Impact of RPAS operations on the ATM Network

Minimum performance and operational requirements for the en-route phase

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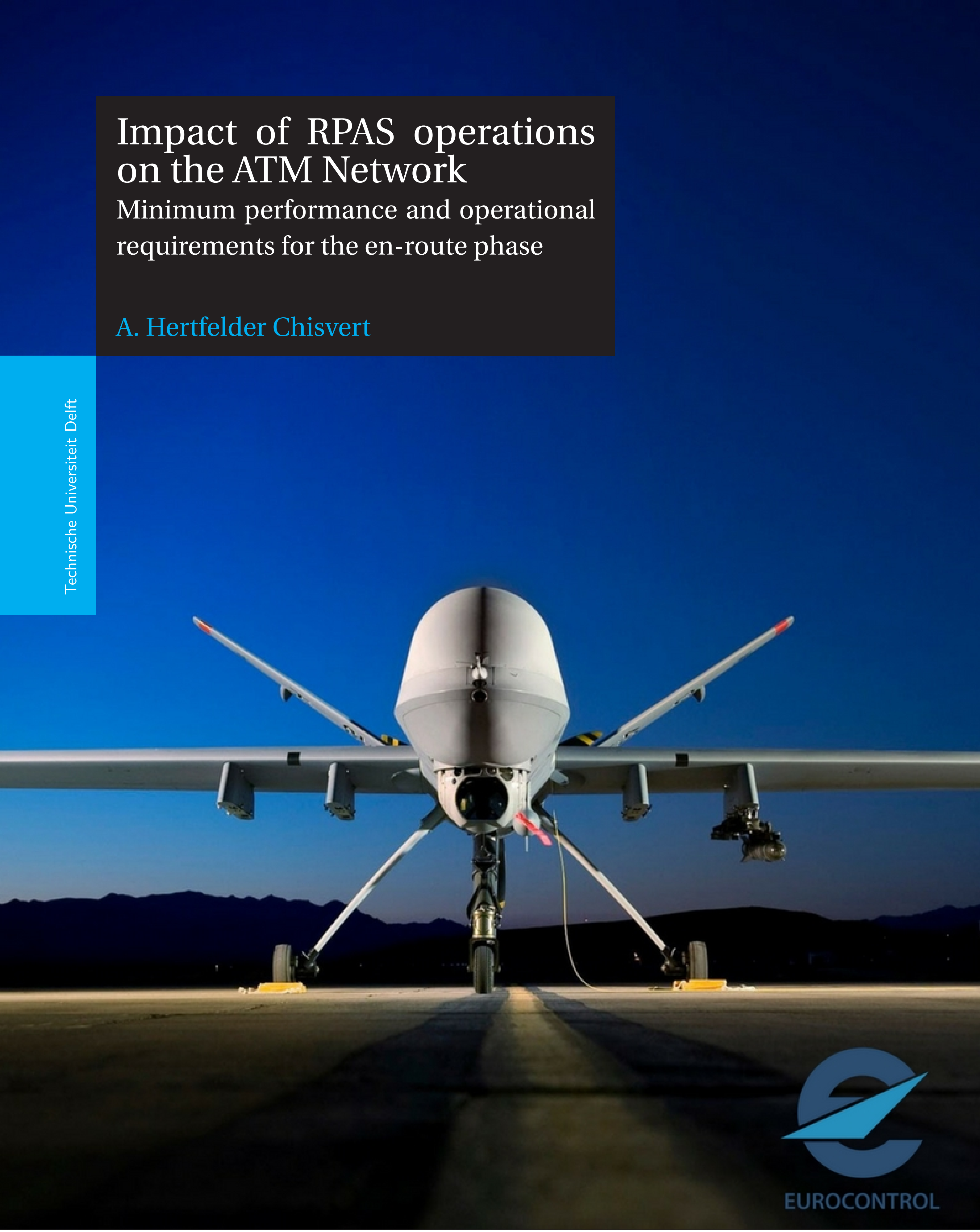

EUROCONTROL

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Challenge the future

Impact of RPAS operations on the ATM Network

Minimum performance and operational requirements for the en-route phase

by

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TU Delft

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I have the feeling that yesterday I was packing all my stuff (which to be honest, is quite a lot) and leaving Spain for the first time, challenged by a couple of years to be spent in a new country and in a new culture. But here I am, writing the acknowledgements of my MSc thesis... It has been a long journey with even a year in a second country in between. I had the chance to meet a lot of people, share a lot of moments and of course, to learn a lot. I have discovered many aspects and skills of myself that were completely unknown, and therefore I would like to take this opportunity to thank to some of people involved in this journey.

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Alejandra
Delft, June 2017

Abstract

The popularity of Remotely Piloted Aircraft Systems (RPAS) is growing at an increasing rate as an alternative to manned aviation for different purposes and applications. So far, most of their operations have been of military character, but the demand for civil and commercial applications is growing exponentially. RPAS have been allowed to operate in segregated airspace by restricting other users from entering the volume associated to the operation of the RPAS. This temporary solution based on accommodating their operations on a case-by-case basis is not feasible on the long-term. Moreover, the latest forecast carried out by SESAR Joint Undertaking (SJU) reveals that by 2050 RPAS will represent 20% of the fleet. The available airspace is a scarce resource and is already saturated, which means that additional unmanned operations would not be possible simultaneously. Integration in non-segregated airspace is the only manner in which the full benefits and capabilities of RPAS will be achieved, while maintaining the same levels of safety and efficiency as manned aviation.

In order to achieve a safe, efficient and transparent integration, a common regulatory framework and new technologies are currently under investigation. However, neither operational nor performance standards of RPAS integration have been addressed properly. For that reason, this project is focused on the development of a methodology to determine minimum operational and performance requirements by assessing the impact of RPAS operations on the Air Traffic Management (ATM) Network. The scope is limited to the en-route phase as a starting point since none of the flight phases have been analysed yet. This project is carried out in collaboration with EUROCONTROL.

RPAS are well known for presenting a wide range of performance characteristics, especially in terms of cruise speed and rate of climb. Thus, two different unmanned performance models have been chosen from the available performance models in the EUROCONTROL database: RP01 (MQ-9), which presents a similar performance to commercial aviation aircraft, and RP02 (RQ4A), which is considered a low-performance RPAS in terms of cruise speed and rate of climb. Building on a base scenario in the Paris Control Terminal Area (CTA), Monte Carlo simulations of the air traffic have been performed in order to randomly vary the main input variable: the set of en-route flights that is substituted by unmanned aircraft. Two different scenarios have been analysed separately in order to establish the requirements: one for same-performance RPAS, and the other for low-performance RPAS. In order to assess the impact, three different Key Performance Areas (KPAs) have been selected: capacity, efficiency and safety. These KPAs are in turn characterized by their corresponding Key Performance Indicators (KPIs), namely sector capacity, sector overload, flight time efficiency, flight path efficiency and number of potential conflicts.

Based on an analysis of the current occupancy of the flight levels, operational requirements are defined in terms of altitude segregation. RPAS are not allowed to operate in the most occupied flight levels (FL): from FL300 to FL400. Therefore, depending on their operation and performance characteristics (i.e. ceiling), they will adapt their cruise FL to operate below FL300 or above FL400. The optimal value of performance requirements for same-performance RPAS has been found to be a minimum cruise speed of 390 kts, while for low-performance RPAS this minimum cruise speed is of 280 kts. Additionally, for low-performance RPAS, it is found that the rate of climb of 1,000 fpm results in the best performing case when changes in FL are required.

The results show that the values of the key performance indicators for the base scenario are difficult to reach when RPAS are sharing the airspace. However, the establishment of minimum operational and performance requirements contributes to a significant reduction of the negative impact that the integration of RPAS operations implies.

The development of this methodology and its application to the characteristics of each airspace sector will contribute to the full integration of RPAS in non-segregated airspace.

Contents

Cover frontpage: URL "`http://www.ga-asi.com/predator-b`", [accessed 10 December 2016]

List of Figures

List of Tables

Nomenclature

4G	Fourth Generation
A-RNP	Advanced Required Navigation Performance
ACAS	Airborne Collision Avoidance System
ACC	Area Control Center
ACT	Actual Crossing Time
ADS-B	Automatic Dependent Surveillance Broadcast
ADS-C	Automatic Dependent Surveillance Contract
AGL	Above Ground Level
AIRAC	Aeronautical Information Regulation And Control
AIP	Aeronautical Information Publication
AIS	Aeronautical Information Service
ANOVA	Analysis of Variance
ANSP	Air Navigation Service Provider
APM	Aircraft Performance Model
APP	Approach Control Unit
AS	Altitude Segregation
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATD	Actual Track Distance
ATFCM	Air Traffic Flow and Capacity Management
ATM	Air Traffic Management
ATS	Air Traffic Services
B-RNAV	Basic RNAV
BADA	Base of Aircraft Data
BRLOS	Beyond Radio line-of-sight
BS	Base Scenario
BVLOS	Beyond Visual line-of-sight
C2	Command and Control
CAPAN	ATC Capacity Analyser tool
CI	Confidence Interval
CNS	Communications, Navigation, Surveillance
CONOPS	Concept of Operations
CPDLC	Controller Pilot DataLink Communication
CS	Cruise Speed
CTA	Control Terminal Area
CTR	Control Zone
DAA	Detect and Avoid
DDR	Demand Data Repository
DME	Distance Measuring Equipment
DSNA	Direction des Services de la navigation aérienne
EASA	European Agency for Safety Aviation
EEC	EUROCONTROL Experimental Centre
EHS	Enhanced Surveillance
ELJ	Entry Level Jet
ELS	Elementary Surveillance
ES	Extended Squitter
EU	European Union
EVLOS	Extended Visual line-of-sight
FAA	Federal Aviation Administration
FIR	Flight Information Region
FL	Flight Level
fpm	Feet per minute
GAT	General Air Traffic
GND	Ground
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HALE	High Altitude Long Endurance

HIL	Human In the Loop
HSD	Honest Significant Difference
ICAO	International Civil Aviation Organization
ICT	Initial Crossing Time
IFR	Instrument Flight Rule
ILS	Instrument Landing System
INS	Inertial Navigation System
ITD	Initial Track Distance
KPA	Key Performance Area
KPI	Key Performance Indicator
LALE	Low Altitude Long Endurance
LASE	Low Altitude Short Endurance
MALE	Medium Altitude Long Endurance
MAV	Micro Air Vehicle
MEL	Minimum Equipment List
MOE	Margin Of Error
MTOW	Maximum Take Off Weight
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NAV	Nano Air Vehicle
NDB	Non-Directional Beacon
NEST	Network Strategic Tool
NEVAC	Network Estimation and Visualisation of ACC Capacity
NM	Network Manager
OLS	Ordinary Least Squares
ORP	Oceanic, Remote and Polar
PANS	Procedures for Air Navigation Services
PBN	Performance Based Navigation
RLOS	Radio line-of-sight
RNAV	Area Navigation
RNP	Required Navigation Performance
ROC	Rate Of Climb
RP	Remote Pilot
RPA	Remotely Piloted Aircraft
RPAS	Remotely Piloted Aircraft System
RPS	Remote Pilot Station
RTO	Regression Through the Origin
RVSM	Reduced Vertical Separation Minima
SA	Sensitivity Analysis
SAAM	System for traffic Assignment and Analysis at a Macroscopic level
SARPs	Standards And Recommended Practices
SATCOM	Satellite Communications
SD	Standard Deviation
SE	Standard Error
SEM	Standard Error of the Mean
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
SJU	SES Joint Undertaking
STAR	Standard Terminal Arrival Route
STATFOR	Statistics and Forecast Service
TAS	True Airspeed
TMA	Terminal Manoeuvring Area/Terminal Control Area
TSA	Temporary Segregated Area
UAS	Unmanned Aircraft System
UAV	Unmanned Aircraft Vehicle
UIR	Upper Information Region
VFR	Visual Flight Rules
VHF	Very High Frequency
VHL	Very High Level
VLJ	Very Light Jet
VLL	Very Low Level
VLOS	Visual line-of-sight
VOR	VHF Omnidirectional Radio Range
VSM	Vertical Separation Minima
VTOL	Vertical Take-Off and Landing
WKPI	Weighted KPI
WL	Workload
WS	Weighted Score
WTC	Wake Turbulence Category

PART I

BACKGROUND

1

Introduction

Remotely Piloted Aircraft Systems, RPAS, are often considered a recent development. However, a glance back in history shows that Unmanned Aerial Vehicles (UAVs) date back to even before the first official manned flight performed by the Wright brothers. In 1804, the unmanned glider designed by Sir George Cayley performed its first successful flight which is more than 100 years before the Wright brothers' flight [1]. In fact, if one considers the first flight performed by the Montgolfier brother's ballon, which was flown with no human inside the basket but with a sheep, a duck and a rooster, then the date can be set to 1783 [2]. Bear in mind that ICAO Annex 1 defines aircraft as *"any machine that can derive support in the atmosphere from the reactions of the air other than the reactions of the air against the earth's surface"* [3]. The aircraft categories that have been defined include but are not limited to aeroplane, helicopter, glider and free balloons. That is the reason why we are referring to UAVs and not to RPAS, since they were unmanned aircraft (according to ICAO definition) but not remotely piloted.

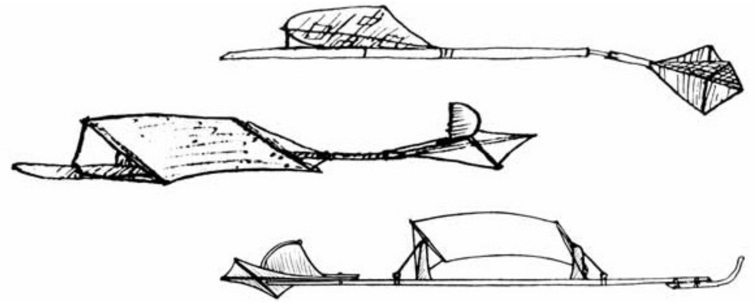

Figure 1.1: Sir George Cayley's glider desgin.[1]

Another milestone in the early history of unmanned aviation was achieved in 1849, during a military conflict between Austrian and Italian troops, when the Austrians attacked Venice with 200 unmanned balloons loaded with explosives [4].

Nonetheless, only in recent decades has the use of UAVs and more specifically RPAS started to grow significantly. This increase originated in the military sector due to the ability of those systems of staying in the air for longer periods of time [4] and operating in high-risk environments without creating a hazard to the pilot. Although it is a matter of time before they will fully exploit their capabilities for commercial applications, there are already examples of use of unmanned aircraft in the civil sector: Shell is using drones to inspect its largest energy plants, Easyjet for maintenance inspections purposes or McCain Foods, which is making use of drone technology to monitor potato fields. The rapid growth of this technology and their affordability are challenging the Air Traffic Management (ATM) system. Contrarily to military applications, where designated and restricted airspace is segregated for their operations, civilian applications will need to be integrated into non-segregated airspace.

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[1] Source "`http://www.fiddlersgreen.net/models/aircraft/Cayley-FlyingMachine.html`", [accessed 10 May 2017]

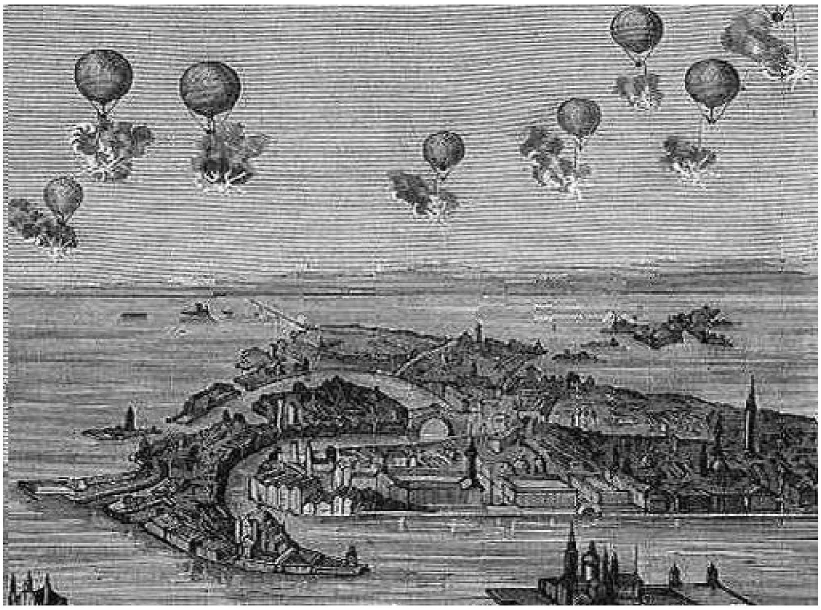

Figure 1.2: Unmanned balloons bombing Venice, 1849.[1]

RPAS have the potential for commercial applications, since they are able to successfully accomplish missions that are not cost effective or safe for manned aviation. Examples of potential uses include scientific research, surveillance, medical courier, monitoring, or even as future commercial transport, to name a few. Private companies like Amazon or DHL are already investigating how RPAS can be used to deliver packages in a faster and more efficient manner than conventional means of transport [5, 6]. At the same time, the market for flying cars seems to be expanding as companies like Airbus, Uber or PAL-V are developing and testing their own flying vehicles in order to start operating by 2020 [7–9]. The following step would be to make these flying cars unmanned in order to leave one more seat for passengers. So, *why are RPAS not operating commercially yet?*

Aside from the personal perception of trusting or not trusting a vehicle where the pilot is absent in the cockpit and other issues like insurance or privacy aspects, integration of RPAS operations in non-segregated airspace needs to face many different challenges that can be summarized in four main categories: technical, operational, regulatory and societal [10]. Currently, regulations, SARPs (Standards And Recommended Practices) and PANS (Procedures for Air Navigation Services) are not in place yet, although this does not prevent their operations on a case-by-case basis in segregated airspace. If the number of operations keeps on growing, segregation is no longer feasible since the volume of restricted airspace will dramatically grow, impeding other airspace users from entering it. SESAR (Single European Sky ATM Research) European Drones Outlook Study predicts a total of 400,000 commercial and government RPAS operating in Europe by 2050, meaning that drones will represent a quarter of the air traffic [11]. Thus, integration in non-segregated airspace seems to be the only possible way of enabling this growth in the number of unmanned operations.

