as opposed to the current fixed value (5 NM). Therefore, ATCOs need a new tool which presents this separation value for each aircraft pair in the airspace that falls 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 a sector, the ASMT.

ASMT shows the ADSM values for each aircraft pair to the ATCO in real time. In other words, the ATCO remains the agent of separation, but the concept of operation in the control exercise will change 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 (ICAO absolute approach for safety assessment [32]) to determine, prior to implementation, whether they are safe. These ADSM are saved in a database for the different possible encounter situations and the ASMT shows the ATCO, in real time, the specific ADSM corresponding to a particular encounter situation, which has been determined strategically.

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 maneuvers to resolve them (horizontal maneuvers, i.e., vectors, which are commonly used by ATCOs for solving conflict situations). 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. Therefore, the ASMT includes CD&R functionalities.

The ASMT was developed for the tactical ATCO (TC), who continuously monitors the state of the aircraft throughout the airspace. It is composed of different modules (red box in Figure 1): trajectory prediction module, situation of interest (SI) detection and characterization module, Ad Hoc separation determination module, conflict detection (CD) module, and conflict resolution (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 will perform their tasks without an increase in their workload (WL). For more information regarding the ASMT, the authors recommend [33], in which the modes of operation of the different modules which comprise the ASMT are explained in depth.

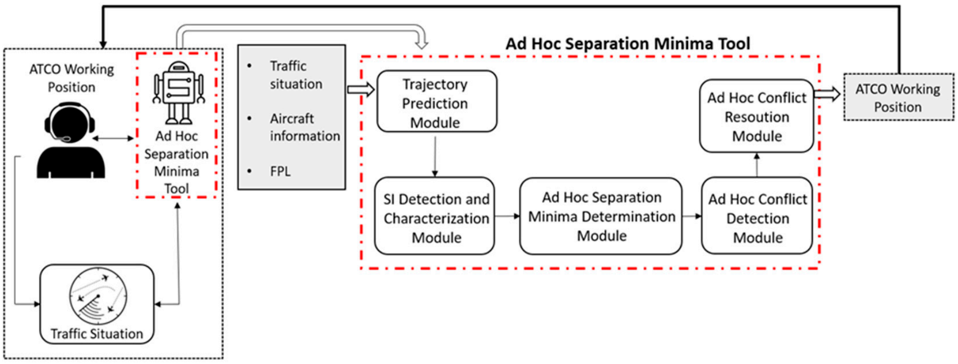


Figure 1. ASMT architecture and relation to the working position of the ATCO.

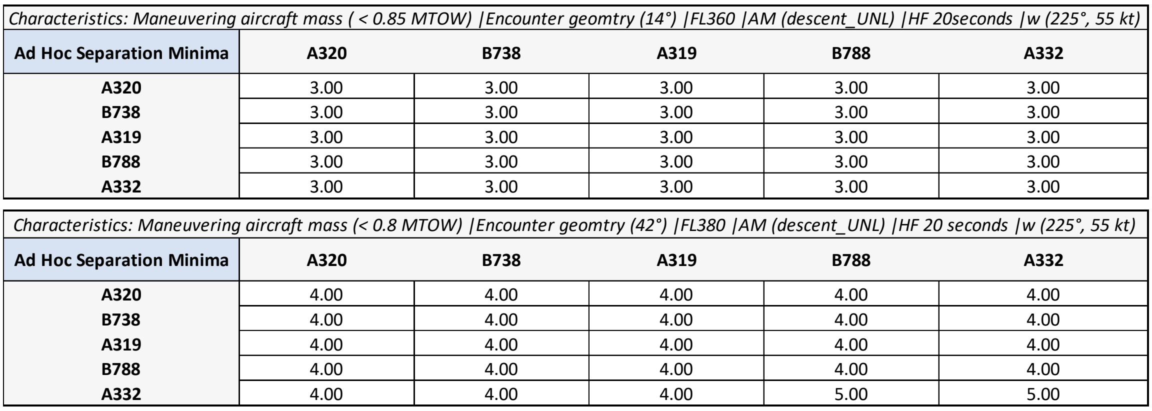
2.3. Ad Hoc Separation Minima Determination

To determine the separation minima to be applied in an airspace, it is necessary to ensure that the air traffic operation is developed while maintaining safety levels in that scenario. According to the ICAO [32], 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 the estimated performance of the proposed system is compared against the performance of a system which has already been judged to be safe [32]. 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 the Target Level of Safety (TLS)).

Generally, the absolute method has been used by the ICAO to determine whether a system is safe for specific separation minima. This is the one used for computing ADSM. Thus, the ADSM values were strategically determined based on a Collision Risk Model (CRM). This CRM, as well as the TLS, were expressly developed and estimated throughout the research on the Ad Hoc separation concept.

Risk values were determined through Monte Carlo simulations, considering navigation and speed uncertainties. Different encounter situations between aircraft pairs were simulated, resulting from the combination of various factors influencing ADSM (aircraft models, aircraft masses, FL, AM, wind conditions, etc.), and the ADSM were obtained (an example of ADSM in NM is shown in Figure 2). The influence of these parameters on ADSM is shown in [29].



Characteristics: Maneuvering aircraft mass (< 0.85 MTOW) |Encounter geomtry (14°) |FL360 |AM (descent_UNL) |HF 20seconds |w (225°, 55 kt)

Ad Hoc Separation Minima	A320	B738	A319	B788	A332
A320	3.00	3.00	3.00	3.00	3.00
B738	3.00	3.00	3.00	3.00	3.00
A319	3.00	3.00	3.00	3.00	3.00
B788	3.00	3.00	3.00	3.00	3.00
A332	3.00	3.00	3.00	3.00	3.00

Characteristics: Maneuvering aircraft mass (< 0.8 MTOW) |Encounter geomtry (42°) |FL380 |AM (descent_UNL) |HF 20 seconds |w (225°, 55 kt)

Ad Hoc Separation Minima	A320	B738	A319	B788	A332
A320	4.00	4.00	4.00	4.00	4.00
B738	4.00	4.00	4.00	4.00	4.00
A319	4.00	4.00	4.00	4.00	4.00
B788	4.00	4.00	4.00	4.00	4.00
A332	4.00	4.00	4.00	5.00	5.00

Figure 2. LECMZMU Ad Hoc separation minima for specific situations in NM.

3. Methodology

Once the CONOPS of the Ad Hoc separation minima has been briefly described, the methodology used for the preliminary impact assessment of the implementation of the Ad Hoc separation mode in a scenario is presented.

KPAs are defined by ICAO [34] as a way to categorize performance aspects relative to high-level ambitions. Key Performance Indicators (KPIs) quantitatively express current, past, or expected future performance, as well as the actual progress in achieving performance objectives [35]. The difference between KPIs and Performance Indicators (PIs) is that KPIs are those which have an associated Validation Target, while PIs are those that do not.

Table 1 shows the KPAs and PIs selected for this research. Other studies with similar objectives also used these indicators [36,37]. It can be seen in Table 1 that there is no metric related to safety. However, it should be noted that the ADSM were determined on the basis of a risk assessment. Each Ad Hoc separation value corresponds to a risk value that was checked against a TLS. Therefore, the values are safe. The following KPAs and PIs were used.

Table 1. KPAs and PIs defined for the preliminary impact assessment of the ADSM concept.

KPA (SESAR)	PI	Units
Capacity	En-route throughput	Number of aircraft entering per hour

Table 1. *Cont.*

KPA (SESAR)	PI	Units
Environment	CO_2 emissions reduction per *LOS* saved Fuel reduction per *LOS* saved Flown distance reduction per *LOS* saved	Kg Kg NM
Airspace User Cost-Efficiency	Strategic Delay reduction per *LOS* saved	Minutes

3.1. Capacity KPA

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 [38]. En-route capacity is analyzed in this study and is commonly estimated using Fast Time Simulations (FTS), employing models based on the ATCO workload (WL). An in-depth analysis of the different models applied in European and North American countries for the capacity estimation is provided in [39].