In order to achieve a safe, efficient and transparent integration, most of the current research is dealing with technical gaps that have been identified, such as the lack of standardized Detect and Avoid (DAA) systems or C2 (command and control) link services, and with the harmonization of the regulatory framework. Operational requirements, which includes performance requirements, have barely been investigated but are as important as any of the other previously mentioned challenges, given that the sharing of airspace between RPAS and manned aviation will impact the ATM Network due to the intrinsic characteristics of RPAS. For that reason, this project is aimed at establishing the methodology needed to assess the impact of RPAS operations on the ATM Network by developing minimum operational and performance requirements for IFR (Instrument Flight Rules) flights. From this point onwards a distinction between operational and performance re-

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[1] Source "`http://thepandorasociety.com/this-week-in-history-august-22nd-to-august-28th/`", [accessed 10 May 2017]

quirements will made: the latter category includes pure performance standards for RPAS such as cruise speed and/or rate of climb (ROC).

This project is carried out in collaboration with EUROCONTROL, one of the main contributors to the European RPAS roadmap [12] and the main leader of ATM integration. The outline of the report is as follows: Chapter 2 includes an introduction to RPAS, the state of the art of their integration in non-segregated airspace and the current requirements (airspace and Communication, Navigation and Surveillance, CNS). The objectives and the research questions that support the achievement of the research goal are included in Chapter 3. Chapter 4 presents the experimental set up gathering information about the scenarios and Chapter 5 provides the explanation about the methodology used within the project. The stochastic analysis is presented in Chapter 6; the Sensitivity Analysis in Chapter 7 and the application to the real scenario in Chapter 8. Finally, conclusions and recommendations for future work are presented in Chapter 9.

2

Theoretical Background

After the overview of the unmanned history provided in Chapter 1, it is necessary to explore and define some concepts for RPAS. Section 2.1 includes a brief introduction to RPAS, showing the different concepts, classifications and elements. Their differences in performance are also analysed in 2.1.5. Once they have been introduced, the state of the art is given in Section 2.2. This will highlight the novelty and the importance of this research project. Finally, Section 2.3 gathers all the current requirements for manned aviation in terms of airspace and CNS that RPAS must meet as well.

2.1. An Introduction to Remotely Piloted Aircraft Systems

All the concepts, classifications and elements that are presented will be used throughout the project. Nowadays different terms are wrongly used to refer to the same concept. Definitions of the most common terms are introduced in Section 2.1.1. RPAS typically consist of several individual elements that are presented in Section 2.1.2. Since the characteristics of RPAS can vary considerably in terms of physical characteristics and performance, the most relevant classification for them has been established according to the intended operation in Section 2.1.3 to set the context of the work. The different traffic classes that have been proposed in the ATM CONOPS [13] are briefly introduced in Section 2.1.4. Finally, an overview of the main performance characteristics of RPAS is given in Section 2.1.5.

2.1.1. System Identification

Unmanned aviation is a rapidly growing aeronautical sector. The affordability and accessibility of unmanned aircraft have contributed to this unexpected growth especially for the small ones often referred as to "buy and fly". Due to this rapid expansion, many different terminologies have been defined and are currently used by operators, regulators and manufacturers. A distinction between the most common and possibly confusing terms that are now being used and might be easily confused.

- The concept of **Remotely Piloted Aircraft System, RPAS**, is introduced by ICAO [14] as *"a remotely piloted aircraft, its associated remote pilot station(s), the required command and control links and any other components as specified in the type design"*.

- **Unmanned Aircraft System, UAS,** is defined by ICAO [14] as an aircraft and its associated elements which are operated with no pilot on board.

- **Unmanned Aerial Vehicle, UAV**, is the term used among professionals defined by ICAO [14] as *"a pilotless aircraft, in the sense of Article 8 of the Convention on International Civil Aviation, which is flown without a pilot-in-command on-board and is either remotely and fully controlled from another place (ground, another aircraft, space) or programmed and fully autonomous"*.

- **Drone** is widely used as a generic term for all classes of unmanned or remotely piloted aircraft and refers to both concepts, RPAS and UAS.

2.1.2. System Description

Based on the previous definitions, a RPAS can be considered a subcategory of UAS that always has a pilot in or on the loop. RPAS are composed by the following items (see Figure 2.1): **RPA**, Remotely Piloted Aircraft, which can be fixed-wing aircraft or rotorcraft; one or more Remote Pilot Station, **RPS**; one or more **C2 links** (Command and Control); and any additional component. The main difference with respect to manned aviation is that the pilot (also known as remote pilot, RP) is located outside the cockpit and the aircraft, at a Remote Pilot Station (RPS) from where the RPA can be controlled and monitored by means of the C2 data link. C2 link is the manner in which the RPA and the RPS are connected to manage the flight.

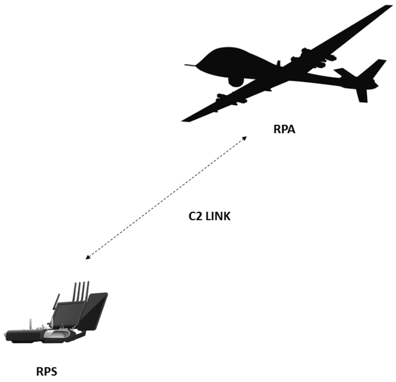


Figure 2.1: Main RPAS elements, created by the author based on [14].

ICAO defines these components [14] as follows:

- **Remotely piloted aircraft (RPA)**: An unmanned aircraft which is piloted from a remote pilot station.
- **Remotely piloted aircraft system (RPAS)**. A remotely piloted aircraft, its associated remote pilot station(s), the required command and control links and any other components as specified in the type design.
- **Remote pilot station (RPS)**. The component of the remotely piloted aircraft system containing the equipment used to pilot the remotely piloted aircraft.
- **Command and control (C2) link**. The data link between the remotely piloted aircraft and the remote pilot station for the purposes of managing the flight. The link may be simplex or duplex. It may be in direct radio line-of-sight (RLOS) or beyond radio line-of-sight (BRLOS) as described in a) and b):
    a) RLOS: refers to the situation in which the transmitter(s) and receiver(s) are within mutual radio link coverage and thus able to communicate directly or through a ground network provided that the remote transmitter has RLOS to the RPA and transmissions are completed in a comparable timeframe (see Figures 2.2a and 2.3a);
    b) BRLOS: refers to any configuration in which the transmitters and receivers are not in RLOS. BRLOS thus includes all satellite systems and possibly any system where an RPS communicates with one or more ground stations via a terrestrial network which cannot complete the transmissions in a timeframe comparable to that of an RLOS system (see Figures 2.2b and 2.3b).

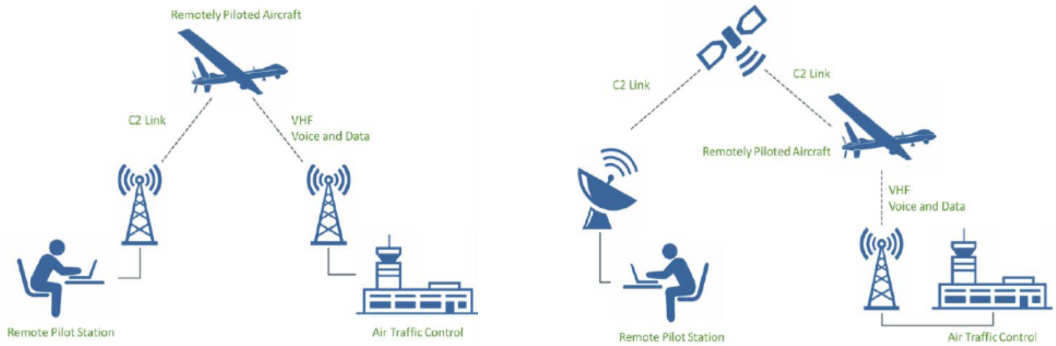
(a) Radio Line Of Sight – RLOS.

(b) Beyond Radio Line Of Sight – BRLOS.

Figure 2.2: C2 Link Control Architectures [14].

- C2 link has two main functions:

  1. Control: to allow the RPS to modify the behavior of the RPA (telecommand) and the function for the RPA to transmit its state to the RPS (telemetry).
  2. Communication: to provide voice and data communication between the RPS, ATC and other users. There are two main groups: via RPA (see Figure 2.3) and without a relay via the RPA (see Figure 2.4). Communications relayed via the RPA are transparent to ATC and no additional infrastructure or equipment are needed in the ATC unit. A wider bandwidth on the C2 link might be required. Communications without a relay via the RPA will require new equipment at the ATC unit: a new broadcast, private or networked communications link between ATC and the RP.



(a) RLOS Relay through the RPA.

(b) BRLOS Relay through the RPA.

Figure 2.3: Relay through the RPA [14].

(a) VHF Radio to VHF Radio.

(b) Ground to Ground Link.

Figure 2.4: Non-Relay through the RPA [14].

2.1.3. Types of Operations

RPAS present a wide range in terms of size, weight, characteristics, etc. That is the reason why their categorization in terms of the classes of operations has been found the most suitable for them. Three different types of operations have been defined in accordance with the altitude of the intended operation:

- **Very Low Level operations, VLL**: from ground up to 500ft AGL. Three different types subtypes of operations can be found:
  - **Visual line-of-sight (VLOS)** operation. An operation in which the remote pilot or RPA observer maintains direct unaided visual contact with the remotely piloted aircraft. The operation is limited up to a range of 500m and an altitude of 500ft from the pilot.
  - **Extended visual line-of-sight (E-VLOS)**. If one or more additional observers are present, the maximum range can be extended.
  - **Beyond visual line-of-sight (B-VLOS)** operation. When neither the remote pilot nor RPA observer(s) can maintain direct unaided visual contact with the RPA, the operations are considered B-VLOS.
- **Instrumental Flight Rules/Visual Flight Rules (IFR/VFR) operations:** from 500ft AGL up to FL600. In order to fly IFR/VFR, the airspace requirements must be met. Additional requirements might be imposed to counteract the absence of the pilot inside the cockpit.
- **Very High Level operations, VHL:** above FL600. This category is intended for suborbital unmanned flights. Within this block of airspace, apart from military users, private companies like Facebook and Google are planning to have around 10,000 unmanned vehicles to provide 4G network in zones where the coverage is not enough. The main issue with this category is that to have a vehicle flying at that altitude, it needs to interact with the airspace below it (where normal commercial aviation is taking place).

2.1.4. Traffic Classes

As defined by EUROCONTROL in the ATM CONOPS [13], different traffic classes are foreseen for each type of operations. They are depicted in Figure 2.5.

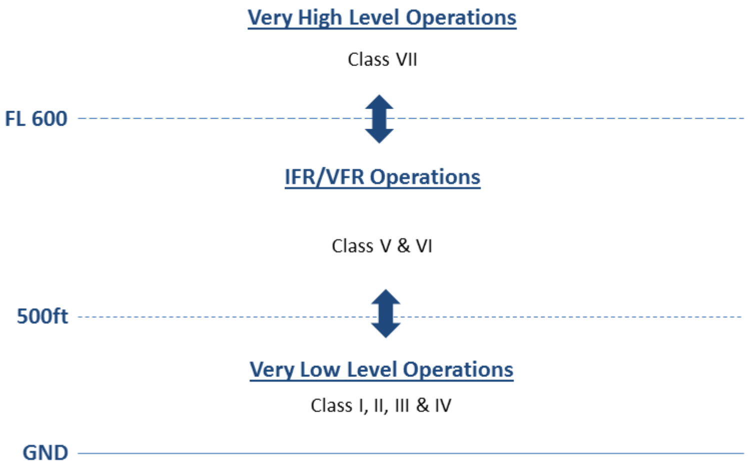


Figure 2.5: Types of operations with the corresponding traffic classes. Created by the author based on [13].

VLL Traffic classes:

- **Class I:** Reserved for RPAS falling under EASA open category operating in VLOS. The buy and fly category that will be able to fly in low risk environments and remains clear of no-drone zones like airports.
- **Class II:** Free flight (VLOS and BVLOS). Can be the specific or certified category (following the categorization of EASA regarding types of RPAS, [15]).

- **Class III:** Free flight or structured commercial route for medium/long haul traffic (BVLOS). Could be both specific and certified capable of operating for longer distances.
- **Class IV:** special operations (this category of RPAS traffic conducts very specific types of operation that will be assessed on a case by case basis. (VLOS and BVLOS). This type could be either specific or certified and can operate in urban areas, airports and other specific locations.

IFR/VFR Traffic classes:

- **Class V** is defined for IFR/VFR operations outside the Network not flying SIDs and STARs. No negative impact on manned aviation. Operations at airports will be accommodated through segregation of launch and recovery. Ground operations can also be accommodated through either towing or wing walking. Operations from uncontrolled airports or dedicated launch and recovery sites are to be conducted initially under VLOS/VFR until establishing radio contact with ATC. No additional performance requirements will be set in this environment compared to manned aviation.
- **Class VI** is set for IFR operations, including Network, TMA and Airport operations with RPAS capable of flying SIDs and STARs as designed for manned operations. These are either manned transport aircraft (civilian air carriers) enabled to fly unmanned with similar capabilities or new types able to meet the set performance requirements for the Network, TMA and airports.

VHL Traffic class

For VHL operations, there is only one traffic class foreseen, **Class VII**. It consists solely of IFR operations above FL600 and transiting non-segregated airspace. RPAS falling within this class are designed for operations at very high altitudes. The launch and recovery of fixed-wing RPAS can be from dedicated airports, unless Class VI requirements are met.

RPAS of this traffic class will have to transit through either segregated or non-segregated airspace to enter or exit the airspace above FL 600. For such cases, temporary segregated airspace should be considered. Transition performance in segregated or non-segregated airspace below FL600 will be very limited since they will be focusing on long missions (up to several months).

2.1.5. RPAS Performance

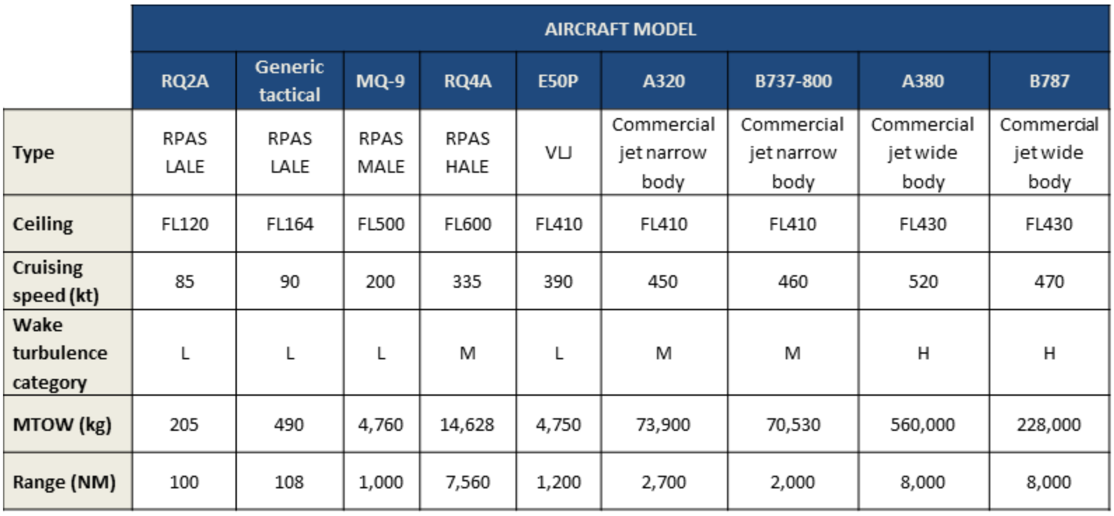
RPAS have operated in segregated airspace due to the fact that the current number of operations has been kept very low. Taking into consideration the forecasted number of RPAS that is expected to be in place by 2050 [11], segregation is no longer feasible since the volume of restricted airspace would increase dramatically and many other airspace users could not have access to it. But integrating RPAS operation is not just a matter of dealing with an increase in the number of airspace users. RPAS present significant dissimilarities in terms of performance compared with airliners.