CAPAN methodology [40] was used for capacity computation in this research. This methodology was developed by EUROCONTROL. The capacity is estimated from the WL values of the tactical ATCO (TC) by means of FTS, with the ATCO WL being expressed in time values. The ATCO WL threshold used to obtain the capacity value was 70%, a value commonly used by several countries, such as Spain, Italy, Portugal, and Norway. Therefore, the capacity calculated with this threshold is equivalent to a WL of 42 min in one hour (70%).

To calculate the ATCO WL, FTS are performed in RAMS software [41]. For this purpose, a 24H traffic sample (FPL trajectories, i.e., not modified by ATCO interventions) is used, which is cloned repeatedly to obtain 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 were obtained from [42] and are detailed in Appendix A. The RAMS software simulates the real behavior of the sector and provides values for the tactical ATCO (TC) and planner ATCOs (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, different days of the busy week (the one containing the busy day) were simulated in RAMS, determining the ATCO WL for each hour of each of the days. Three scenarios were considered for the capacity study: the 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 Ad Hoc separation is implemented and the ASMT tool is available for the ATCO. However, this tool only includes the Ad Hoc separation determination functionality for each aircraft pair, not the CD&R functionality.
- Scenario 2: scenario in which the concept of the Ad Hoc separation is implemented and the ASMT support tool is available, which includes, among its functionalities, the CD&R.

A key assumption regarding the capacity computation in a scenario in which the concept of Ad Hoc separation is implemented is the issue that the ATCO WL could change. From the point of view of separation management, the concept of Ad Hoc separation could seem 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).

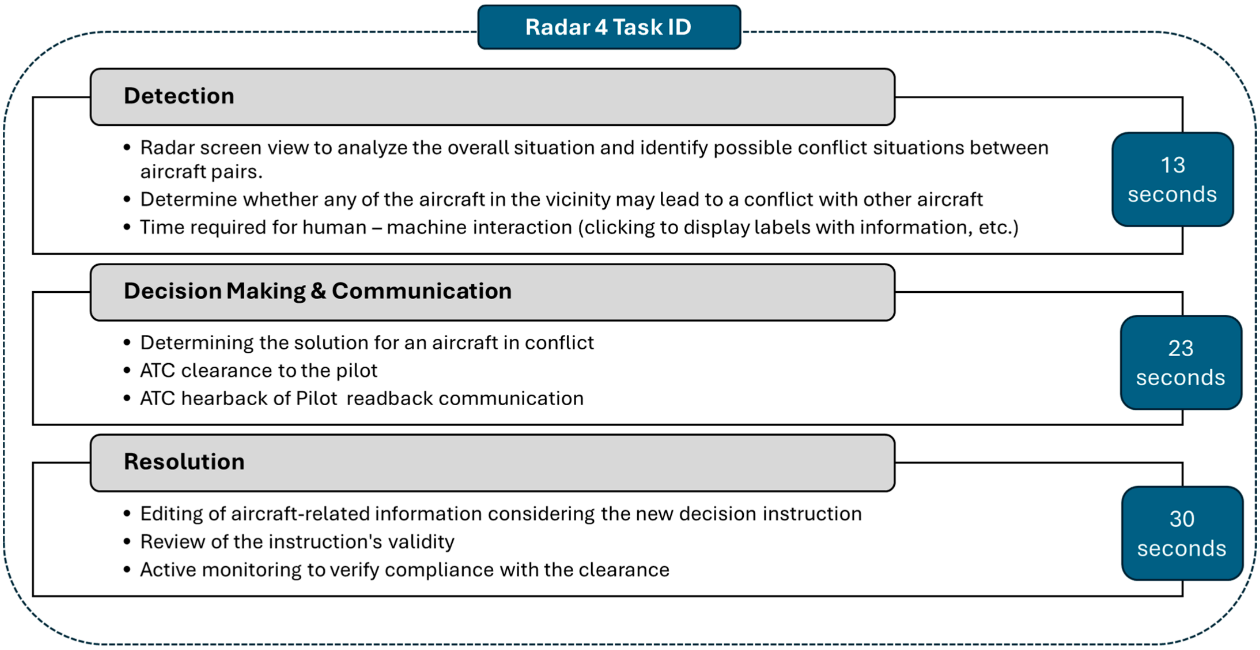
The number of *LOS* decreases because of reducing separation minima. That is, *LOS* that could occur with a separation value of 5NM, now, with Ad Hoc separation, may not occur (*LOS* saved). The ATCO time associated with each of these *LOS* saved (detection and resolution tasks), which translates into 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.

Appendix A shows the tasks and their associated times, defined in RAMS for the calculation of the ATCO WL, which were extracted from [42]. These tasks are classified into five categories: Conflict Search, Flight Data Management, R/T Task, Co-ordination, Radar Task.

The Radar Task category includes those tasks associated with CD&R actions (Table A1, Appendix A). This category is divided into seven different tasks (Radar 1–7) depending on the *LOS* conditions (stabilized flight, same direction, etc.). Each of these tasks encompasses a set of actions, as follows:

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

Different meetings were arranged with experts from the European Union Aviation Safety Agency (EASA) and Spanish Air Navigation Service Provider (ANSP), to quantify the different actions (detection, decision making and communication, and resolution) in these tasks (Radar 1–7 tasks). Figure 3 shows an example of how Radar 4 Tasks were divided into the different actions, along with the associated times.



- Radar screen view to analyze the overall situation and identify possible conflict situations between aircraft pairs.
- Determine whether any of the aircraft in the vicinity may lead to a conflict with other aircraft
- Time required for human – machine interaction (clicking to display labels with information, etc.)

- Determining the solution for an aircraft in conflict
- ATC clearance to the pilot
- ATC hearback of Pilot readback communication

- Editing of aircraft-related information considering the new decision instruction
- Review of the instruction's validity
- Active monitoring to verify compliance with the clearance

Figure 3. Radar 4 task split (from Appendix A) 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 [33], a 50% improvement in the detection action and a 20% improvement in the decision making action is estimated 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 determine whether any of the aircraft in the vicinity may lead to a conflict with other aircraft. Meanwhile, the 20% enhancement in decision making action is due to

ASMT functionality to present a range of conflict resolution maneuvers to the ATCO after having detected a conflict. Therefore, the ATCO time associated with the evaluation of the resolution maneuver is reduced. In Figure 3, for the Radar 4 task split, this means a time reduction of 6 s in detection and 5 s in decision making.

3.2. Environment and Airspace User Cost-Efficiency KPAs

Further KPAs in which the Ad Hoc separation concept could provide some benefits are the environmental and airspace user cost-efficiency KPAs. In particular, the environmental impact was analyzed based on three indicators: flown distance reduction, fuel consumption reduction, and CO_2 emissions reduction. The airspace user cost-efficiency KPA is quantified through the reduction in strategic delays.

For this purpose, based on the previous FTS, the number of LOS that would not occur under the Ad Hoc separation concept was considered. If the separation was 5NM, the ATCO would provide 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 emissions, and delay related to such resolutions are computed. Thus, it is possible to define the average, maximum, and minimum values of distance (Equation (1)), fuel consumption (Equation (2)), CO_2 emissions (Equation (3), [43]), and delay (Equation (4)) per LOS that could be saved with ADSM.

$$\Delta Distance\ reduction\ per\ LOS\ saved = sector\ flight\ distance_{actual} - sector\ flight\ distance_{scheduled} \tag{1}$$

$$\Delta fuel\ reduction\ per\ LOS\ saved = actual\ fuel - scheduled\ fuel \tag{2}$$

$$\Delta CO_2\ reduction\ per\ LOS\ saved = \Delta fuel\ per\ conflict\ saved * 3.15 \tag{3}$$

$$Delay\ reduction\ per\ LOS\ saved = sector\ flight\ time_{actual} - sector\ flight\ time_{scheduled} \tag{4}$$

It is worth noting that the outcomes achieved in terms of flight distance reduction, fuel reduction, CO_2 emissions reduction, and delay reduction are a result of minimizing ATCO interventions in aircraft trajectories by reducing the number of LOS through the Ad Hoc separation application.

3.3. Scenarios for the Ad Hoc Implementation

Three en-route scenarios from the Madrid ACC were selected for the implementation of Ad Hoc separation. These sectors are LECMZMU (Reference Scenario), LECMTLU and LECMDGU (Figure 4).

LECMZMU sector is located in the west part of the Madrid ACC (Figure 4), on the border between FIR Madrid (LECM) and FIR Lisbon (LPPC). The demand in the sector is strongly conditioned 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. According to the IATA definition, the busy day is the second busiest day in an average week during the peak month [44]. Pre-pandemic traffic levels were considered for this analysis (2019 year). Therefore, the peak month of traffic in LECMZMU during the year 2019 was July, and the busy day was the 13th of July. AIRAC 1907 data were used, obtained from EUROCONTROL DDR2 [45]. LECMZMU was designed as reference scenario.

The LECMTLU sector is located in the southern part of the Madrid ACC (Figure 4), 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 and the busy day for the year 2019 was 6th of July.

The LECMDGU sector is centrally located in the Madrid ACC (Figure 4). It 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 and the busy day for the year 2019 was 7th of July.

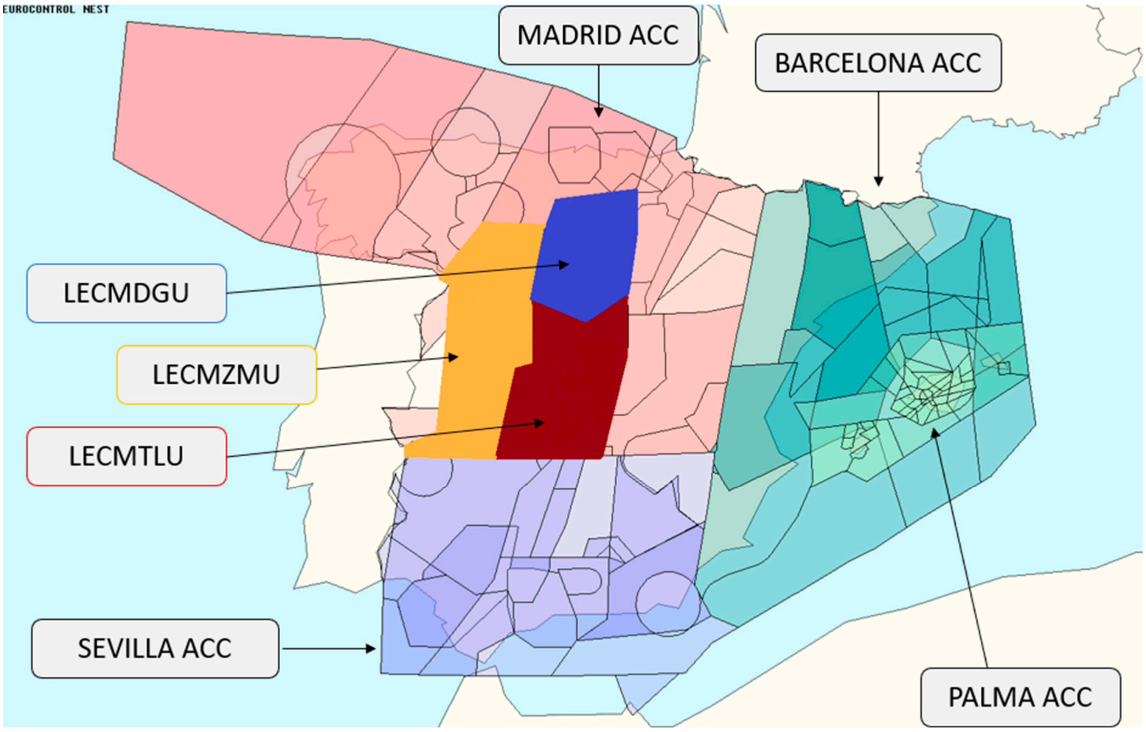


Figure 4. LECMZMU, LECMTLU, and LECMDGU sectors of MADRID ACC.

4. Fast Time Simulation Results

Within this section, the findings derived from the FTS are presented. These results are categorized by scenario and KPAs. Firstly, the results obtained for the reference scenario are analyzed (LECMZMU). Secondly, the concept is applied in alternative en-route sectors (the LECMTLU and LECMDGU sectors of Madrid ACC) to verify whether benefits could be realized in airspaces other than the reference scenario. An analysis of the impact of this concept on the capacity, environment, and airspace user cost-efficiency KPAs is presented below.

4.1. LECMZMU Sector

4.1.1. Capacity

- Baseline scenario
  The capacity value obtained from the FTS computed during the busy week (8–14 July) is 46 aircraft/hour (46.95 aircraft/hour), as shown in Figure 5 (red arrow). The declared capacity of the LECMZMU sector is slightly lower, 45 aircraft/hour. Therefore, the value obtained from the CAPAN methodology is considered acceptable. The 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.
- Scenario 1
  The new TC WL in the LECMZMU sector with the Ad Hoc separation concept implemented results in a new capacity value. This was computed by simulating the LECMZMU scenario again but applying the ADSM between the different aircraft pairs. As shown in Figure 6, the obtained result is 47 aircraft/hour (47.79 aircraft/hour).
- Scenario 2
  Considering that ASMT includes CD&R functionalities, from a conservative perspec-

tive, it can be assumed that there would be a 50% improvement in the detection task and a 20% improvement in the decision making. This means a time reduction of 6 s in detection and 5 s in decision making, as mentioned before. Therefore, by calculating the new 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 7.