RPAS are also very wide by varying in terms of performance, and they can present better, similar or lower performance, as can be seen in Table 2.1. Four out of the three RPAS that are presented in Table 2.1 correspond to military unmanned platforms. The lack of publicly available data of civil unmanned vehicle makes difficult to build accurate performance models. Military classifications of UAS platforms are commonly used based on characteristics such as range (or endurance), size and altitude. In line with these criteria, there are six categories [16]:

- **MAV/ NAV (Micro Air Vehicle / Nano Air Vehicle)**: This type of miniaturized unmanned vehicle operate at very low altitudes, below 100 ft, and their endurance is very limited.
- **VTOL (Vertical Take-Off and Landing)**: VTOL vehicles are an alternative to large fixed-wing unmanned vehicles. VTOL UAS have the capability of hovering and manoeuvrability. Their characteristics are very wide in terms of size and performance.
- **LASE (Low Altitude Short Endurance)**: This category can fly VLOS for a period of time between 45 minutes and 2 hours below 1,500 ft.

- **LALE (Low Altitude Long Endurance)**: They can fly for longer periods of time (around 20-24 hours) and at altitudes up to 16,500 ft.
- **MALE (Medium Altitude Long Endurance)**: Their more advance design allows them to operate at altitudes above 40,000 ft (with very limited endurance at that altitude) although typically they fly at altitudes between 16,500 and 30,000 ft. At these altitudes, the endurance ranges from 20-40 hours depending on the operation and the payload.
- **HALE (High Altitude Long Endurance)**: This category can fly above 14 km (45,000 ft) for extended periods of time: days, weeks or even months.

Table 2.1: Comparative table of various characteristics for different aircraft models. Data for manned aviation has been gathered from the Aircraft Performance Database [17] and for the unmanned ones, from BADA RPAS package release note [18].



	AIRCRAFT MODEL								
	RQ2A	Generic tactical	MQ-9	RQ4A	E50P	A320	B737-800	A380	B787
Type	RPAS LALE	RPAS LALE	RPAS MALE	RPAS HALE	VLJ	Commercial jet narrow body	Commercial jet narrow body	Commercial jet wide body	Commercial jet wide body
Ceiling	FL120	FL164	FL500	FL600	FL410	FL410	FL410	FL430	FL430
Cruising speed (kt)	85	90	200	335	390	450	460	520	470
Wake turbulence category	L	L	L	M	L	M	M	H	H
MTOW (kg)	205	490	4,760	14,628	4,750	73,900	70,530	560,000	228,000
Range (NM)	100	108	1,000	7,560	1,200	2,700	2,000	8,000	8,000

2.2. State of the Art

A few years ago, when SESAR developed the first European ATM Master Plan (2009) and subsequently, its first update (2012), RPAS were not accounted in the SESAR definition phase: their potential growth remained unpredictable at that time. The emergence of this new aviation sector, providing new features and benefits to society, made it necessary for RPAS to be included in the latest update of the Master Plan (2015) [19]. They are considered as any other type of air vehicle and their integration is defined as a SESAR solution for all the flight phases, as Figure 2.6 shows.

There is a large interest to integrate RPAS operations in non-segregated airspace from both, the European Commission (Europe) and the FAA (USA). Regarding the European perspective, the time line established began with VLOS (visual line of sight) operations of RPA (Remotely Piloted Aircraft) below 150 kg, followed by IFR operations and finally, VFR (Visual Flight Rules) operations.

At an international level, ICAO (International Civil Aviation Organization) has publised a set of documents related to RPAS: amendments to some of its annexes (the only annex that is not envisaged to be amended is Annex 5, *Units of Measurement to be Used in Air and Ground Operations*); *Circular 328 Unmanned Aircraft Systems (UAS)* [20] and the *Manual on Remotely Piloted Aircraft System* [14]. This set of documents aims to contribute to the establishment of an unique regulatory framework for RPAS based on technical standards and operational procedures. RPAS integration will be only concluded when SARPs (Standards And Recommended Practices) and PANS (Procedures for Air Navigation Services) are published. However, they have not been developed yet, making the impact assessment more difficult.

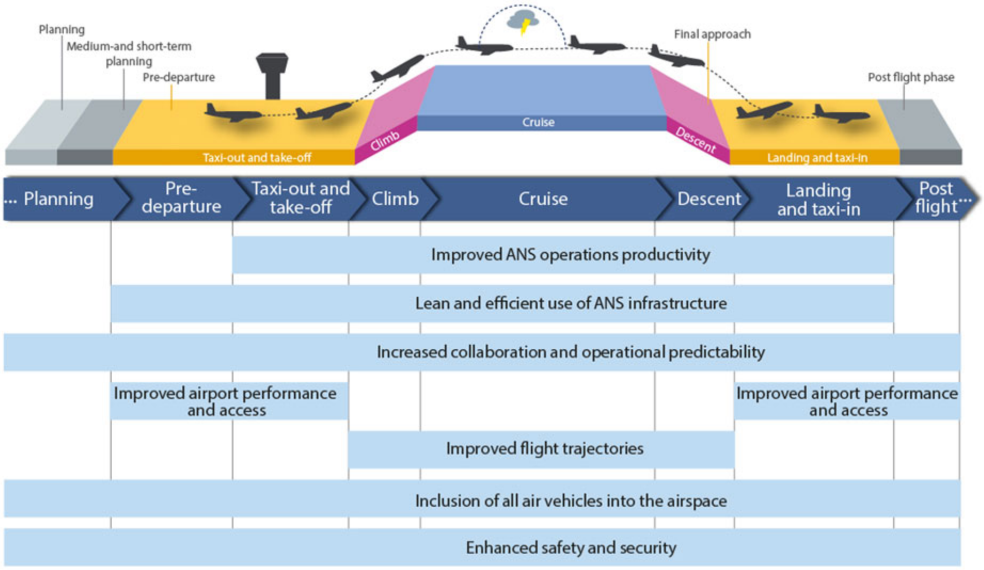


Figure 2.6: SESAR's improvements per flight phase, [19].

IFR routes, standard instrument departure (SID) and standard terminal arrival route (STAR) charts are published by the corresponding national Air Information Service (AIS), normally responsibility of the ANSPs. Prescription of navigation performance standards for IFR flights has been highlighted in [21] instead of focusing on Minimum Equipment List (MEL). The authors also present different use cases based on the combination of the type of airspace (segregated/non-segregated), the type of operation (VLOS, BVLOS, beyond visual line of sight, IFR or VFR). The necessity of adapting flight procedures for unmanned aircraft is also stressed in [22], remarking explicitly that rules of the air as stated in ICAO Annex 2 will not be modified. Authors of [23] also mention to the need for RPAS to adapt to the current ATM system citing their performance as one but without mentioning the methodology to assess this performance requirements or how ATM systems should evolve to cope with these differences (respect to manned aviation).

Research studies have also addressed contingency procedures and separation management through real time HIL (human in the loop) simulations, with either pilots or controllers part of the HIL [24–26]. From an ATC perspective, different and varied solutions have been proposed, such as a sector-less environment with a specific controller position for RPAS [27]. Even in that case, the detected number of conflicts turns to be quite high emphasizing the requirement of standardization of contingency procedures. For the time being, contingency procedures have not been standardized and the same applies to separation minima (for integrated operations). The need to develop techniques to quantify RPAS impact from different points of view (safety, capacity and inefficiency) is also identified in [26].

With the previous premises, a knowledge gap is found regarding the establishment of minimum performance and operational requirements for RPAS operating in IFR conditions, as well as for the impact of RPAS operations. It has been mentioned in many articles and publications, but it has not been properly addressed yet. To that end, this project will assess this impact and will try to reduce it by proposing the implementation of performance and operational requirements.

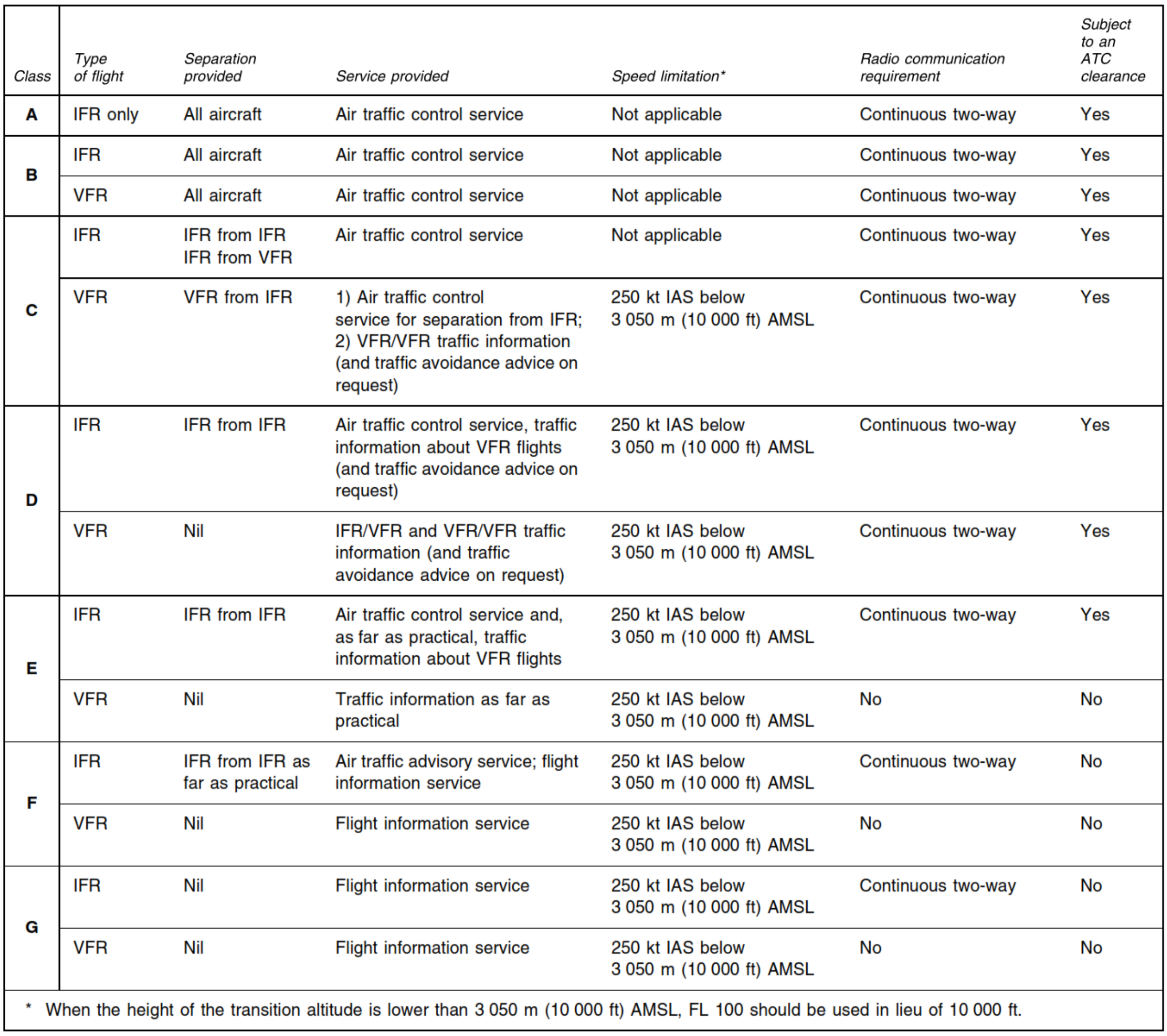
2.3. Air Navigation System Requirements

Apart from performance or operational requirements, RPAS must comply with actual requirements as the rest of the aviation does. In this section the different requirements of the air navigation system are divided into two main categories: airspace (Section 2.3.1) and CNS requirements (Section 2.3.2).

2.3.1. Airspace Entry Requirements

Airspace classification is aimed to provide different levels of Air Traffic Services (ATS) including requirements, services and obligations to pilots. RPAS operating as IFR traffic within airspace classes A-G must comply with the relevant airspace requirements that have been defined by ICAO in Annex 11, Air Traffic Services. They are contained in Table 2.2.

Table 2.2: ATS Airspace Classes — Services Provided and Flight Requirements, [28].



Class	*Type of flight*	*Separation provided*	*Service provided*	*Speed limitation**	*Radio communication requirement*	*Subject to an ATC clearance*
A	IFR only	All aircraft	Air traffic control service	Not applicable	Continuous two-way	Yes
B	IFR	All aircraft	Air traffic control service	Not applicable	Continuous two-way	Yes
	VFR	All aircraft	Air traffic control service	Not applicable	Continuous two-way	Yes
C	IFR	IFR from IFR IFR from VFR	Air traffic control service	Not applicable	Continuous two-way	Yes
	VFR	VFR from IFR	1) Air traffic control service for separation from IFR; 2) VFR/VFR traffic information (and traffic avoidance advice on request)	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	Yes
D	IFR	IFR from IFR	Air traffic control service, traffic information about VFR flights (and traffic avoidance advice on request)	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	Yes
	VFR	Nil	IFR/VFR and VFR/VFR traffic information (and traffic avoidance advice on request)	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	Yes
E	IFR	IFR from IFR	Air traffic control service and, as far as practical, traffic information about VFR flights	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	Yes
	VFR	Nil	Traffic information as far as practical	250 kt IAS below 3 050 m (10 000 ft) AMSL	No	No
F	IFR	IFR from IFR as far as practical	Air traffic advisory service; flight information service	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	No
	VFR	Nil	Flight information service	250 kt IAS below 3 050 m (10 000 ft) AMSL	No	No
G	IFR	Nil	Flight information service	250 kt IAS below 3 050 m (10 000 ft) AMSL	Continuous two-way	No
	VFR	Nil	Flight information service	250 kt IAS below 3 050 m (10 000 ft) AMSL	No	No

* When the height of the transition altitude is lower than 3 050 m (10 000 ft) AMSL, FL 100 should be used in lieu of 10 000 ft.

Airspace can be divided into two main types: controlled airspace (classes from A to E) and uncontrolled airspace (classes F and G). The main difference is found on the air traffic control services that are provided to IFR and VFR flights according to the specific airspace class. The purpose of the ATC services is to prevent collisions between aircraft or between aircraft and any other obstacle and to expedite and maintain an orderly flow of traffic [28]. Controlled airspace includes CTAs (Control Areas), TMAs (Terminal Control Areas), airways and CTRs (Control Zones), which are different manners in which airspace is divided and classified. In Europe, airspace above FL195 has been classified as Class C [29].

For all IFR flights either in controlled or uncontrolled airspace, continuous two-way radio communications are required. Table 2.3 includes an example of a pilot requesting clearance to enter controller airspace, since as shown in Table 2.2, controlled airspace is subject to ATC clearance to enter. Standard phraseology is necessary to enable quick and effective communications between the pilot and the controllers, thus reducing the possible misunderstandings. Non-standard phraseology is often the cause of incidents or even accidents. To be in accordance with the integration requirements for RPAS, no special ATC phraseology should be required for RPAS operations, although this matter has not been researched yet and no standards have been agreed upon.

Table 2.3: Examples of phraseology to request access/crossing controlled airspace, [30, 31].

Examples of communications between the pilot and the controller		
Clearance to cross controlled airspace	Pilot	"Zenda Control ABCDE, request cross A1 at Benton", or "request Zone crossing".
	Controller	"ABCDE, Zenda Control, advise intentions"
	Pilot	"Zenda Control, ABCDE is a Cessna 172 from Midburg to Sandville, 20 miles South of Purl VRP at 2500 feet on 1010, VMC, request transit your CTA from Purl to Nitting at 2500 feet, estimate Purl at 1235"
Wait for clearance	Pilot	"Zenda Control ABCDE, request cross A1 at Benton".
	Controller	"ABCDE, Zenda Control, Standby" If the reply was "Standby", then you do not have clearance but must wait, staying out of the controlled airspace. If you do not get clearance by the 10 NM point, turn back.
Clearance to enter controlled airspace	Pilot	"Metro Radar, Big Jet 345, T3F, passing 2300 feet climbing to 6000 feet".
	Controller	"Big Jet 345, Metro Radar, radar contact".

2.3.2. CNS Requirements

CNS are those technological systems, procedures and programmes for pilots and ATCos aimed at enabling the communications, navigation and surveillance. Communications provide the necessary means to exchange information (voice and data) in air-ground and ground-ground communications. Air navigation provides the means to determine the position and the desired trajectory of the aircraft as well as the required assistance to the pilot to follow the pre-established route. Surveillance provides the means to monitoring the aircraft that are within a given airspace in order to get to know their position, track and the desired route [32]. The different requirements that have been set for each component of the CNS system are introduced in the following subsections.

a) Communications

Being remotely piloted makes them suitable for many applications that cannot be performed by manned aviation either due to the risk or the affordability of the operation. However, this also implies that there are new challenges which have not been addressed yet. Having the pilot located outside the cockpit in a RPS which may not even be in the same geographical area as the RPA introduces two main issues: latency in communications and contingency issues.