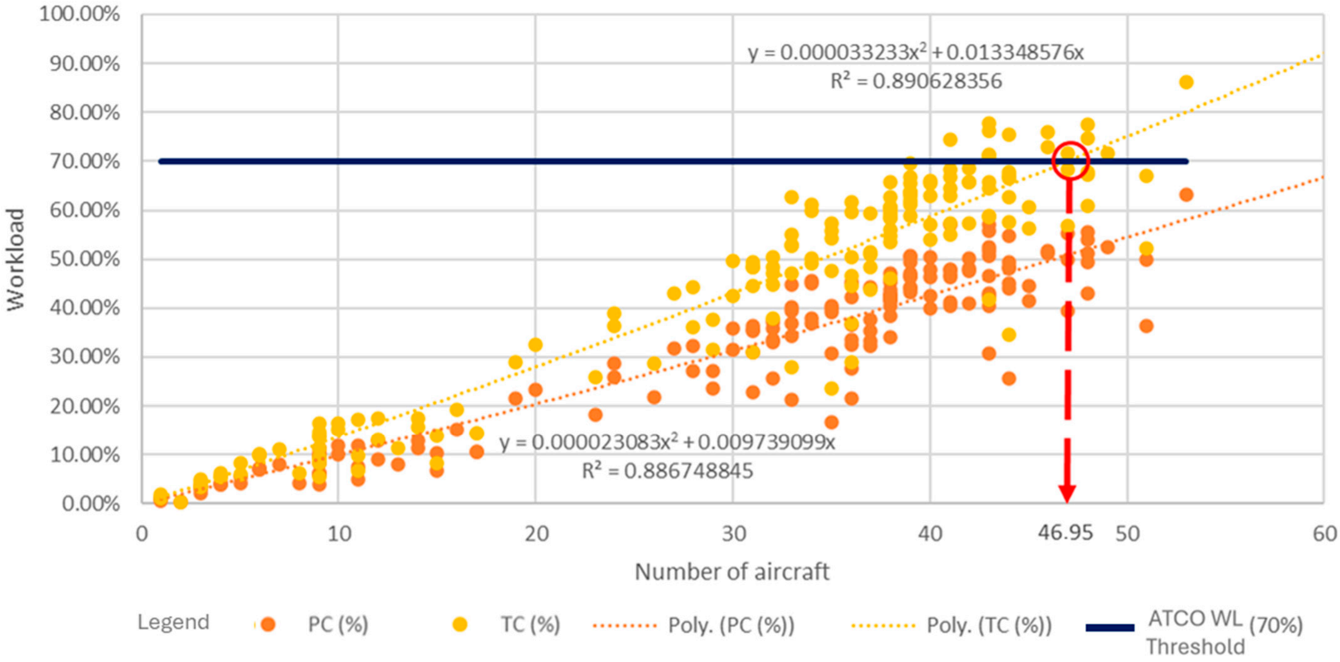


Figure 5. LECMZMU capacity 5NM separation—Baseline Scenario.

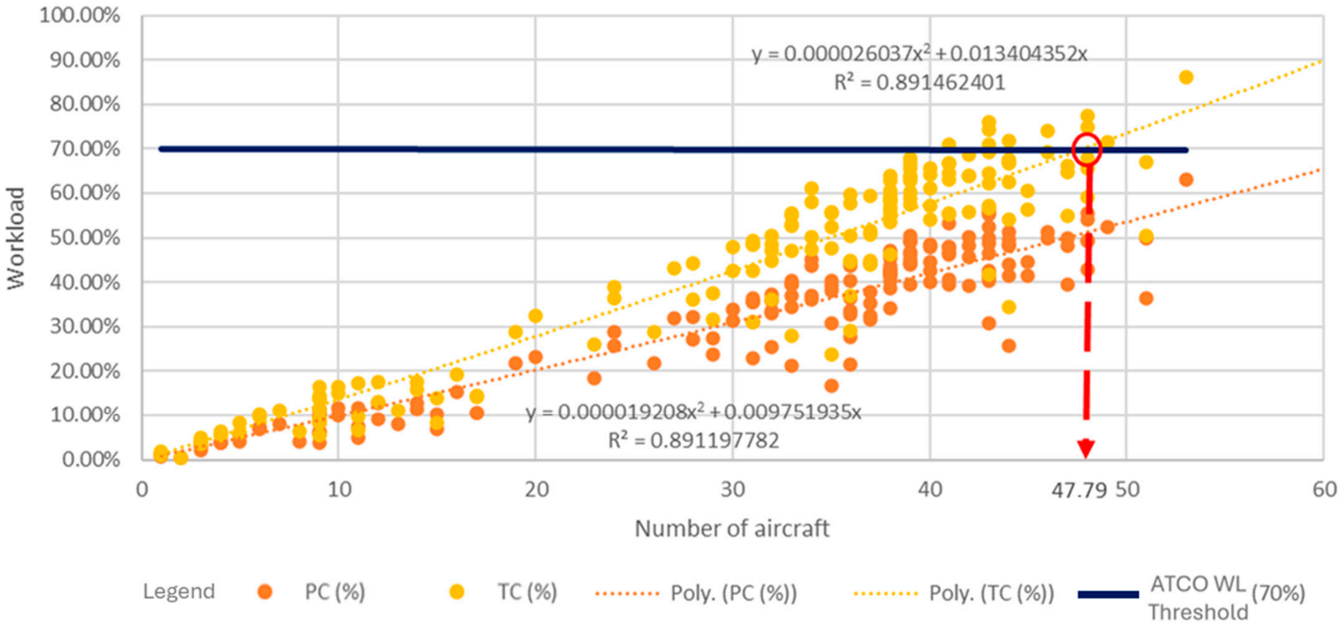


Figure 6. LECMZMU capacity Ad Hoc separation—Scenario 1.

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

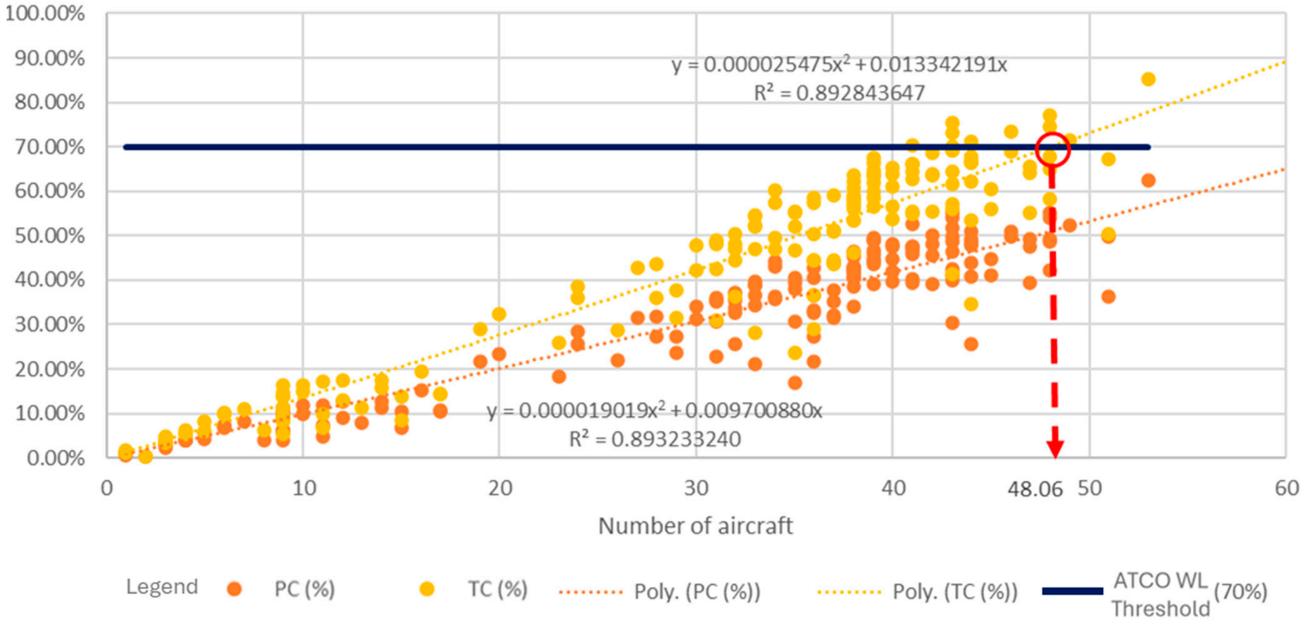


Figure 7. LECMZMU capacity Ad Hoc separation—Scenario 2.

Table 2. 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)	48.06	48	1.1	2.3%

4.1.2. Environment and Airspace User Cost-Efficiency

Figure 8 shows the values obtained for the LECMZMU sector. These results are categorized by lateral *LOS*, longitudinal *LOS* and total *LOS* (lateral and longitudinal). This classification is made according to the type of resolution maneuver that the ATCO of the RAMS software has cleared the aircraft to perform, i.e., a level change (FL) or a horizontal maneuver (vector).

The greatest benefits are obtained in the resolution of lateral *LOS* by applying a horizontal maneuver (vector). Resolution maneuvers in the horizontal plane are preferred by ATCOs compared to vertical ones (FL changes). This is due to several factors, such as less traffic disruption, the fact that 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 [46], in LECMZMU, the average flown distance is 84NM, and the average flight time in the sector is 11 min. Consequently, if lateral *LOS* with horizontal resolution maneuvers are analyzed, the results obtained are as followed:

- 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 min per *LOS* saved, which represents 6.18% of the total flight time in the sector.
- Fuel and CO_2 emissions: reduction, on average, of 28.7 kg in fuel and 90.50 kg in CO_2 emissions.

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

Figure 8. Environment and cost-efficiency results for the LECMZMU sector.

For longitudinal *LOS*, benefits are obtained, although they are smaller than for the lateral ones. The distribution of horizontal resolution maneuvers and level change maneuvers is equitable. Resolution maneuvers by level changes provide greater benefits in terms of fuel consumption and CO_2 emissions reductions. In general, favorable average results are obtained for the analyzed indicators, with 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.

4.2. LECMTLU Sector

4.2.1. Capacity

To compute the capacity in the LECMTLU sector, the days of the busy week (1–7 July 2019) were simulated in RAMS, determining the WL for each hour of each of the days. The capacity value determined for the Baseline Scenario is 46 aircraft per hour (46.81 aircraft/hour). The declared capacity for the LECMTLU sector is slightly lower, 45 aircraft per hour (the same as the LECMZMU sector). Consequently, the capacity value derived using the CAPAN methodology is deemed acceptable.

For Scenario 1, the implementation of the Ad Hoc separation concept results in a new TC WL in the LECMTLU sector, which yields a new capacity value of 47 aircraft per flight hour (47.24 aircraft/hour). In Scenario 2, the capacity computation considers ADSM implementation, with anticipated decreases in ATCO detection and decision making times due to the CD&R functionalities of the ASMT tool. The resulting capacity value for this scenario is 47 aircraft per flight hour (47.74 aircraft per flight hour).

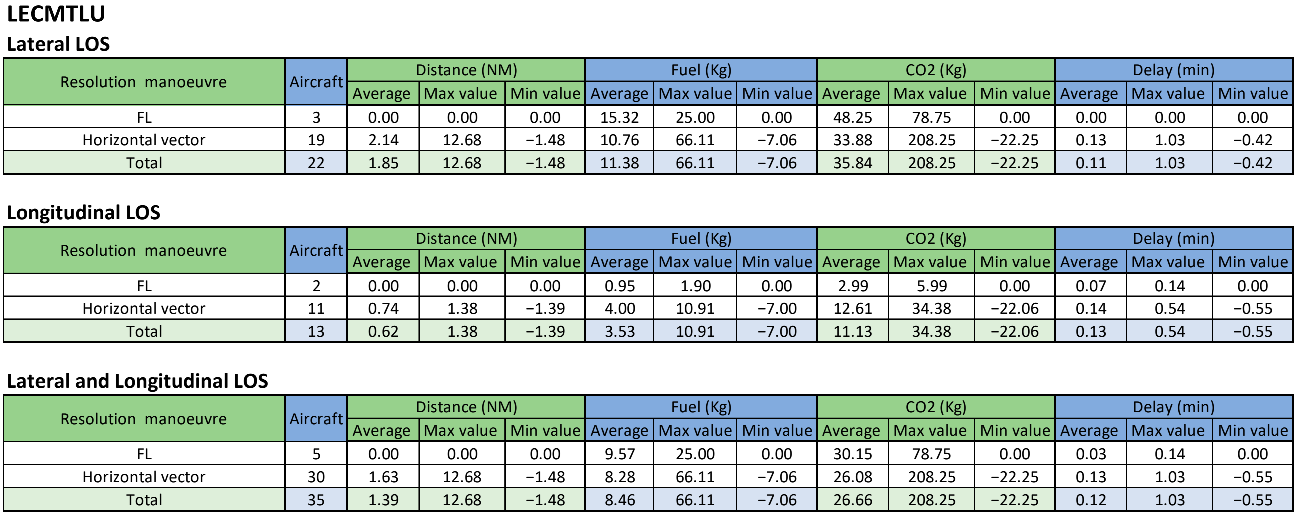
Table 3 compares the capacity outcomes attained in the LECMTLU sector, which are slightly lower than those of the LECMZMU sector. However, in relative terms, there is an increase from 46 aircraft per flight hour to 47 aircraft per flight hour. In absolute terms, this represents nearly 1 aircraft per hour of increased capacity, signifying a growth of 2% in the sector's capacity.

Table 3. 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%

4.2.2. Environment and Airspace User Cost-Efficiency

Figure 9 shows the results obtained for the LECMTLU sector. Positive results were 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 maneuvers (vector).



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

Figure 9. Environment and cost-efficiency results for the LECMTLU sector.

These values should be placed in the context of the sector's characteristics. In LECMTLU, the average crossing distance is 115 NM and the average flight time in the sector is 15.5 min (obtained from NEST data [46]). Therefore, if the lateral *LOS* with horizontal resolution maneuvers are analyzed, the following 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 min per *LOS* saved, representing 0.84% of the total flight time in the sector.
- Fuel and CO_2: average reduction of 10.76 of kg fuel and 33.88 kg of CO_2 emissions.

Benefits are also obtained for longitudinal *LOS*, although fewer than in lateral *LOS*. Horizontal resolution maneuvers predominate for both types of *LOS*, longitudinal and lateral. Finally, in general terms, favorable average results are obtained for the analyzed indicators, with all of them being positive.

4.3. LECMDGU Sector

4.3.1. Capacity

The days of the busy week (1–7 July 2019) were simulated in RAMS for the computation of the capacity in the LECMDGU sector. The capacity value obtained in the Baseline Scenario after performing the FTS in RAMS was 46 aircraft/hour (46.74 aircraft/hour). The declared capacity of the LECMDGU sector is slightly lower, 44 aircraft/hour. Hence, there is a difference of two aircraft/hour, whereas for the LECMZMU and LECMDGU, the difference was only one aircraft/hour. Nevertheless, this capacity value should be considered as a benchmark to compare the capacity values associated with the other two scenarios. In Scenario 1, the capacity outcome is 47 aircraft/hour (47.17 aircraft/hour) while in Scenario 2, this stands at 47 aircraft/ hour (47.63 aircraft/hour).