- **Latency in communications**

For manned aviation, communication is carried out between ATC and the pilot, which makes only one-way trip necessary for air-ground communication and two one-way trips in case of SATCOM. In turn, communications in RPAS related operations are based on two main segments: C2 link (C2 between RPA and RPS) and ATC communications (between ATC and RPS). This brings new communication architectures based on multiple segments which lead to an increase in the latency.

Manned aviation has high standards for latency in communications [33, 34]. The maximum acceptable one-way voice latency for ATC communication in oceanic, remote and polar (ORP) areas has been set to 485ms, while for the rest of areas is reduced to 130 ms. Satellite communications experience higher latencies due to the travel of the signal from the geostationary orbit to the surface of the Earth. This latency is typically between 500 and 700 ms (one-way). For calculation purposes worst case scenario, which corresponds to the highest value of latency (700 ms), is chosen.

C2 link delay might contribute to break ATCos workflow if the latency is considerable, due to the fact that their response is noticeable slower than the ones that are being received coming from manned aviation. Latency issues have not been defined yet, but they will be considered for the simulations to assess their impact in the network.

Given the previous values and the different communication architectures that have been defined in the ICAO Manual [14], the following cases are considered.

1. **Ground-Ground communications**. The ground only network formed by ATC voice to/from the RPS has a maximum acceptable value for VHF latency of 48 5ms in ORP areas and 130 ms in the rest.

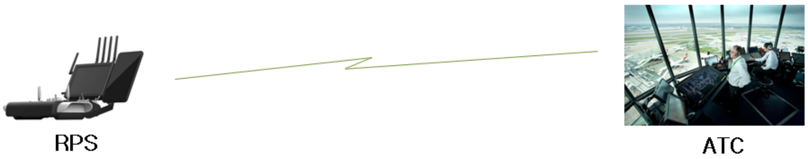
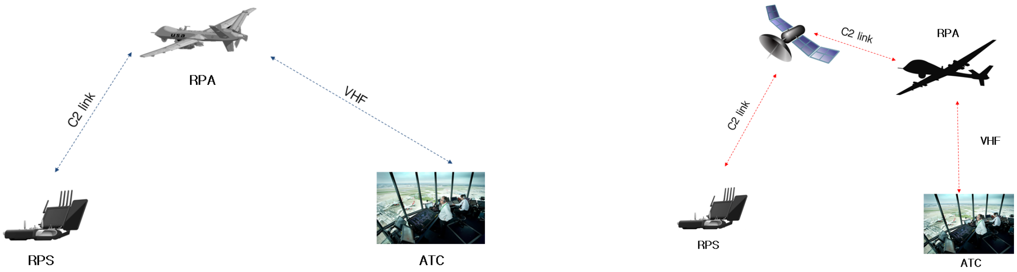


Figure 2.7: Ground-Ground communications. Created by the author based on [14].

2. **Ground communications through RPA**. C2 link architectures aimed to support RPAS operations are divided in RLOS and BRLOS. ATC communications may be relayed between the RPA and the RPS on the same C2 link [14].



(a) ATC comms relayed via the RPA: RLOS.

(b) ATC comms relayed via the RPA: BRLOS (via satellite).

Figure 2.8: ATC communications to/from RPS through RPA.

These types of architecture with a relay through the RPA have an extra latency added since there is a new communication path. These situations present the challenge about the maximum acceptable value for the latency. Depending on the distance (RLOS/BRLOS operation and continental/ORP areas), the latencies are slightly different:

   (a) RLOS:
      - C2 link + VHF(ORP) = 700 + 130(485) = 830 (1185) ms
      - C2 link + SAT = 700 x 2 = 1400 ms
   (b) BRLOS:
      - C2 link x 2 + VHF(ORP) = 700 x 2 + 130(485) =1530 (1885) ms
      - C2 link x 2 + SAT = 700 x 3 = 2100 ms

   Comparing these values with the correspondent to manned operations, the difference in latency is noticeable, becoming an issue to simulate and to analyse its effect on the surrounding traffic.

3. **Oceanic/Remote area operations, ground communications through RPA**. For these operations, the latency is expected to be: C2 link x 2 + ATC link x 2 = 700 x 4 = 2800 ms

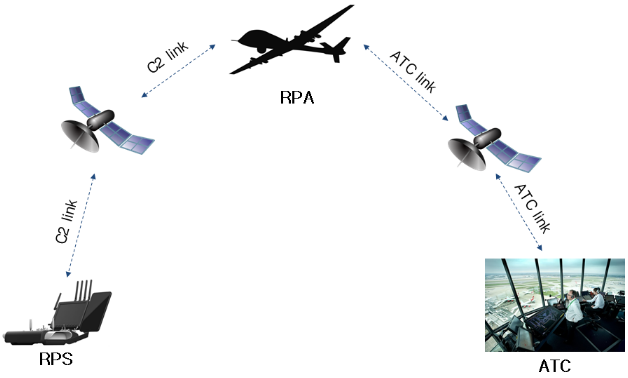


Figure 2.9: Ground communications in ORP operations.

- **Contingency procedures**

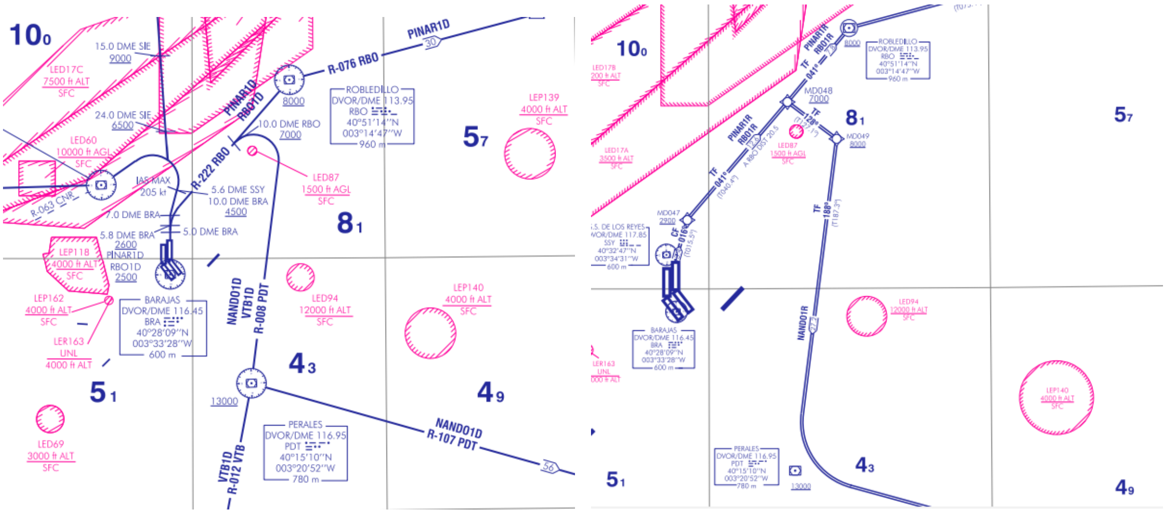
Any type of contingency has an impact on the surrounding traffic, air traffic flow management and ATC workload. As an example, if the ATCo workload increases, the airspace capacity is reduced in the short term. This might not affect the long-term declared capacity of the sector but the situation awareness may be reduced leading to an increase in the risk of failing to identify a conflict situation.

During the execution of a flight (either manned or unmanned operation) different contingencies may occur, such as ATC communications loss, engine failure, etc. Specific procedures are developed to overcome these situations. From an unmanned aircraft point of view, those contingency procedures that are originated from issues that are common for both manned and unmanned aviation should remain as similar as possible to be transparent to ATC. However, C2 link is a key component of RPAS (not present in manned aviation) that can be affected by different factors (equipment failure, human error, interference or propagation related issues) leading to an inability to perform its main functions, communication and control between RPS, RPA and ATC. The loss of C2 link does to necessarily mean that the RPA becomes unsafe if contingency procedures are developed.

For the time being, and despite the efforts of many international and European organizations, contingency procedures have not been standardized yet. Intentions are heading the establishment of different procedures according to the area or flight phase where the contingency takes place: en-route (ACC) and terminal areas (APP). For the en-route phase, it is intended that the RPA will continue with the original flight plan until reaching the next point (previously defined by the operator in the flight plan) where it will try to recover the link.

b) Navigation

Originally, air navigation in continental airspace is based on conventional ground-based routes supported by the radio aid infrastructure: VOR (Very High Frequency Omni-directional Range), NDB (Non-Directional Beacon), DME (Distance Measuring Equipment), and ILS (Instrument Landing System). Beacon-to-beacon flight paths limit the possible route network and reduces the efficiency, since the optimal route is not usually the one published in the charts according to the location of these navaids. To overcome the growth in air traffic and to optimize the use of the airspace RNAV, or area navigation, has been developed. This type of navigation is a method based on IFR in which the trajectory can be planned following any course within the coverage of the ground-based navaid network instead of flying from one navaid to the next one. Figure 2.10 shows the difference between the conventional and the RNAV SIDs, both correspond to RWY 36R Adolfo Suárez Madrid-Barajas airport, ICAO airport code LEMD.



(a) Conventional departure procedure.

(b) Departure procedure based on RNAV.

Figure 2.10: Conventional/RNAV SID - RWY 36R LEMD,[35].

The conventional departure route is based on the navaids close to the airport using VOR radials and DME distances to denote the waypoints or the route. However, in the RNAV route, the waypoints are given by the geographical coordinates and can be defined as fly-by wayopoints or fly-over waypoints. The routes are defined by magnetic headings. Approval and certification for this type of operations is required, which would also apply to RPAS intending to operate following these routes.

Performance Based Navigation (PBN) is the evolution of RNAV. It specifes performance requirements instead of the required equipment (as it is the case of RNAV). *"The performance-based navigation (PBN) concept specifies that aircraft RNAV system performance requirements be defined in terms of accuracy, integrity, availability, continuity and functionality required for the proposed operations in the context of a particular airspace concept, when supported by the appropriate navigation infrastructure"* [36]. This ICAO concept made a major shift from the traditional sensor-based to performance-based navigation. These performance requirements are identified as navigation specifications, which can be RNAV or RNP (Required Navigation Performance) specifications. The different between them is that the latter includes a requirement for performance monitoring and alerting system. Navigation specifications are applied in a different manner according to the correspondent flight phase.

In 2008, two different navigation applications were set for continental en-route airspace: in the Middle East and in Europe, it is supported by RNAV 5 (also known as Basic RNAV or B-RNAV). In the US this airspace is supported by RNAV 2. This value is evolving with the European's Airspace Concept to include the use of Advanced RNP (A-RNP), which will ensure its flexible application independently of the airspace of the operation. The oceanic and remote continental airspace is supported by RNAV 10 and RNP 4, being both GNSS reliant to support the navigation. The main difference is that RNAV 10 does not require any form of ATS surveillance whilst RNP 4 requires ADS-C (Automatic Dependent Surveillance - Contract) in order to agree under which terms and conditions information needs to be exchanged between the ground system and the aircraft via data link. Only those aircraft (which includes RPAS) approved for B-RNAV operations will operate under IFR conditions on the ATS routes of the main European FIR/UIR (Flight Information Region/Upper Information Region). In case they are not properly equipped but they still meet RNP 5 accuracy, the State may authorise their operation by restricting their operations within the lower airspace [37]. Further information regarding ATM operational requirements for RNP/RNAV can be found in ICAO Doc 9750 Appendix A to Chapter 4.

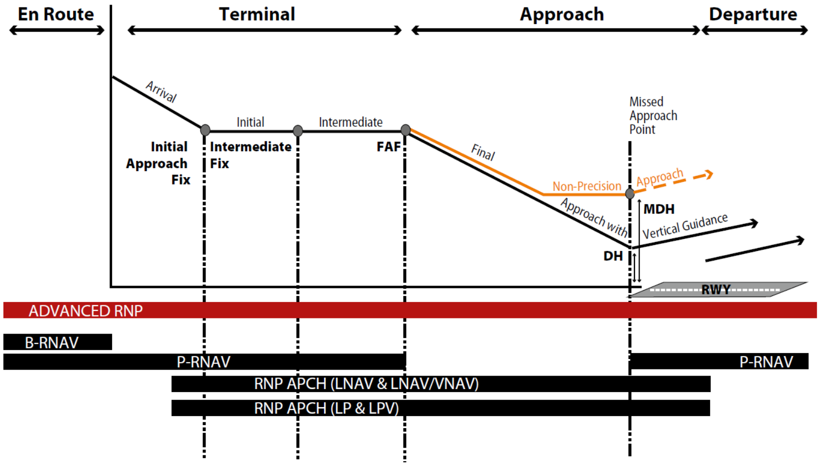


Figure 2.11: Navigation specification per flight phase [29].

Finally, GNSS systems are the latest improvement in terms of navigation. They are a key element in the implementation of the PBN concept since so far, it is the only system able to meet the most exigent navigation specifications for PBN. The actual ground-based navaid network would be maintain as a back-up system once GNSS will be fully and effectively implemented. Some European countries like France, Germany or the UK are already using satellite navigation in all flight phases.

Regarding the navigation perspective for unmanned aviation, RPAS are usually (if not always) equipped with GPS (Global Positioning System) sensors and Inertial Navigation Systems (INS)to determine their position and orientation. If these sensors are proved to meet the requirements and specifications needed for each flight phase, RPAS would be certified or approved to operate RNAV/PBN.

c) Surveillance

Current European regulation (Regulation (EU) No 1207/2011) [38], states that all the aircraft operating IFR/GAT are to be compliant with Mode S by January 2015, for new aircraft, and December 2017 for retrofit aircraft. It enables altitude capability and data exchange. RPAS operating under IFR conditions fall within the first category and therefore, they must be equipped with Mode S. Additionally, from 2016 for new aircraft and 2020 for aircraft needing retrofit, according to the same regulation, aircraft operating IFR/GAT in Europe with a MTOW exceeding 5,700 kg or having a maximum cruising TAS capability greater than 250 kts are required to carry and operate Mode S Level 2s transponder(s) with Mode S Elementary Surveillance (ELS), Enhanced Surveillance (EHS) (for fixed wing aircraft) and ADS-B 1090 MHz Extended Squitter (ES) capabilities. Mode S level 2 will be required for RPAS depending on their performance capabilities or their MTOW.

A few months later, in December 2011, the European Commission published the Commission Regulation (EU) No 1332/2011 (which was updated later in 2016) to mandate the use and carriage of ACAS II within the EU airspace. The implementing rule is applicable in case of aircraft whose MTOW exceeds 5,700 kg or that are authorised to transport more than 19 passengers. The decision of whether this is applicable or not to RPAS cannot be generalized: their intended missions and their MTOWs are very wide and this rule must be applied on an individual basis.

3

Research Objective and Questions

This chapter introduces the definition of the research objective (Section 3.1) which is supported by the research questions and the strategy needed for the project (Section 3.2). The definition of the project is concluded with the definition of the scope (Section 3.3) and the assumptions that have been formulated in Section (3.4).

3.1. Research Objective

RPAS operations have been taking place through segregation by restricting the airspace volume of the intended operation entering or leaving temporary segregated areas (TSA), and by enlarging separation criteria. As has been discussed in Chapter 2, if the number of operations would remain as low as it is nowadays, accommodation of these flights could be the solution. However, it is not feasible if the number of simultaneous operations increases. According to the latest study published by SESAR Joint Undertaking (SJU), unmanned aviation will represent nearly 20% of the fleet by 2050 (400,000 aircraft approximately) [11], leading to an unavoidable mix of different types of aircraft in the airspace. Operating in a mixed environment could require additional performance requirements in terms of speed, climb/descent rate or latency in communications. To be consistent with the ATM objective and ensure safe and efficient flights from departure to arrival, the challenge is no other than to integrate them safely and efficiently. Otherwise, if the number of accommodated operations keeps increasing, the Network would be negatively affected and other airspace users would not be allowed to enter those TSAs. Integration is the only long-term feasible solution.

This project will contribute to integration of RPAS in non-segregated airspace by determining the minimum performance and operational requirements which will allow these systems to operate while minimizing the ngative impact on the ATM Network. Therefore, the objective can be formulated as **the establishment of a methodology to determine minimum operational and performance requirements for the en-route phase by assessing the impact of RPAS operations on the ATM Network.**

The project is based on a case study in Paris CTA. Although the concise values of operational and performance requirements may vary from one airspace sector to another (requirements are dependent on the traffic, vertical limits of the airspace sector, etc.), the same methodology that will be developed in this project can be applied in other airspace sectors in order to come up with the specific requirements.