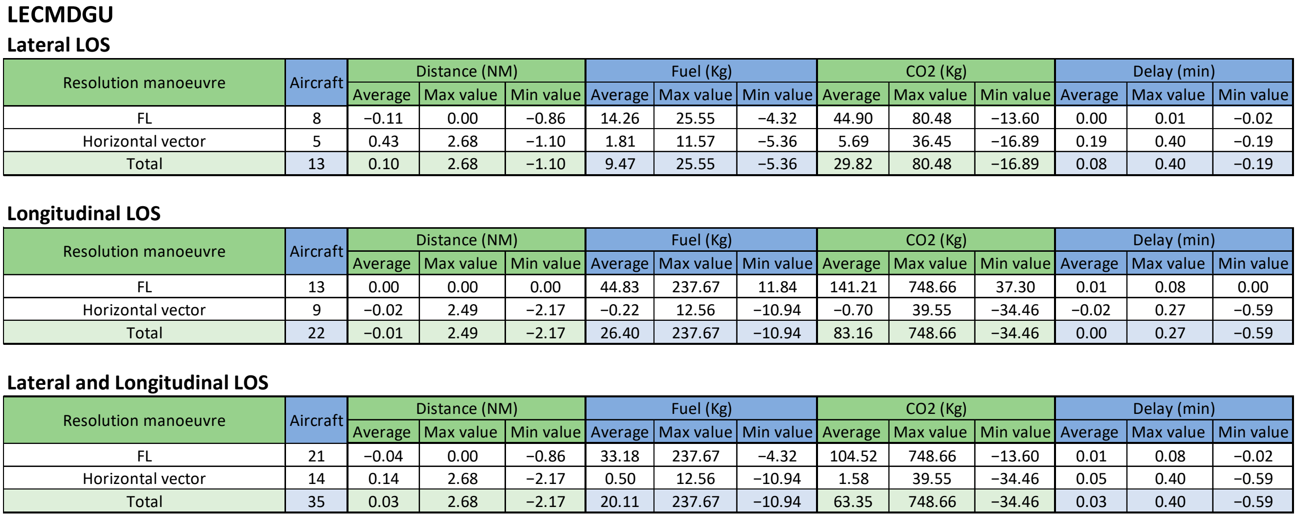
Table 4 presents a comparison of the capacity results obtained for the LECMDGU sector. It is observed that the increase in capacity is similar to that in LECMTLU, though slightly lower. In relative terms, there is a shift from 46 aircraft/ hour to 47 aircraft/hour. However, in absolute terms, the increase in the best-case scenario (Scenario 2) is 0.9 aircraft/hour, signifying an almost 2% capacity increase in the sector.

Table 4. 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%

4.3.2. Environment and Airspace User Cost-Efficiency

Figure 10 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 primarily involves level change maneuvers. 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 implementing the Ad Hoc separation concept.



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

Figure 10. Environment and cost-efficiency results for the LECMDGU sector.

These values are contextualized 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 min (obtained from NEST data [46]). Therefore, if the total *LOS* results (lateral and longitudinal) are analyzed considering both maneuvers together, the following results are obtained:

- Distance: reduction, on average, of 0.03 NM per *LOS* saved, or 0.03% of the total distance travelled in the sector.
- Delay: reduction, on average, of 0.03 min 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 emissions.

5. Discussion

After applying the concept in three different scenarios, the achieved outcomes are compared. Regarding the environment and cost-efficiency KPAs, it should be noted that the best results for LECMZMU and LECMTLU are obtained for lateral *LOS* resolved with horizontal maneuvers. For LECMDGU, lateral *LOS* resolved with horizontal maneuvers provide the highest benefits in flown distance and delay while for fuel and CO_2 emissions, the best results are obtained for longitudinal *LOS* resolved with level change. However, a comparison of results was made regarding the average resolution values corresponding to the total *LOS* (lateral and longitudinal). Therefore, the average values obtained, considering the total *LOS* resolved with horizontal and vertical maneuvers, are discussed.

- **Capacity:** the results are favorable in all three scenarios, with an increase in the number of aircraft per hour. The most significant improvement is observed in the LECMZMU scenario, where capacity is enhanced by 2.3%. In LECMTLU, the increase is 2%, while in LECMDGU it is 1.9%. These outcomes are obtained considering that the ATCO is aided by the ASMT tool, which, in addition to determining the Ad Hoc separation, incorporates CD&R functionalities.

  These results underscore the positive impact of the Ad Hoc separation concept on capacity (increase of one aircraft/hour). However, they highlight that the separation minima are not a key factor in capacity computation for an ENR scenario.
- **Environment and airspace user cost-efficiency**: positive results are obtained for these KPAs. The values obtained for distance flown, fuel, CO_2, and delay reduction, are for each *LOS* saved by applying the Ad Hoc separation concept.

  For the LECMZMU sector, the most favorable outcomes occur when lateral *LOS* is resolved with horizontal maneuvers. Considering both lateral and longitudinal *LOS* (total *LOS*), along with both resolution maneuvers (level change and horizontal vector), there is an average reduction of 1.30NM/*LOS* in distance saved (1.6% of the flown distance in the sector), a delay of 0.09 min/*LOS* saved (0.8% of the flight time in the sector), 12 kg fuel/*LOS* saved, and 37 kg CO_2/LOS saved.

  For the LECMTLU sector, the best results are obtained for lateral *LOS* resolved with horizontal maneuvers (vectors), as in LECMZMU, although the benefits are slightly lower. Considering the total *LOS* (lateral and longitudinal) and both resolution maneuvers (level change and horizontal vector), there is an average reduction of 1.39NM/*LOS* in distance saved (1.2% of the flown distance in the sector), a delay of 0.12 min/*LOS* saved (0.8% of the flight time in the sector), 8.5 kg fuel/*LOS* saved, and 27 kg CO_2/LOS saved.

  For the LECMDGU sector, the obtained benefits are lower than in LECMZMU and LECMTLU. However, due to the predominance of *LOS* resolutions with level changes, the best results are observed for fuel consumption and CO_2 metrics. Considering the total *LOS* (lateral and longitudinal) and both resolution maneuvers (FL change and horizontal vector), there is an average reduction of 0.03NM/*LOS* in distance saved (0.03% of the flown distance in the sector), a delay of 0.03 min/*LOS* saved (0.2% of the flight time in the sector), 20 kg fuel/*LOS* saved, and 63 kg CO_2/LOS saved. It should be noted that, in these results, there may not be a correlation between the reduced distance indicator and fuel consumption (as occurs in LECMDGU), since when a *LOS* is resolved with FL change, there is fuel consumption but the difference in terms of the flown distance at resolution and the planned distance is considered negligible.

  The best results are obtained for the reference scenario LECMZMU. However, there are also benefits in the LECMTLU and LECMDGU sectors, albeit smaller. In conclusion, it could be stated that if the concept were implemented in a broader scenario (ACC) rather than in a single sector, the obtained benefits would be more significant.

The improvements in flight distance, fuel, CO_2 emissions, and delay are a result of minimizing ATCO interventions in aircraft trajectories by reducing the number of *LOS* through the Ad Hoc separation application. Given the compelling findings outlined above, it is suggested to pursue further development and research into this innovative separation mode.

Future research on Ad Hoc separation would follow a stepwise process. Firstly, this would entail the technical development, validation, verification, and certification of the ASMT tool, all based on the ASMT tool prototype. The certification process of this system should be conducted in accordance with the EASA and European Commission regulations [47]. The validation of this concept would follow the Eurocontrol E-OCVM methodology [48].

Upon positive validation, the implementation of this concept could be extended to futuristic scenarios, such as free route scenarios. Finally, the concept could be generalized to 3D and applied to other scenarios, including Terminal Maneuvering Areas (TMAs).

6. Conclusions

The air transport system is expected to experience a continued increase in the number of movements. The current focus is to address the shortage of capacity to handle the forecasted demand while maintaining safety levels. Although the forecasts are long-term, ATM adopts strategic solutions to meet future challenges through the SESAR macro-program.

One of the factors related to airspace capacity is separation minima. SESAR encourages an exploration of the evolution of the separation minima. A novel concept that was developed is Ad Hoc separation. This concept refers to the application of different separation minima values between aircraft flying in the same volume of airspace depending on certain factors.

In this research, an analysis of the impact of the Ad Hoc separation concept's application in different en-route sectors (LECMZMU, LECMTLU, and LECMDGU) of Madrid ACC was presented. When new concepts are introduced in the system, generally, the complexity increases. Therefore, it is important to perform an analysis, even at a preliminary level, to check whether it is beneficial to apply this concept in a scenario or whether, instead, the complexity of the system is being increased in exchange of no benefit. En-route airspace capacity, CO_2 emissions, fuel consumption, flown distance, and strategic delay indicators were selected for the impact assessment. The improvement in these last indicators (flight distance, fuel, CO_2 emissions, and delay) stems from the reduction of ATCO interventions in aircraft trajectories. This is achieved by diminishing the number of LOS through the application of the Ad Hoc separation concept. FTS simulations were performed in RAMS to determine the benefits.