3.2. Research Question and Subquestions

In mid-2012, an expert group known as the European RPAS Steering Group was appointed by the European Commission. This group involves the participation of organizations such as EASA (European Aviation Safety Agency), Joint Authorities for Rulemaking on Unmanned Systems (JARUS), EUROCONTROL or SJU. In 2013, they published the first document related to the integration of RPAS into Europeain airspace, the European RPAS Roadmap [12]. In this document, technological and operational gaps were identified, making clear the necessity to develop technical systems and operational procedures linked to the regulation and development of standards. Extensive research is now focused on the development of the technical part such as DAA systems or C2 link, while only a few researchers have addressed the establishment of performance and operational requirements on a high level so far. From an operational point of view, the question is: *"How can RPAS be integrated in non-segregated airspace without affecting the actual Network performance?"*

In order to support the research question, the following subquestions will need to be answered within the project:

a) Considering the standard performance of commercial aviation (in terms of cruise speed and ROC), from the RPAS performance models available, which performance model would correspond to "same-performance" and "low-performance" RPAS?

b) Of the Key Performance Areas (KPAs) defined for the ATM Network, which are the most critical areas?

c) Which are the Key Performance Indicators (KPIs), derived from the critical KPAs, most suitable for assessing the impact of RPAS operations on the ATM Network?

d) What is the impact of RPAS operations on the ATM Network as it is now (if no further requirements for RPAS are established)?

e) What are the minimum operational and performance requirements for same-performance RPAS to enable full ATM integration? Performance requirements are established in terms of:

    (a) Cruise speed.
    (b) ROC.

f) What are the minimum operational and performance requirements for low-performance RPAS to enable full ATM integration? Performance requirements are established in terms of:

    (a) Cruise speed.
    (b) ROC.

g) What would be the impact on the ATM Network of a mixed environment (both types of RPAS and manned aviation sharing the airspace) besides a future air traffic growth?

3.3. Scope

Many types of RPAS operations exist, depending on characteristics such as the type of operation, the flight phases, etc. For that reason, it is necessary to limit the scope of the project in terms of the operations that are going to be analysed.

- **Type of operation: IFR.** From the different types of operations that have been defined for RPAS according to the intended altitude of the operation, only IFR operations will be analysed. VFR operations are not expected to be developed and carried out in the near future: the absence of the pilot on board makes difficult (if not impossible) to determine the visual meteorological conditions required for VFR flights.

- **Flight phase: en-route.** IFR operations include airports, TMA and en-route. Due to time constraints, only the en-route phase has been chosen. It is defined as "Any level flight segment after reaching initial cruise altitude until the start of descent to the destination".

- **Type of airspace: controlled.** From the airspace classes that have been defined in ICAO Annex 11, only those corresponding to controlled airspace are considered. These are identified as classes A to E.

- **Type of manoeuvre: point-to-point.** The introduction of RPAS will bring a wide range of operation profiles with different flight paths such as orbiting, loitering, grid or the traditional point to point. The users who will operate in the upper airspace will be most likely performing point to point missions for cargo/passengers transport purposes. Thus, this type of manoeuvre is chosen for the project.

3.4. Assumptions

The following assumptions are considered in this project. Although they will not be verified (most of them refer to future developments not yet in place), the majority do limit the applicability of the results.

- C2 link service is provided.
- Detect and Avoid (DAA) is available. The absence of a pilot on board the RPA makes the traditional "see and avoid" responsibility infeasible for RPAS since the remote pilot cannot see all the traffic and other hazards around the RPA for B-VLOS operations. As a consequence, a new term "Detect and Avoid" has been defined as the capability needed to enable RPAS to detect hazards and to make them detectable. DAA is aimed to ensure the safe execution of the operation and to enable full integration in all airspace classes with all airspace users.
- Contingency procedures are not considered. It is assumed that since only one airspace sector is going to be analysed for this project, if a C2 link loss occurs, the next recovery point is outside the sector chosen for the project, and thus, transparent for that sector. Furthermore, for this project RPAS are considered as unique systems. In case of a communication failure between the RPA and the RPS, it is assumed to take place inside the system and thus, it is out of the scope of the project. In case of a failure in communications between the RPS and ATC (relayed or not through the RPA these communications), there are alternative means to establish an alternative communication, as for example using the telephone. Therefore, contingency is out of the scope and not taken into account for the project.
- There are four main integration requirements that apply as constraints for the project:
  - The integration of RPAS shall not imply a significant impact on the current users of the airspace;
  - RPAS shall comply with existing and future regulations and procedures;
  - RPAS integration shall not compromise existing aviation safety levels nor increase the risk;
  - RPAS must be transparent to ATC and other airspace users.

  In order to be compliant with these requirements, rules of the air contained in ICAO Annex 2 will not be adapted.
- Separation standards are not modified. RPAS are assumed to be RVSM (Reduced Vertical Separation Minima) compliant and therefore between FL295 and FL410 the vertical separation is set to 1,000 ft. Surveillance systems, either radar, ADS-B or multilateration, are assumed to be in place and, thus, the minimum horizontal separation is 5NM (as prescribed by ICAO Doc 4444 [39]).
- An airspace assessment has been executed and no-drone zones are published in the relevant Aeronautical Information Publication (AIP). It is assumed that there are not no-drone zones in the volume of the airspace selected for the project.
- No wind condition is assumed to limit the scope of the project. Communications between the controller and the remote pilot will contain meteorological information regarding the sensitivity of many RPAS to severe wind conditions. In case of a severe weather change, it is expected that the flight plan will be modified accordingly to avoid the area affected by the meteorological phenomenon at hand.
- Wake turbulence is not considered. ICAO established three main categories for wake turbulence based on the MTOW: Heavy (H), Medium (M) and Light (L). The lightest category is defined for those aircraft whose MTOW is lower than 7,000 kg, where most of the RPAS fit. RPAS are much lighter than commercial jets, which makes them more vulnerable to wake vortexes, especially when flying behind a heavy aircraft (e.g. A380). As a consequence, hazardous situations may lead to a mid air collision , a ground collision or even to a combination of both [40]. Although wake turbulence separation criteria are mainly intended for arrivals and departures [41], they are also applied for those lighter aircraft whose projected trajectory will cross the trajectory of a heavier one at the same altitude or up to 1,000 ft below. For this first approach and set of simulations, wake turbulence effects are not considered.

PART II

EXPERIMENTAL SET UP

4

Experimental Set Up

This chapter presents the different components used in the simulations. The simulation environment that has been used is briefly introduced in Section 4.1. The description of the scenario, meanwhile, is divided into four different parts: selection of the airspace sector (Section 4.2), date and time (Section 4.3), breakdown of the traffic sample (Section 4.4) and the RPAS performance models selected (Section 4.5).

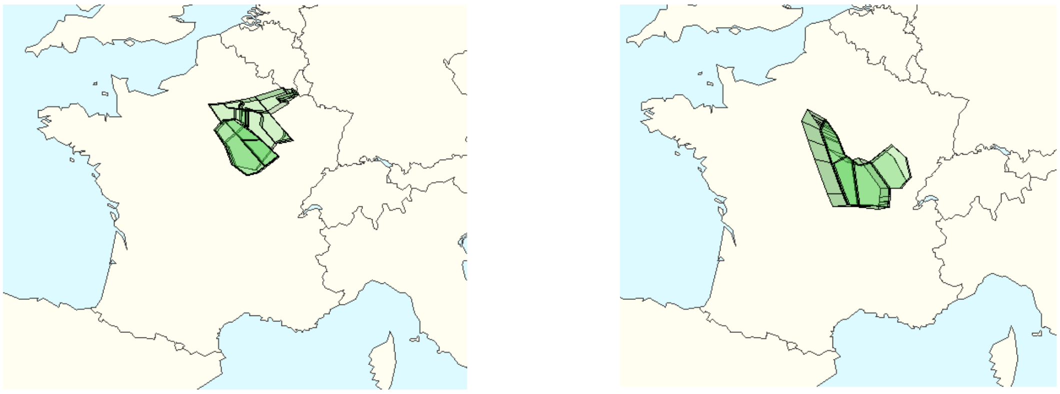
4.1. Simulation Platform

EUROCONTROL has at its disposal different platforms used for research and experimentation processes, most of them developed by the EUROCONTROL Experimental Centre (EEC). The main tool that has been used in this thesis is NEST (Network Strategic Tool), which integrates its two predecessors SAAM (System for traffic Assignment and Analysis at a Macroscopic level) and NEVAC (Network Evaluation and Visualisation of ACC Capacity) tools. It is currently used by the Network Manager and the ANSPs at the strategic level. Their functions include, but are not limited to, capacity planning, post-operations analysis and ad-hoc studies at local and network level [42]. However, some of the features of SAAM are not fully integrated in NEST and, therefore, SAAM has also been used in this thesis for analyses of the scenarios and results. Air traffic demand data (past, actual and future) has been gathered from the DDR (Demand Data Repository), as an integrated functionality in NEST.

In addition to NEST, BADA (Base of Aircraft Data) has been used to provide the performance models for RPAS. This is necessary since RPAS have not been defined yet as commercial aircraft and, thus, are not available in NEST. Through a NEST shell script, BADA files are converted in order to make them compatible with NEST.

4.2. Airspace Sectors

The ACC selected is PARIS ACC, since it is one of the busiest airspace sectors in Europe. Within this sector, there are 27 different elementary sectors (hereafter subsectors) that are grouped or collapsed into 37 different combinations [43]. These collapsed sectors will be denoted as sectors. After analysing their vertical limits and their geographical extension, two candidates are found to be representative and were therefore chosen: AOML and LMHJ (see Figure 4.1).



(a) AOML sector.

(b) LMHJ sector.

Figure 4.1: Possible sectors within LFFFCTA.

In order to select the most suitable one for this project, a few characteristics of each of the sectors must be compared:

- The first feature is the geographical extension. Both sectors have been selected to be representative enough and cover approximately one fourth of the Paris ACC extension.
- The second characteristic is the number of subsectors that each one comprises: AOML is defined by 5 different subsectors (A0, AR, TL, TM, US) and LMHJ is formed by 6 (HP, PU, TU, UJ, UP, UT) [43].
- The final charateristics are the vertical limits. AOML goes from the surface up to FL345 whilst sector LMHJ has no upper limit and the lower one is set to FL195 [43].

Since the number of subsectors and the extension are not much different between the two sectors, the selection criterion will be based on the vertical limits. Considering that the scope of the project is limited to the en-route flight phase, the vertical limits of LMHJ are more convenient and thus, **LMHJ** is the sector selected.

4.3. Date and Time

NEST provides, based on the data available in DDR, two types of flight lists: entry counts and occupancy counts. Entry counts provide information about the flights that enter the specific sector at a specified period of time (for example, from 08:00 to 09:00) while occupancy counts refers to the flights that are crossing the sector in that period of time, which includes all flights that entered before that time and that are still inside the sector. To be more accurate with the information that is going to be used for the simulations, occupancy counts are used. The reason is that there might be some flights that entered the sector before 08:00 (for example at 07:53) but remain there in the interval of time that is being analysed, 08:00-09:00 (its exit time is at 08:15). If entry counts are selected, only those flights which strictly entered from 08:00 to 09:00 are accounted for, while there might be some flights still in the sector that entered before 08:00. So, the previous example would not be taken into account in the entry data (as it entered before 08:00) while it is considered for the occupancy data (since between 08:00 and 09:00 it has been crossing the sector).

NEST also provides three types of traffic data: initial (with information from the latest filed flight plan), regulated (with the information from the flight plan updated with regulations) and actual (flight data information updated with radar data). Actual data is used in the simulations since it contains the real data about the traffic. In order to have an overview of the differences between the three types of data, Figure 4.2 shows the sector occupancy information (initial data in light blue, actual data in dark blue and regulated data in grey) for the 7-06-2016.

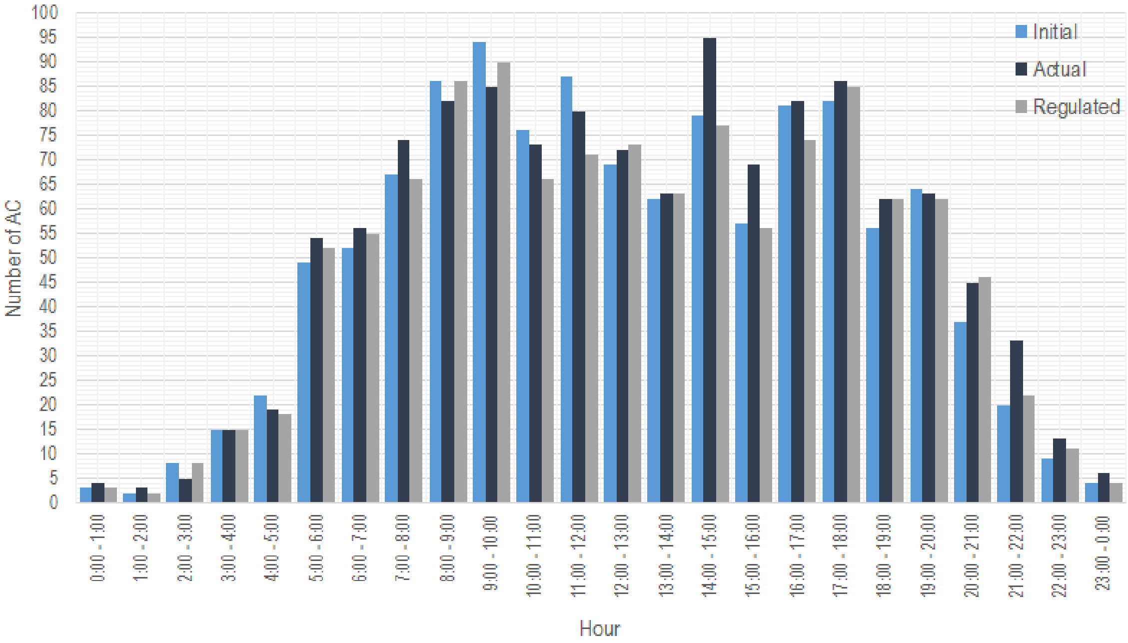


Figure 4.2: Sector occupancy comparison between initial and actual data. Obtained from NEST.

In order to select a representative date and time for the scenario, two different AIRAC (Aeronautical Information Regulation And Control) cycles are studied: AIRAC 1605 (from 28-04-2016 to 25-05-2016) and AIRAC 1606 (from 26-05-2016 to 22-06-2016). This comparison will avoid selecting a date influenced by seasonal or special events effects. The time, 10:00-11:00, has been selected in such a manner that it is neither the peak nor the off-peak hour. The day of the week, Tuesday, has been randomly chosen from the weekdays since it is not expected to be influential.

The next step is to select the traffic sample. For this, a concrete date needs to be selected in order to obtain the traffic information for that day. To that end, traffic information for the set of dates defined previously has been gathered as presented in Table 4.1.

Table 4.1: Number of flights between 10:00-11:00 for different Tuesdays of two AIRAC cycles.

Number of flights between 10:00-11:00									
	2^{nd} week			3^{rd} week			4^{th} week		
	Occupancy	Entry	Daily total	Occupancy	Entry	Daily total	Occupancy	Entry	Daily total
AIRAC 1605	57	46	933	77	65	1016	80	70	1016
AIRAC 1606	77	67	1040	74	63	1073	68	58	835

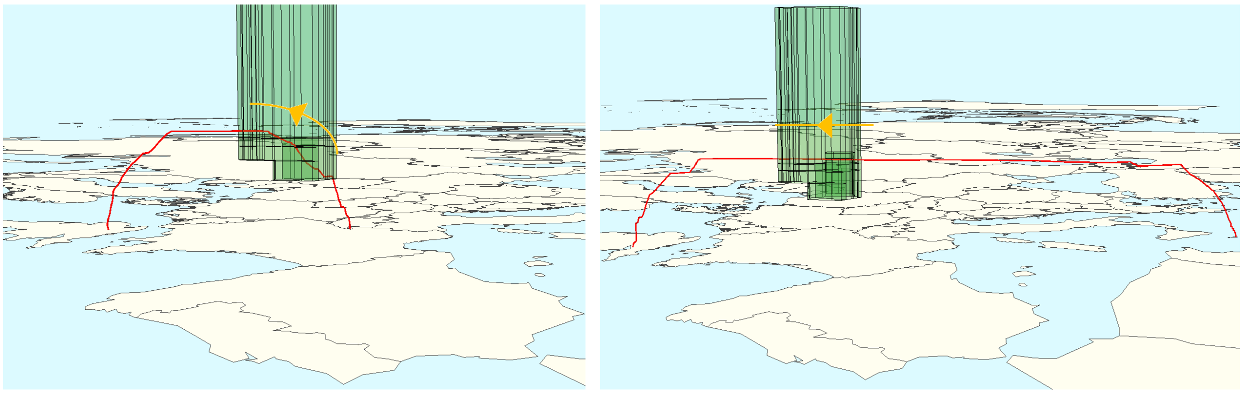
To select the most appropriate date, firstly the extreme values are discarded (which correspond to 57 and 80 flights as can be seen in Table 4.1). Secondly, the traffic for the remaining dates are analysed. The **31^{st} May** is the most suitable day because from the four remaining dates, it is the one that has the greatest percentage of cruise flights (61%) and thus the best one for the simulation scenarios. To confirm the suitability of the date and time, between 10:00 and 11:00 there were 77 flights crossing the collapsed sector, which represents 38.3% of the total number of flights in Paris CTA (LFFCTA) during that period of time. This percentage can be considered as a representative sample of an en-route traffic sample within the Paris CTA.