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 separation minima are not a key factor in estimating the capacity of an en-route scenario. Regarding the environment and the airspace user cost-efficiency, the results showcased favorable outcomes for both KPAs, although the impact may not be deemed very significant. The application of this concept in a broader scenario (ACC) than in a single sector would provide major benefits.

Furthermore, through Ad Hoc separation, the number of ATCO interventions in the aircraft (for preventing or resolving LOS) is minimized, improving the aircraft and system performance (according to the previous findings). The outcomes obtained for these three sectors are representative and can be extrapolated to other sectors of similar complexity.

Finally, according to the previous findings, it is suggested that continuing the development and research on this new separation mode could be beneficial for the ATM system. In addition, research areas were identified on which future work could focus: (1) ASMT verification and ATCO expert judgement for ASMT HMI graphical design; (2) more in-depth study of the E-OCVM validation methodology; (3) extending the application of the concept to Free Route airspaces; (4) generalization of the ADSM methodology.

Author Contributions: Conceptualization, L.S.-M. and L.P.S.; methodology, L.S.-M., J.A.P.-C. and M.P.M.; software, A.C.L.; validation, L.S.-M. and A.C.L.; formal analysis, L.S.-M. and J.A.P.-C.; resources, L.P.S. and E.S.A.; data curation, L.S.-M. and A.C.L.; writing—original draft preparation, L.S.-M.; writing—review and editing, L.P.S., J.A.P.-C., A.C.L., E.S.A. and M.P.M.; funding acquisition, L.P.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: Notably, the authors acknowledge ISA Software, who granted us the license to use RAMS Plus (6.7 version). This tool has been crucial for performing this research.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

ACC	Area Control Center
ADSM	Ad Hoc Separation Minima
AIRAC	Aeronautical Information Regulation and Control
AM	Avoidance Maneuver
AMAN	Arrival Manager
ANSP	Air Navigation Service Provider
ASMT	Ad Hoc Separation Minima Tool
ATC	Air Traffic Control
ATCO	Air Traffic Control Officer
ATM	Air Traffic Management
CCO	Continuous Climb Operation
CD	Conflict Detection
CDO	Continuous Descent Operation
CD&R	Conflict Detection and Resolution
CR	Conflict Resolution
CRM	Collision Risk Model
CONOPS	Operational Concept
DAC	Dynamic Airspace Configuration
DMAN	Departure Manager
EASA	European Union Aviation Safety Agency
ECAC	European Civil Aviation Conference
FL	Flight Level
FTS	Fast Time Simulations
HF	Human Factor
ICAO	International Civil Aviation Organization
IFR	Instrumental Flight Rules
Kg	Kilograms
KPA	Key Performance Area
KPI	Key Performance Indicator
LECM	FIR Madrid
LEMD	Madrid-Barajas Adolfo Suárez airport
LPPC	FIR Lisbon
LPPT	Lisbon Humberto Delgado airport
LOS	*LOS*s of separation
MONA	Monitoring of Aircraft Trajectories
MWS	Minimum Wake Vortex Separation
NEST	Network strategic tool
NM	Nautical Miles
PBN	Performance-Based Navigation
PC	Planner ATCO
PI	Performance Indicator
RNP	Required Navigation Performance
RECAT-EU PWS	European Recategorization Pairwise
SESAR	Single European Sky ATM Research
TBS	Time-Based Separation
TC	Tactical ATCO
TMA	Terminal Maneuvering Area
WL	Workload

Appendix A ATC Tasks Specifications

This annex provides the tasks and their associated times, as defined in RAMS, for the computation of the ATCO WL, extracted from [42].

Table A1. RAMS tasks and times for the simulation of ATCO WL.

Conflict Search

Task id	Task Description	Execution Time (seconds) Planning ATCO	Execution Time (seconds) Tactical (Executive) ATCO
CFSch1	Conflict search to establish an initial clearance for a night 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 ATCO	Execution Time (seconds) Tactical (Executive) ATCO
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 ATCO	Execution Time (seconds) Tactical (Executive) ATCO
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 ATCO	Execution Time (seconds) Tactical (Executive) ATCO
Coord1	Inter sector co-ordination (N/A)	15	-
Coord2	Inter center 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	-

Table A1. *Cont.*

Radar Task			
Task id	**Task Description**	**Execution Time (seconds)** **Planning ATCO**	**Execution Time (seconds)** **Tactical (Executive) ATCO**
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