4.4. Traffic Sample Description

Once the date and the time have been set, traffic information can be gathered. In order to get traffic information, monitor it, and apply ATFCM (Air Traffic Flow and Capacity Management) measures, it is necessary to select the traffic volume associated to the sector. Traffic volume is the tool used by NM and allows comparing traffic load and average capacity. The difference between a sector and a traffic volume is that a sector is a just the geographical volume defined in the AIP, while a traffic volume is the geographical volume (that can be either a sector, an airport, a navigation point or an ACC) with traffic flows that can be included or excluded. In other words, a traffic volume is related to a reference location that, in this case, is an airspace volume. The flow of a traffic volume is the total number of flights which cross the given geographical volume during a given period of time and that are subject to ATFCM measures [44]. The traffic sample corresponding to the selected date and time contains 75 flights, which is considered to be representative of a typical sector traffic for a period of time of one hour. These flights need to be categorized in terms of their flight phase to select those that are en-route. As a first approximation, the traffic is divided into three main categories (climbing, cruising and descending) as follows:

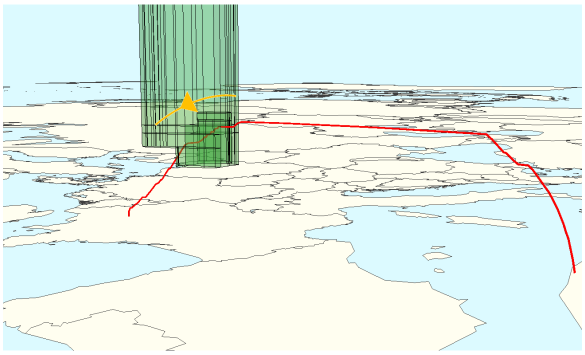
$$\Delta FL = FL_{\text{entry}} - FL_{\text{exit}} = \begin{cases} < 0 \;\; \text{AC climbing} \\ = 0 \;\text{AC cruising} \\ > 0 \;\text{AC descending} \end{cases}$$

However, there might be cruising flights that change their flight level during this phase or flights that enter the sector climbing but start the cruise phase immediately after. Thus, from the remaining fights that have been categorized as climbing or descending and by analysing flight by flight, three flights were found to be cruising but with a change in FL while crossing the sector. Of the total number of flights from the traffic sample, 17 flights are descending, 10 flights are climbing and 48 flights are cruising (see Figure 4.3).



(a) Example of a flight (LFPO-LIRN) climbing while crossing LMHJ sector.

(b) Example of a flight (LMML-EGGD) cruising while crossing LMHJ sector.



(c) Example of a flight (DAAG-LFPO) descending while crossing LMHJ sector.

Figure 4.3: Examples of ascending, cruising and descending flights whilst crossing the sector.

Only those flights considered to be in en-route mode (cruising) will be taken into account hereafter for replacing and adding extra traffic, since the scope is focused on the en-route phase. The mean cruise flight level is found to be FL360. Taking a look at the occupancy of the cruise flight levels, it can be seen that the busiest one is FL380.

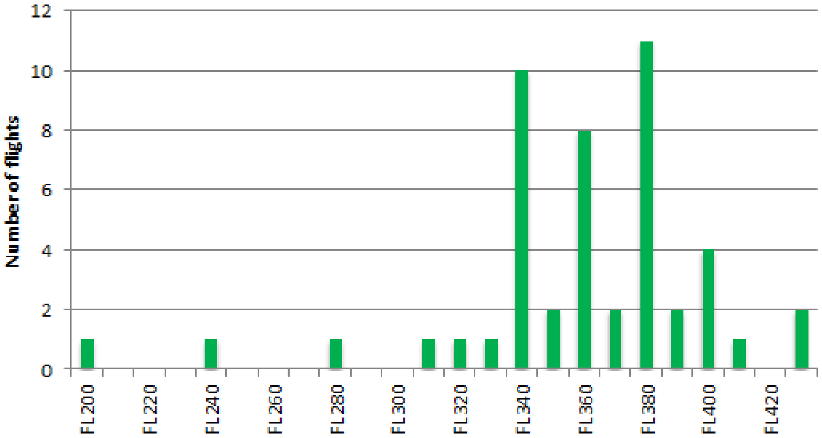


Figure 4.4: Distribution of flights per FL.

The breakdown of the total traffic by AC type is presented in Figure 4.5. Overall, it can be seen that there are aircraft of all categories, ranging from a Pilatus PC-12 to a B777-200.

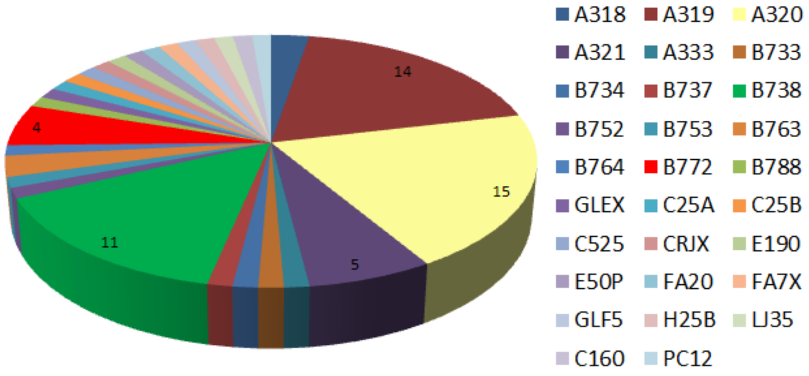


Figure 4.5: Distribution of the total number of flights per AC type.

4.5. RPAS Models

Now that their performance characteristics have been introduced in Chapter 2 and the base scenario has been defined in terms of airspace sector(lower and upper limit), traffic information, etc., it is time to select the RPAS models that are going to be used in the simulations according to the research goal. Two different unmanned performance models will be used. The first type with the "same" -or as similar as possible- performance as a typical commercial aircraft: medium size, single aisle and twin-engined, e.g. the Airbus A320 or Boeing B737-800; and the other model with lower performance. Regarding the performance characteristics that have been presented in Table 2.1, from the four available RPAS models that are defined in BADA, RQ4A and MQ-9 are respectively chosen as the same-performance and low-performance (see Figure 4.6).

The reason behind the selection of the MQ-9 as low-performance example and not any other of the three remaining is due to its ceiling. Most of the en-route sectors are defined as the one that has been selected (from FL195 onwards) which is incompatible with the defined ceilings of the other two RPAS models that are available in BADA, RP03 and RP04. Another question that could arise is about changing the sector and selecting one which starts from the surface. However, the mean number of flights below FL195 for a given sector is one, meaning that the introduction of RPAS operations will not cause much impact when compared to a higher and busier flight level. Thus, the interest lies on assessing the impact on the Network (having a normal amount of traffic) when there are RPAS operating in a shared environment which introduces significant differences in terms of performance. Even though the speed of this RPAS might not be as low as desired, the nominal value is already half of the nominal cruise speed for manned aircraft (or even less). However, it should be noted that although this data is standard, a different speed could be considered along the simulations to make the speed difference even bigger.

(a) MQ-9.[1] (b) RQ4A.[2]

Figure 4.6: RPAS models selected for the project.

MQ-9 Reaper, also known as Predator B, has the size of an F-16. Depending on the weapon configuration (and thus, the weight) the endurance can reach values up to 42 hours, although the nominal value has been established as 14h. As of November 2015, there were 104 units manufactured by General Atomics [18]. The principal users are United States Air Force, U.S. Customs and Border Protection, Royal Air Force (British) and Italian Air Force.

The RQ4A, on the other hand, has been designed and manufactured by Northrop Grumman. The main clients are United States Air Force, NASA and NATO. The performance model of the RQ4A has been defined and verified by both BADA and Multi Aircraft Control System (MACS, created by NASA), while for the MQ-9 only the BADA model has been verified. The endurance of the RQ4A ranges up 35h but the nominal value has been established in 28h. The number of units that have been built in 2015 is 42 [18].

As was mentioned in Chapter 3, the aim of the project is to analyse how the increase of unmanned traffic in the volume of air traffic impacts the Network and to develop minimum performance requirements for RPAS. For that reason, it is necessary to investigate the effect of an increase in the number of RPAS either having lower or the same performance than manned aviation. The challenges for each type of profile are different: the profiles that have lower performance are expected to increase the number of speed conflicts due to the slower cruising speed and rate of climb/descent. For the profiles that have a similar performance, the new issues to consider are the latency in communications and the standardization of new contingency procedures for those aspects that are RPAS specific.

In order to visualize these differences in a practical manner , a typical mission for each type of RPAS defined in BADA has been plotted in Figure 4.7a (see Table 4.2 for further details about the missions that have been simulated). Figure 4.7a shows how the flight profiles are extremely different from one type of RPAS (RP01) to another one (RP04). Figure 4.7b compares RPAS typical mission with the ones that commercial aircraft are performing nowadays. Manned aircraft (A320 and B787-800) have been selected as the most representative ones since they are the most widely used AC models in commercial aviation for short-haul flights. The details about their flights are also included in Table 4.2.

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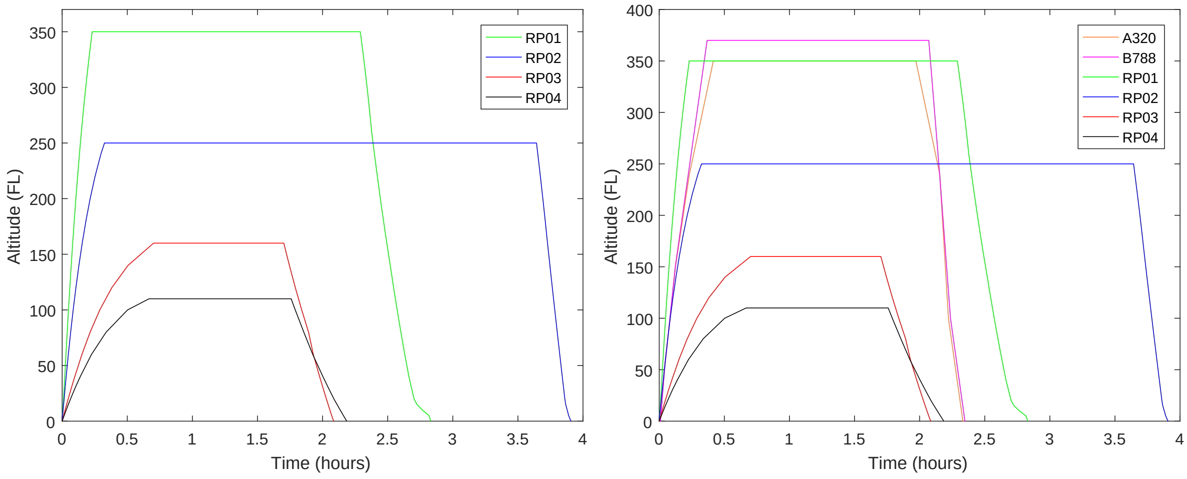
[1] Source: "`http://www.ga-asi.com/predator-b`",[accessed 18 February 2017]

[2] Source: "`https://www.nasa.gov/sites/default/files/thumbnails/image/ed13-0399-17.jpg`" [accessed 18 February 2017]

Table 4.2: Mission details for manned and unmanned aircraft. TAS has been obtained from the corresponding .PTF BADA file or/and has been calculated through interpolation if data were not available.

AC Model	**BADA code**	**Cruise level**	**Cruise speed (TAS, kts)**	**Cruise range (NM)**	**Nominal mass (kg)**
RQ4A	RP01	FL350	340	700	9,889
MQ-9	RP02	FL250	211	700	3,916
Generic Tactical	RP03	FL160	90	90	440
RQ2A	RP04	FL100	82.5	90	191
A320	A320	FL350	450	700	64,000
B787-800	B788	FL370	470	800	189,110



(a) Mission comparison: RPAS models.

(b) Mission comparison: manned and unmanned.

Figure 4.7: Representation of typical missions for different AC models.

The mission comparison graph (Figure 4.7) highlights the main differences in terms of performance of unmanned aviation regarding manned aviation: ceiling (see cruise altitude for RP03/RP04 compared to A320/B788), ROC (more steep climbs for commercial aviation and RP01/RP02 than for RP03/RP04) and the most striking characteristic, the time to complete the mission. By taking a deeper look at Figure 4.7b an estimation of the ROC can be obtained by dividing the cruise altitude (in feet) by the time necessary until reaching it (in minutes). However, this is a simplification of the calculation of the ROC since it does not have a constant value; instead, the climb performance varies with altitude: the higher the altitude, the lower the ROC. But this estimation allows comparing the notable differences in performance metrics. The results are presented in Table 4.3. It should be noted that the values cannot be compared directly since the climb performance is not linear with the altitude. Time to reach FL100 can be compared to get a better insight on climb performance differences. These differences will have to be kept in mind when analysing the results of the simulations.

Table 4.3: Estimations of the ROC.

AC type	**Altitude (ft)**	**Time (min)**	**ROC (fpm)**	**Time to reach FL100 (min)**
A320	35,000	24.92	1404.61	4.99
B788	37,000	22.07	1676.18	4.91
RP01	35,000	13.84	2529.63	2.91
RP02	25,000	19.49	1282.45	5.07
RP03	16,000	42.11	379.92	17.35
RP04	11,000	40.05	274.66	30.16

5

Methodology

With the set up defined, it is necessary to establish the method followed in order to obtain the KPIs to assess the results. Operational requirements are introduced in Section 5.1, based on a previous study carried out for the integration of Very Light Jet (VLJ) [45]. The breakdown of the different scenarios and the steps that are needed for each of them are given in Section 5.2, and the Key Performance Indicators (KPIs) used to quantify the change of each iteration of requirements are included in Section 5.3. In order to assess one of these indicators, capacity, it is necessary to compute controllers' workload. The procedure followed in this process is explained in Section 5.4. Workload is also included in the estimation of the capacity based on the CAPAN method as detailed in Section 5.5.

5.1. Operational Requirements

For RPAS whose performance characteristics are lower than those of commercial aircraft, the most similar configuration is found to be general aviation, and, more specifically, very light jets (VLJ). These are also known as entry level jets (ELJ). This category is defined as small business jets with a MTOW of less than 4540 kg, a single pilot and carrying from 4 to 8 passengers on board. The purpose of this new category of aircraft is to reduce the operating costs, to cover areas which are ignored by the larger airlines and to provide a point-to-point service for either personal or commercial purposes [46]. Some examples of this category are Embraer Phenom 100 and Cessna Citation Mustang, shown in Figure 5.1.

(a) Embraer Phenom 100.[1]

(b) Cessna Citation Mustang.[2]

Figure 5.1: Examples of VLJ.

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[1] Source:"`http://www.airliners.net/photo/Pakistan---Air/Embraer-EMB-500-Phenom/1827784/L`",[accessed 25 January 2017]

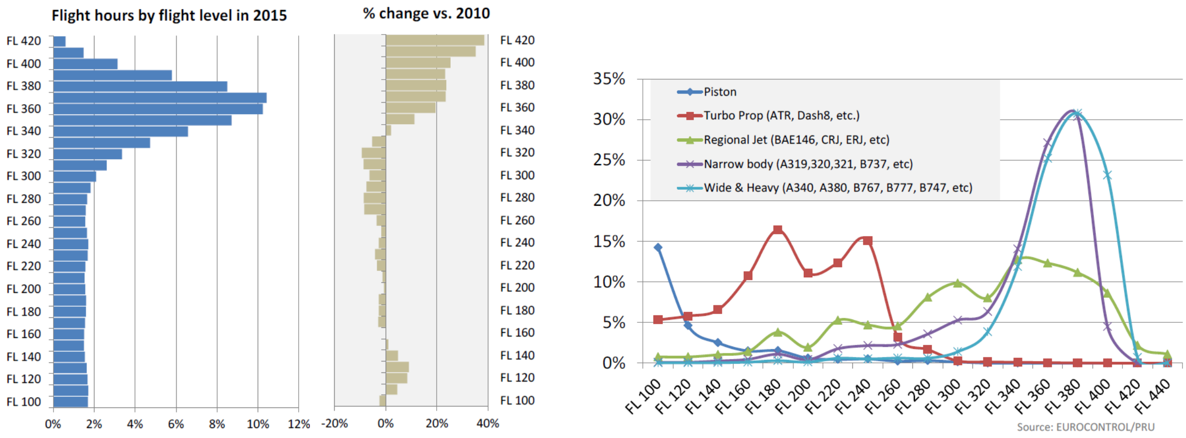
[2] Source:"`http://www.aircharterservice.com/aircraft-guide/private/cessnaaircraftcompany-usa/cessnacitationmustang`",[accessed 25 January 2017]

Regarding the performance characteristics of these aircraft, they present notable differences with respect to conventional jets. The two most important differences are:

- Optimal cruising levels between FL210 and FL390, while for commercial aircraft these range from FL330 to FL450.
- Cruising speed: 300-420 kts, compared to 400-500 kts of commercial jets.

This first caused an impact regarding their integration in the ATM Network since the difference in performance increases the controller workload. Focusing on the en-route phase, the most critical aspect is again the difference in speeds, which leads to an increase in the number of potential conflicts. In case of a slow aircraft flying a specific route, the aircraft that is flying immediately behind it will need to slow down or be redirected to avoid the collision. Both options would induce an impact on the surrounding traffic which would might have consequences in the whole Network. To avoid a negative impact on the Network, altitude segregation is performed by keeping the slower aircraft at lower flight levels than the other traffic with higher cruise speeds [47]. The same solution will be considered as well for both types of RPAS if the impact on the Network is found to be negative.

To that end, it is necessary to take a look at the occupancy of the flight levels in order to analyse which are the busiest ones, so that they can be avoided. The distribution of the flight hours by flight level (see Figure 5.2a) shows that most of the demand is concentrated in the upper airspace. The two most demanded flight levels are FL360 and FL370. This trend has been increasing for the past few years, while the amount of flight hours below FL330 has decreased. Focusing on the distribution per aircraft type (Figure 5.2b), it can be seen that these flight levels are mainly occupied by narrow body and wide body aircraft. It should be noted that in 2015 56.4% of the controlled flights were performed by narrow body jets.



Source: EUROCONTROL/PRU

(a) Distribution of flight hours by flight level in 2015.

(b) Distribution of requested flight levels in 2015 per AC type.

Figure 5.2: Flight level occupancy in 2015 [48].

To compare this information with more recent data to analyse if the region of the airspace that is more occupied is a trend over the years or something occasional, PRISME Data Warehouse[1] provided data about the flight level occupancy in September 2016 (see Figure 5.3). The most occupied flight levels are within the range of FL330 and FL400 (61.96% of the flights). However, almost half of the flights (49.51% of the total) are within the top five (FL350-FL390).

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[1] In-house data provided by PRISME (Pan European Repository of Information Supporting the Management of EATM) Data Warehouse

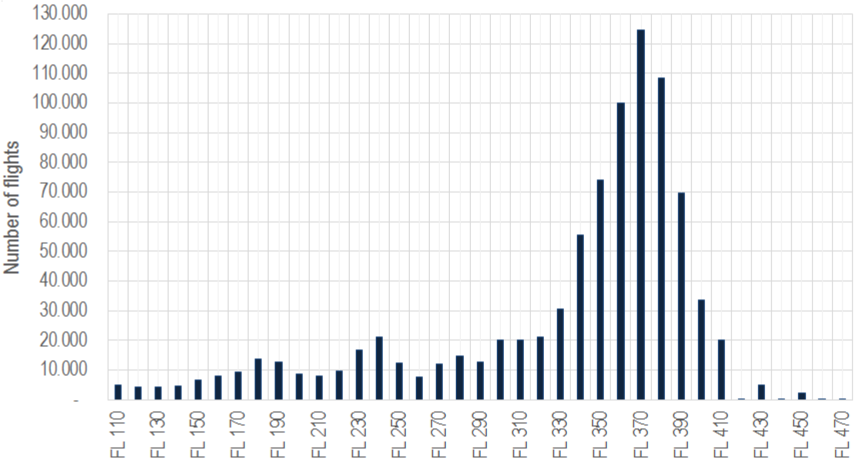


Figure 5.3: Flight level occupancy in September 2016.

By observing 5.3 and 5.2a, it can be deduced that the most occupied FL are maintained over time. Thus, a possible solution would be to allow RPAS to fly in flight levels with less traffic. For example, a cruise level can be selected below FL300 for the ones which will perform shorter flights, and above FL400 for long haul flights. Moreover, flying below FL290 or above FL410 alleviates the requirement of being RVSM compliant, since the vertical limits go from FL290 up to FL410.

5.1.1. Altitude Segregation Rules for Same-Performance RPAS

Rules for altitude segregation for same-performance RPAS are based on the results of the FL occupancy that was stated in Section 5.1. A flight level constraint is thus defined for AC type RP01 as follows:

- If the original flight level is above FL350, they will be allowed to fly above or at FL400.
- If the original flight level is below FL350, they will be able to fly below or at FL300.
- If the original cruise level is included in the allowed region for RPAS operations, the cruise level does not change.

It should be noted that this is a simple assumption that has been made for simulation purposes, to distribute the traffic avoiding the most congested area. The limits would be expected to be set by the correspondent ANSP. However, the operator or the remote pilot might be able to negotiate with ATC the desired FL prior to the flight. It could be the case that a flight that has been assigned to the lower allowed part (cruise level < FL300) is more efficient if it could fly above FL400. Assume the following example. The flight AZA217 has as original cruise level FL340. However, if it is performed by an RP01, it will be changed to FL380. To distribute the flights that take place at even FL, flights at FL360 are reassigned to FL400 and FL380 are reassigned to FL420. Otherwise, FL400 would saturate and the number of conflicts would increase. Finally, it should be kept in mind that RPAS operating between FL290 and FL410 should be RVSM compliant, to avoid creating a higher impact on the ATM Network.

5.1.2. Altitude Segregation Rules for Low-Performance RPAS

Before moving on in the development of AS rules for this type of RPAS, it is necessary to clarify the following aspects:

- FL310 has been defined in BADA as the maximum operating altitude for RP02, although the ceiling is set to 500,000 ft (see Annex A). Therefore, cruising levels above FL310 are automatically changed to the maximum operating altitude (FL310) when running the trajectory simulation.
- However, by changing the original cruising level to FL310, RVSM criteria are not respected. Original odd cruise level are changed to FL310 while the even ones, are changed to FL300 (see RP02 FL RVSM*[1] column).

Looking at the allowed region of the airspace for RPAS operations (above FL400 and below FL300), this type of RPAS will fly below or at FL300. Thus, an additional consideration is needed to avoid having all of them at the same FL, i.e. the maximum allowed, while compliant with RVSM rules, which apply starting at FL290. The rule is as follows:

- If the original flight level is an odd number, the FL is reassigned to either FL270 or FL290 (except for values below FL300, for which the original FL is maintained).
- If the original flight level is an even number, the FL is reassigned to either FL280 or FL300 (except for values below FL300, for which the original FL is maintained).

5.2. Scenarios

For this project three different scenarios have been defined. Each one has different aims and characteristics. The breakdown is shown in Figure 5.4.

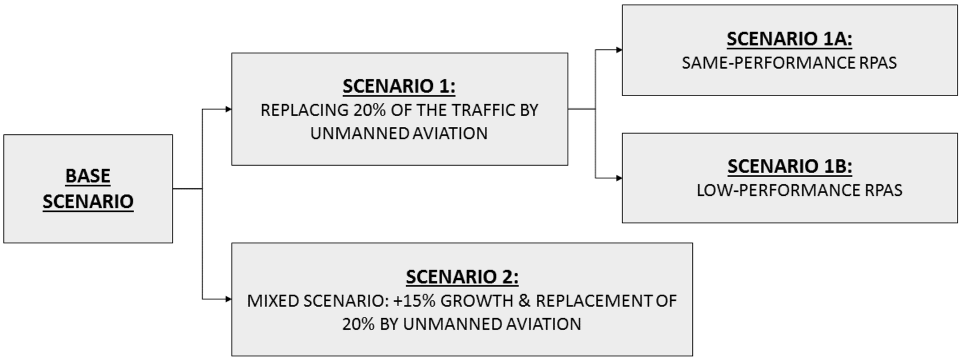


Figure 5.4: Breakdown of the different scenarios.

- **Base scenario:** This scenario is based on the real traffic data (in NEST, actual data) gathered from DDR for the selected date and time, 31st May from 10:00 to 11:00. Therefore, only manned IFR operations are included. This first scenario will be used as the reference to compare the resulting KPIs that will be obtained in the following scenarios.

- **Scenario 1:** This scenario is aimed at defining the operational and performance requirements for RPAS to minimize the impact of their integration on the ATM Network. It is based on the base case, but assumes replacing 20% of the flights by unmanned operations. The substitution is carried out randomly among the flights that are cruising, and not among the descending/climbing flights, due to the focus on the en-route flight phase of this project. Two different sub-scenarios are proposed: one for the RPAS model that has the same performance as commercial aircraft (hereafter this sub-scenario will be denoted with letter A), and a second one for the RPAS model that has lower performance than commercial aircraft (letter B).

  In scenario 1A, the impact of RPAS operations is assessed by comparing the resulting values of the KPIs with the values obtained from the base scenario. Since this type of RPAS already has the same performance, it does not make sense to define stricter performance requirements than those of manned aviation, since that would be detrimental. Nonetheless, due to the wide range of cruise speeds even for those considered to have the same performance, it is necessary to assess the minimum cruise speed required for their operations in order to reduce the negative impact to the minimum. Another objective is to analyse the effect of the RPAS characteristics such as latency and the resulting mixed traffic. Once this has been done, scenario 1B will follow the same procedure, to establish the minimum performance requirements for the second type of RPAS.

In this scenario, there is one approach based on a stochastic model. In order to develop the stochastic model, Monte Carlo simulations are needed, randomly varying the input variable (e.g. the set of flights that is replaced by RPAS) and investigating the variability of the outcome through a sensitivity analysis for different scenario parameters.

The strategy for the development of the project is the same for both types of RPAS. It is based on the following steps (see Figure 5.5): replacement of the agreed percentage of unmanned flights; implementation of operational requirements based on altitude segregation rules; assessment of the minimum cruise speed (this might require several iterations until finding the one that reduces the most the impact); and, finally, assessment of the minimum ROC.

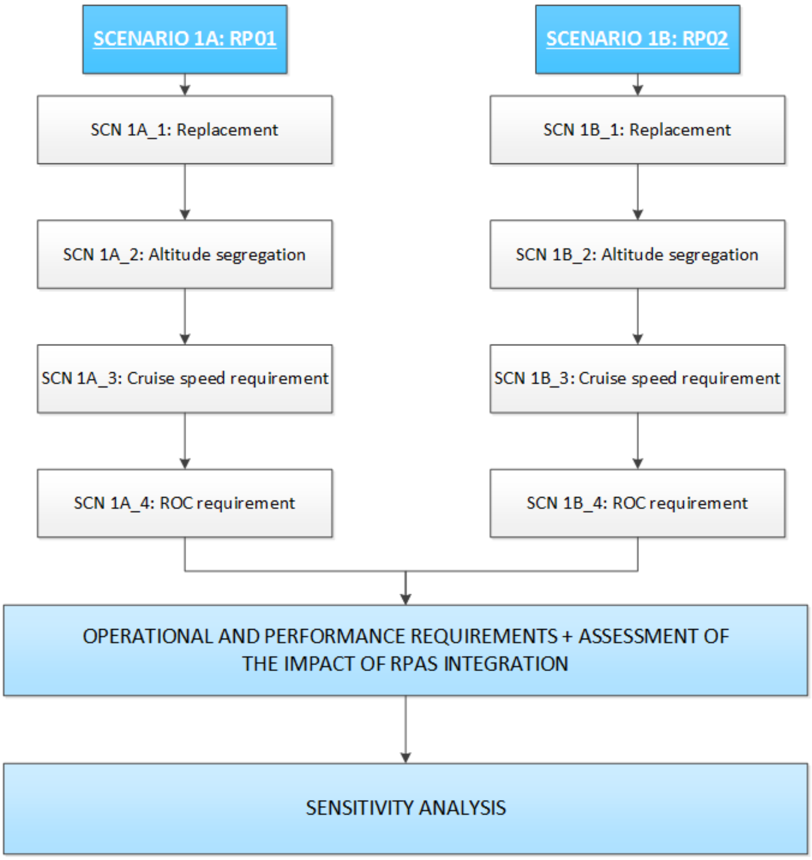


Figure 5.5: Project strategy breakdown.

- **Scenario 2:** Finally, as air traffic tends to grow over time, a second scenario is proposed in order to simulate a future "mixed" scenario where both types of RPAS are operating. The requirements obtained in scenarios 1A and 1B are implemented. On one hand, this scenario accounts for an increase in air traffic of 15% and, on the other hand, it mixes both types of RPAS with manned aviation, which in the future is expected to happen. The percentage of manned and unmanned aircraft will also be the values forecasted by SJU [11]: 80% of manned aviation and 20% of unmanned. The value of the air traffic growth has been chosen taking into account the latest long-term forecast done by STATFOR [49]. It should be noticed that this scenario is based on a specific study-case.

5.2.1. Scenario 1A

Even though RP01 has been defined as same-performance RPAS, minimum performance requirements should be established for them to let them fly and create a mixed and safe environment. The RPAS type chosen for this scenario has a nominal cruise speed of 335 kts. But cruise speed for commercial aviation normally ranges between 400 and 450 kts. For that reason, different speeds for RPAS ranging from 350 up to 400 kts at intervals of 10 kts will be analysed to see which one would provide the best outcome and thus, to set the minimum cruise speed for same-performance RPAS. Moreover, if they are required to fly faster than commercial aviation, this will incur in an increase in the number of conflicts due to differences in speed (in this case the RPA would be the AC that goes faster and not the contrary). For later reference, the sub-scenarios are named from 1 to 6 in ascending order of speed (e.g: 350kts corresponds to 3_1 and 400kts to 3_6).

Although altitude segregation rules are expected to improve the safety indicator (the number of potential conflicts) it will be necessary to verify that the results of scenario 1A_3 for the two best cases would be better than only requiring the minimum cruise speed, without altitude segregation. To that end, two final simulations are performed setting the minimum cruise speed to the best two candidates for minimum cruise speed.

After analysing the minimum cruise speed for unmanned aviation, the following step would be to analyse the rate of climb (ROC). By establishing a minimum value, the impact would be reduced and the results could get closer to the outcome of the BS. Figure 5.6 represents the ROC (in fpm) for different types of aircraft: commercial manned aviation, such as A320 or B787-800, and the unmanned model used in this scenario, RP01. It can be seen that the climb performance of this particular RPAS is better than any of the other commercial aircraft considered, which means that for this type of RPAS the ROC requirement does not need to be set: they already have a better profile.

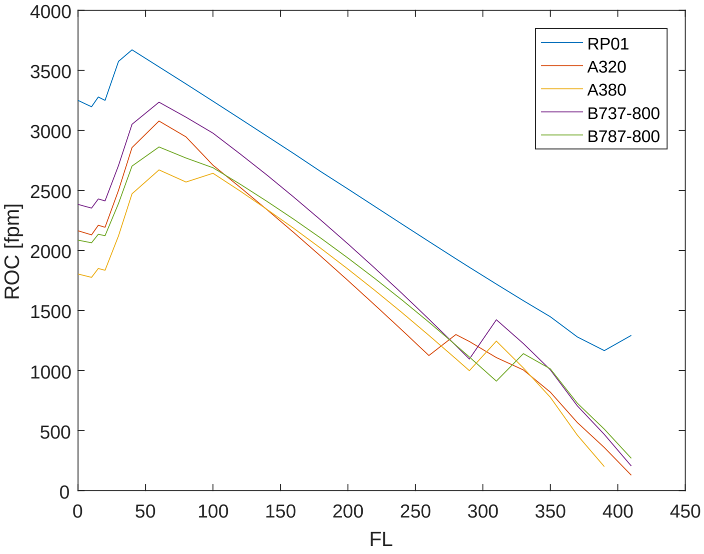


Figure 5.6: Comparison of ROC values for different aircraft models.

Looking at the ROC for FL100, it can be seen that for commercial aviation it is within the range [2500, 3000 fpm] while for RP01 this value is around 3200 fpm. Considering now FL400, the ROC for commercial aircraft is below 500 fpm and above 1,000 for RP01. The difference between the RP01 performance and commercial aircraft is noticeable especially at high altitudes, where ROC is almost twice the value corresponding to manned aircraft.

However, the fact of having a better climb performance is influenced by the fact that there is only one type of RPAS presenting a similar or better performance (in general) than commercial aviation from the performance models defined in BADA, which is the model chosen for scenario 1A. It could be the case that another type of RPAS would have the same cruise speed but lower ROC. Therefore it can be concluded that RPAS falling within the category of same-performance should have a ROC similar or better than manned aviation, between 500 and 1,000 fpm for high altitudes (FL300-FL400), and between 1,000 and 2,000 fpm for low altitudes (FL200-FL300).