References

1. EUROCONTROL. *Aviation Outlook 2050 Main Report*; EUROCONTROL: Brussels, Belgium, 2022.
2. SESAR Joint Undertaking. *SESAR 2020 Concept of Operations*; SESAR Joint Undertaking: Luxembourg, 2017.
3. Bolić, T.; Ravenhill, P. SESAR: The Past, Present, and Future of European Air Traffic Management Research. *Engineering* **2021**, *7*, 448–451. [CrossRef]
4. Lema-Esposto, M.F.; Amaro-Carmona, M.Á.; Valle-Fernández, N.; Iglesias-Martínez, E.; Fabio-Bracero, A. Optimal Dynamic Airspace Configuration (DAC) based on State-Task Networks (STN). In Proceedings of the 11th SESAR Innovation Days, Virtual, 7–9 December 2021.
5. SESAR Joint Undertaking. *A PBN Solution to Link FRA to Final Approach*; SESAR Joint Undertaking: Luxembourg, 2015.
6. SESAR Joint Undertaking. Improved Performance of CD/R Tools Enabled by Reduced Trajectory Prediction Uncertainty. Available online: https://www.sesarju.eu/sesar-solutions/improved-performance-cdr-tools-enabled-reduced-trajectory-prediction-uncertainty (accessed on 13 February 2024).
7. SESAR Joint Undertaking. Enhanced Tactical Conflict Detection & Resolution (CD&R) Services and Conformance Monitoring Tools for En-Route. Available online: https://www.sesarju.eu/sesar-solutions/enhanced-tactical-conflict-detection-resolution-cdr-services-and-conformance (accessed on 13 February 2024).
8. SESAR Joint Undertaking. Continuous Descent Operations (CDO) Using Point Merge. Available online: https://www.sesarju.eu/sesar-solutions/continuous-descent-operations-cdo-using-point-merge (accessed on 13 February 2024).
9. Gui, D.; Le, M.; Huang, Z.; Zhang, J.; D'Ariano, A. Optimal aircraft arrival scheduling with continuous descent operations in busy terminal maneuvering areas. *J. Air Transp. Manag.* **2023**, *107*. [CrossRef]
10. ICAO. *Doc 9931 Continuous Descent Operations (CDO) Manual*, 1st ed.; ICAO: Montreal, QC, Canada, 2010.
11. ICAO. *Doc 9993 Continuous Climb Operations (CCO) Manual*, 1st ed.; ICAO: Montreal, QC, Canada, 2013.
12. Pérez-Castán, J.A.; Comendador, F.G.; Rodríguez-Sanz, Á.; Valdés, R.M.A. Separation minima for continuous climb operations. *J. Aircr.* **2019**, *56*, 262–272. [CrossRef]
13. Pérez-Castán, J.A.; Comendador, F.G.; Arnaldo, R.M.; Navarrete, C.; Cidoncha, A. Conflict resolution algorithms for the integration of continuous climb operations in a terminal maneuver área. In Proceedings of the ICAS 2016, 30th Congress of the International Council of the Aeronautical Sciences, Daejeon, Republic of Korea, 25–30 September 2016.
14. Toratani, D.; Wickramasinghe, N.K.; Westphal, J.; Feuerle, T. Feasibility study on applying continuous descent operations in congested airspace with speed control functionality: Fixed flight-path angle descent. *Aerosp. Sci. Technol.* **2020**, *107*, 106236. [CrossRef]
15. Chen, H.; Solak, S. Lower cost arrivals for airlines: Optimal policies for managing runway operations under optimized profile descent. *Prod. Oper. Manag.* **2015**, *24*, 402–420. [CrossRef]
16. Ho-Huu, V.; Hartjes, S.; Visser, H.G.; Curran, R. Integrated design and allocation of optimal aircraft departure routes. *Transp. Res. D Transp. Environ.* **2018**, *63*, 689–705. [CrossRef]
17. Dalmau, R.; Prats, X. Fuel and time savings by flying continuous cruise climbs. Estimating the benefit pools for maximum range operations. *Transp. Res. D Transp. Environ.* **2015**, *35*, 62–71. [CrossRef]
18. SESAR Joint Undertaking. Free Route through the Use of Free Routing for Flights Both in Cruise and Vertically Evolving in Cross ACC/FIR Borders and within Permanently Low to Medium Complexity Environments. Available online: https://www.sesarju.eu/sesar-solutions/free-route-through-use-free-routing-flights-both-cruise-and-vertically-evolving (accessed on 14 February 2024).
19. SESAR Joint Undertaking. DMAN Baseline for Integrated AMAN DMAN. Available online: https://www.sesarju.eu/sesar-solutions/dman-baseline-integrated-aman-dman (accessed on 14 February 2024).
20. Jelinek, F.; Quesne, A.; Carlier, S. *The Free Route Airspace Project Environmental Benefit Analysis*; EUROCONTROL Experimental Centre: Bretigny Sur Orge Cedex, France, 2002.
21. Gencoglu, Y.; Baspinar, B. Free Routing in High-Complexity Airspace: Impact Assessment for Environment and Aviation Stakeholders. *J. Aerosp. Inf. Syst.* **2023**, *20*, 627–635. [CrossRef]
22. Industry Consultation Body. *Improving the Environmental Sustainability of European ATM*; Industry Consultation Body: Vedbæk, Denmark, 2022.
23. DFS Aviation Services, Arrival Manager (AMAN). *High-Performance System for Optimal Operational Decisions*; DFS Aviation Services, Arrival Manager (AMAN): Langen, Germany, 2020.
24. Jun, L.Z.; Alam, S.; Dhief, I.; Schultz, M. Towards a greener Extended-Arrival Manager in air traffic control: A heuristic approach for dynamic speed control using machine-learned delay prediction model. *J. Air Transp. Manag.* **2022**, *103*, 102250. [CrossRef]
25. SESAR 3 Joint Undertaking. *Biannual Work Programme 2022–2023*, 5th ed.; SESAR Joint Undertaking: Luxembourg, 2023. [CrossRef]
26. SESAR Joint Undertaking. *European ATM Master Plan 2020*; SESAR Joint Undertaking: Luxembourg, 2020. [CrossRef]
27. EUROCONTROL. *Approach and Departure Optimised Wake Turbulence Re-Categorisation and Pair-Wise Separation Minima*; EUROCONTROL: Brussels, Belgium, 2023.
28. Bustos, J.; Ruiz, S. *Final Project Report R-WAKE*; SESAR Joint Undertaking: Luxembourg, 2018.
29. Serrano-Mira, L.; Sanz, L.P.; Pérez-Castán, J.A.; Netjasov, F.; Moreno, I.G.; Ayra, E.S. Preliminary Feasibility Study of the Ad Hoc Separation Operational Concept. *Aerospace* **2023**, *10*, 539. [CrossRef]

30. Feuerle, T.; Steen, M.; Hecker, P. New concept for wake-vortex hazard mitigation using onboard measurement equipment. *J. Aircr.* **2015**, *52*, 42–48. [CrossRef]
31. Steen, M.; Stanisak, M.; Hecker, P. In-flight testing of airborne LIDAR for wake vortex detection, characterization and tracking. In Proceedings of the 6th AIAA Atmospheric and Space Environments Conference, Atlanta, GA, USA, 16–20 June 2014; Volume 51. [CrossRef]
32. ICAO. *Doc 9689 Manual on Airspace Planning Methodology for the Determination of Separation Minima*, 1st ed.; ICAO: Montreal, QC, Canada, 1998.
33. Serrano-Mira, L.; Sanz, L.P.; Pérez-Castán, J.A.; Mas-Sardá, J.S.-C. Preliminary design of an ATC support tool for the implementation of the Ad Hoc Separation Minima concept in an en-route sector. *J. Phys. Conf. Ser.* **2024**, *2716*, 012079. [CrossRef]
34. ICAO. *Doc. 9883. Manual on Global Performance of the Air Navigation System*, 1st ed.; ICAO: Montreal, QC, Canada, 2009.
35. ICAO. *Doc. 9750-AN/963. Global Air Navigation Plan 2016–2030*, 5th ed.; ICAO: Montreal, QC, Canada, 2016.
36. Maroto, M.P.; García-Heras, J.; Sanz, L.P.; Serrano-Mira, L.; Pérez-Castán, J.A. Performance Impact Assessment of Reducing Separation Minima for En-Route Operations. *Aerospace* **2022**, *9*, 772. [CrossRef]
37. García-Heras, J.; Soler, M.; González-Arribas, D.; Eschbacher, K.; Rokitansky, C.H.; Sacher, D.; Gelhardt, U.; Lang, J.; Hauf, T.; Simarro, J.; et al. Robust flight planning impact assessment considering convective phenomena. *Transp. Res. Part C Emerg. Technol.* **2021**, *123*, 102968. [CrossRef]
38. SESAR. *PJ19.04: Performance Framework (2019)*; SESAR: Luxembourg, 2019.
39. Majumdar, A.; Ochieng, W.Y.; Bentham, J.; Richards, M. En-route sector capacity estimation methodologies: An international survey. *J. Air Transp. Manag.* **2005**, *11*, 375–387. [CrossRef]
40. EUROCONTROL. *Pessimistic Sector Capacity Estimation*; EUROCONTROL: Bretigny-Sur-Orge Cedex, France, 2003.
41. ISA Software. RAMS Plus—Gate-to-Gate ATM/Airport Fast-Time Simulator. 2016. Available online: https://www.ramsplus.com/ (accessed on 29 May 2022).
42. EUROCONTROL. *Model Simulation of Czech Republic Airspace*; EUROCONTROL: Bretigny-Sur-Orge Cedex, France, 1999.
43. Sciabica, J.-F.; Jeandel, A.; Alvord, D.; Thamm, G.; Hark, M.; Schwanke, S.; Troit, R.; de la Loma, E.M.; Sampedro, M.S.; Riccardi, G.; et al. *SESAR Environment Assessment Process*; SESAR Joint Undertaking: Luxembourg, 2019.
44. IATA; ACI. *Airport Development Reference Manual*, 10th ed.; IATA: Montreal, QC, Canada, 2016.
45. Demand Data Repository (DDR) | EUROCONTROL. Available online: https://www.eurocontrol.int/ddr (accessed on 10 December 2023).
46. Network Strategic Tool (NEST) | EUROCONTROL. Available online: https://www.eurocontrol.int/model/network-strategic-modelling-tool (accessed on 26 July 2023).
47. European Commission. *Comission Delegation Regulation (EU) 2023/1768*; European Commission: Brussels, Belgium, 2023.
48. EUROCONTROL. *European Operational Concept Validation Methodology E-OCVM, Version 3.0*; EUROCONTROL: Brussels, Belgium, 2010; Volume I.