5.2.2. Scenario 1B

Scenario 1B takes into account low-performance RPAS. First of all it is necessary to recall that the cruise speed of this type of RPAS is 200 kt, quite low compared to the typical range of commercial aviation (300-400 kts). The nominal ROC is 250 fpm at altitudes around FL280 is very low compared to commercial aviation (typically between 1,000 and 1,500 fpm). Given their nominal cruise speed and rate of climb, it is foreseen that the impact on the ATM Network is going to be much larger.

For this second case, where RP02 has been chosen, the cruise performance is analysed starting from the nominal cruise speed (200 kts) up to 300 kts, in increments of 10 kts. The decision of limiting the cruise speed to 300 kts is because they are still considered low-performance RPAS and if the cruise speed is set to a value greater than 300 kts, then the speed is similar to the manned one and this type of RPAS would be significantly penalized. Due to their ceiling, they will operate in the lower airspace (below or at FL300). Even though they are flying above and below the most congested areas, they are operating together with manned aviation such as jets or even very light jets whose speed is lower than commercial aviation. Thus, if in that region the speed of the RPAS is dramatically larger than the one of the jet aircraft, conflicts due to differences in speed appear again.

In this scenario, most of the cruising flights are crossing the sector at a given FL without any further change in altitude. However, in real life, RPAS might need to change their cruise level, either climbing or descending, due to an ATC command or because it is defined in the flight plan. Therefore, it is necessary to assess how this difference in ROC would affect the ATM Network. In order to avoid performing a very different simulation compared to the base scenario, a maximum altitude is defined for five waypoints belonging to the sector to simulate that RPAS passing through them are given an instruction from ATC. These waypoints are: OKEKO and OKASI (LFFFUP), MOKIP (LFFFUT), IBABA (LFFFUJ) and PEKIM (LFFUP). Two elementary sectors have no waypoints included in the previous list because of their vertical limits: their lower limit is higher than the ceiling of this type of RPAS.

An example of a waypoint with a maximum altitude of FL270 is provided in Figure 5.7. This flight corresponds to the callsign AMC215B. The cruise phase of the original flight was performed at FL290 (see blue dashed line). The modified profile is presented in light green. To optimise the flight, the first part of the cruise is performed at the same altitude as the maximum altitude defined for the waypoint OKASI. This cruise altitude is kept until the aircraft reaches the point. After that point, it climbs up to the cruise level (FL290).

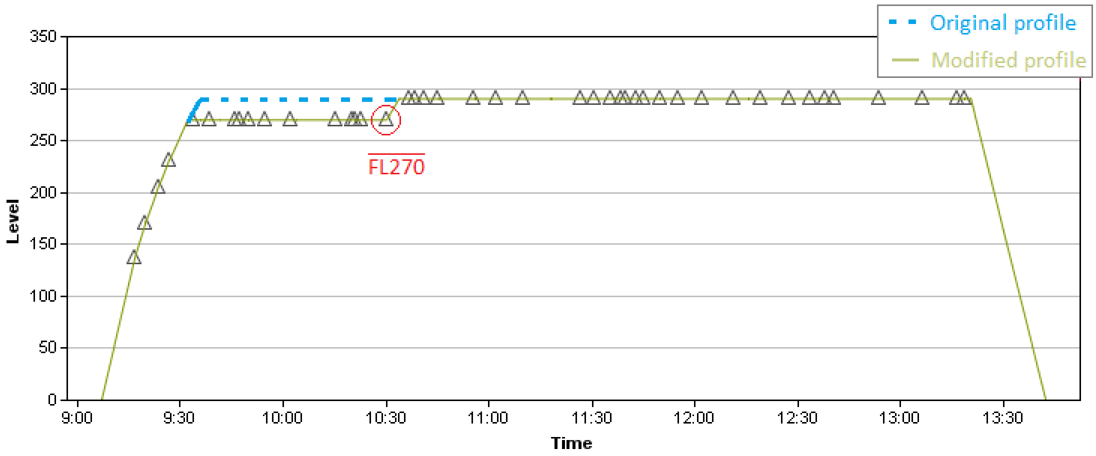


Figure 5.7: AMC215B Vertical profile change (flight performed by RP02 with a change in FL.

RPAS passing through these waypoints will have to keep a FL lower than their cruise altitude until they reach the waypoint that is in their trajectory, and after flying over the waypoint, they will continue climbing until the desired altitude.

By taking a look at Figure 5.8, where different climb profiles for different aircraft types are shown, it can be deduced that the climb profile of RP02 type is very poor, climbing at approximately 250 fpm at cruise levels between FL280 and FL300.

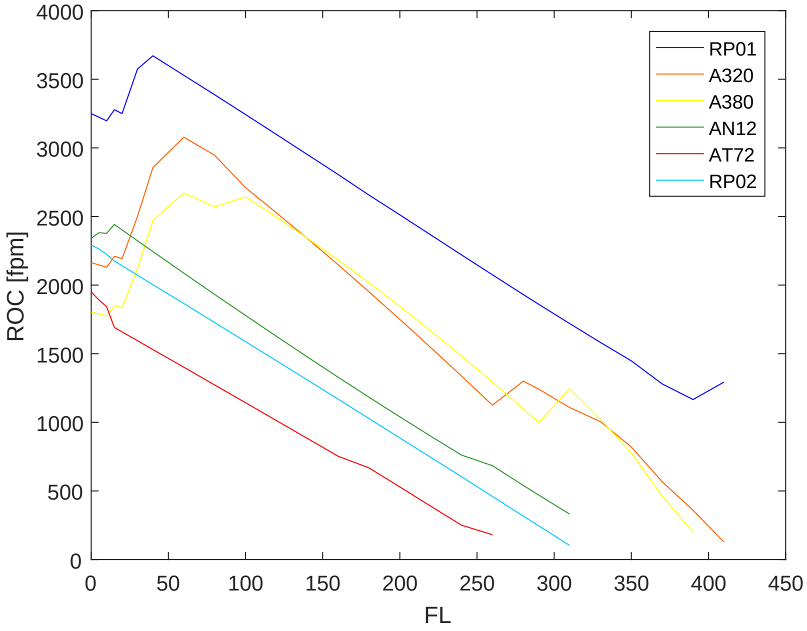


Figure 5.8: Comparison of ROC values for different aircraft models.

Comparing the performance of RP02 with the different manned aircraft, it can be seen that RP02 climbs at 1,000 fpm for altitudes below FL175. This ROC is maintained for commercial aviation up to FL300-FL350. Looking at the climb performance at high altitude, RP02 climbs at 500 fpm up to FL250 while this climb performance is found for commercial aviation at altitudes between FL300 and FL400.

To assess which should be the minimum ROC for unmanned low-performance RPAS, the performance model of RP02 is modified in order to allow it to reach ROC up to 1,000 ft for altitudes around FL300. Its nominal ROC at FL300 is of 250 fpm, but it might be required to have a greater value to reduce the negative impact. Four different values of ROC are analysed: 250, 500, 750 and 1,000 fpm. They are indicated as A,B,C and D following the scenario numbering used so far. First they are analysed with no requirement for cruise speed, and secondly the best two candidates driven from the cruise speed iterations will be simulated. The reason why they are also analysed for the case with no cruise speed requirement is to see the isolated effect of ROC in the scenario, without considering higher speeds than the nominal one.

5.3. Key Performance Indicators

In order to validate the performance requirements, it is necessary to define which Key Performance Areas (KPA) have to be analysed. Once the areas of interest are defined, the evaluation is done through their corresponding Key Performance Indicators (KPI). NEST provides many different analytics and statistics which can be used for the calculation of the KPIs. However, since the duration of the simulations is set to 60 minutes and limited to one collapsed sector, some of them cannot be used e.g. if they are intended for days or for different sectors.

In aviation, different KPAs have been identified depending on the target (airports, airlines, airspace, and so on). From the 11 KPAs defined by ICAO [50], three of them are selected based on the available information that can be obtained from the simulations and taking into consideration the possible limitations when choosing them (for example, there is no human interaction or there is only a part of the network that is going to be used): Capacity, Efficiency and Safety. Safety, Capacity and Delays (or Efficiency) have been identified as the most critical areas for ATM systems which have to be improved in order to respond to air traffic growth and to allow new airspace user access [51]. For each KPA, at least one indicator has been chosen to quantify the performance and to compare the base scenario with the remaining scenarios (see Figure 5.9).

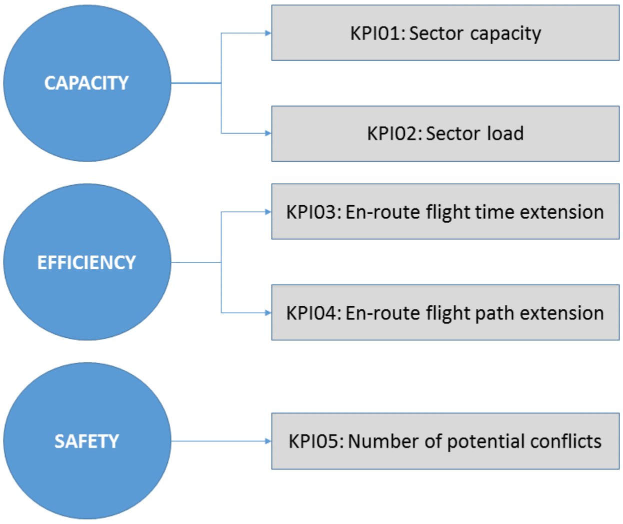


Figure 5.9: Key Performance Areas and the corresponding key performance indicators.

- **KPA01: Capacity**. Within this area, two main indicators (KPIs) will be used: Sector capacity and sector load (also known as capacity efficiency). Both are expressed in AC/h.
  - **KPI01. Sector capacity**: maximum number of flights within an airspace sector that are accepted under normal conditions and for a given period of time. This indicator takes into account the available resources and other external and internal factors such as weather or the level of training of the controllers [52, 53]. Airports and airspace sectors have a predefined and fixed capacity (declared capacity) which can be reduced if different factors affect it negatively. This declared capacity is used in the base scenario as the reference capacity.
  - **KPI02: Sector load.** If demand exceeds capacity, the immediate solution would be to hold the aircraft that are on the ground, which is cheaper than holding the aircraft in the air [51]. However, this solution creates delays that are propagated through the network, causing a negative impact on it. Thus, it is necessary and interesting at the same time to analyse how many units the demand exceeds the capacity. Sector overload is calculated by comparing the demand and the capacity values for a given period of time. For the base scenario, the sector load is calculated making use of the declared capacity and the demand of the sector.

$$\text{KPI02} = \text{Demand} - \text{Capacity} \tag{5.1}$$

- **KPA02: Efficiency**. KPIs reporting efficiency are related to improvements in terms of time or track distance. These have an economic impact which at the same time affects all stakeholders: ANSPs (investment on new technologies), airlines (flying routes closer to the optimal) and even on the users (saving time and money). Given the information that can be extracted from the simulations, two KPIs are selected: en-route flight time extension and en-route flight path extension. They are a variant form adapted for this project from the efficiency KPIs defined in Reference [52].
  - **KPI03. En-route flight time extension:** RPAS are well known for having a wide range of cruise speeds. For the ones that fly slower than commercial aviation, even though the flight path might remain the same, it will take them longer to fly it, which leads to an increase in the average time spent in the sector. The longer they stay in the sector, the greater the controllers' workload (the controller is active for a longer period; more time is spent in communication activities and in

manual operations) [54]. By monitoring the change in this KPI (en-route flight time extension), the relationship with the workload will also be analysed. It can be calculated as follows:

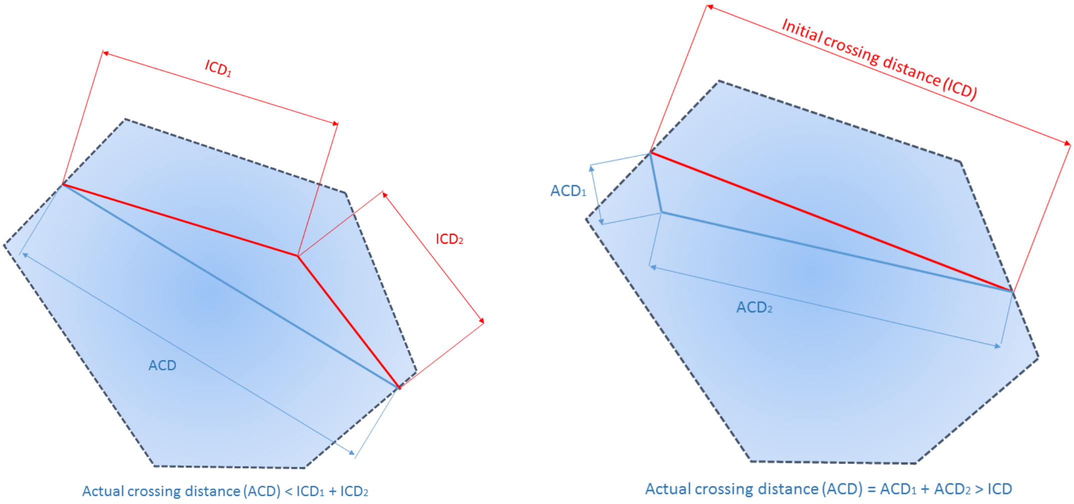
$$\text{KPI03} = \frac{\sum_{i=1}^{n} (\text{ICT}_i - \text{ACT}_i)}{n}, \tag{5.2}$$

where ICT is the initial crossing time, ACT the actual crossing time, and n the total number of en-route flights. It is measured in seconds. If the value is greater than the threshold value, the aircraft is crossing the sector faster than for the base scenario, spending less time in the operation. In contrast, if the value is lower than the reference, they are flying slower and thus spending more time crossing the sector.

- **KPI04. En-route flight path extension:** average difference in terms of the elapsed distance between the initial trajectory (contained in the initial flight plan) and the actual trajectory (the flown one) per en-route traffic volume.

$$\text{KPI04} = \frac{\sum_{i=1}^{n} (\text{ITD}_i - \text{ATD}_i)}{n}, \tag{5.3}$$

where ITD and ATC are the initial and actual track distance respectively, and n the total number of flights. It is expressed in nautical miles (NM). Values greater than zero mean that the flown routes have been more direct (and thus, shorter) than the ones that were filed in the flight plan. If the value is lower than zero, the flown routes have been less direct than the original ones.



(a) Example of a sector crossing where ACD is shorter than ICD, KPI04>0.

(b) Example of a sector crossing where ICD is shorter than ACD, KPI04<0.

Figure 5.10: Examples of enroute flight length extension.

- **KPA03: Safety**. Last but not least, safety is one of the main and most important areas for aviation. Safety, measured through conflict risk increase, can be approximated as the square of the traffic density [51]. The safest situation would be to have all the aircraft on the ground, which is obviously infeasible if air transport takes place. In this regard, the number of potential conflicts is the KPI chosen to assess the safety of the scenario and simulation.
  - **KPI05. Number of potential conflicts**. Expressed in AC/h. One of the post-simulation analysis of the output is the number of potential conflicts within the traffic sample. A conflict is considered when there is an impending loss of vertical or horizontal separation. Horizontal separation has been set to 5 NM and vertical separation to 1,000 ft when RVSM is applicable; and 2,000 ft otherwise. Trajectory simulation functionality does not take into account aircraft separation since ATCo instructions are not simulated. Therefore, conflicts are only detected but not resolved. Further details about conflict detection can be found in Subsection 5.3.1

The indicators KPI03 and KPI04 only contain information for the en-route flight phase. Although the scope of the project is limited to this flight phase, the remaining KPIs are evaluated at sector level, i.e. including all flight phases. The reason behind this is that it makes no sense to ignore conflicts that take place in other flight phases since this could be a consequence of the introduction of cruising RPAS. KPI01 and KPI02 are also analysed per sector, to follow the most commonly adopted definition of sector capacity. These KPIs are first evaluated for the base scenario to establish the reference values, and to assess if after each scenario the results are converging on the reference values. Results obtained from a simulation of the reference case are presented in Table 5.1.

Table 5.1: KPI values for the base scenario.

	KPI01	**KPI02**	**KPI03**	**KPI04**	**KPI05**
Base Scenario	48	17	-131.24	-16.88	1

The outcome of each scenario is going to be assessed based on five different KPIs. But in order to be able to select the best scenario and to define the minimum performance requirements, a single scalar is necessary to compare the results. However, not all the KPIs have the same level of importance. From the three KPAs, safety is by far the priority for the ATM network. In order to reflect this priority, and to help in the selection of the scenario with the best performance, a weighted combination of KPIs (WKPI or Weighted Score, WS) is calculated as follows, with *i* the index corresponding to each scenario:

$$WKPI_i = KPI01_i + KPI02_i + KPI03_i + KPI04_i + 2.5 \cdot KPI05_i \tag{5.4}$$

The values obtained for the KPIs are not added directly: first it is necessary to evaluate them by normalization, assigning to the best value of the KPI a 1 and to the worst value a 0. The values in between those extremes are normalized. In order to differentiate them from the nominal value of the indicator obtained immediately after the simulation (with no weight associated), they are indicated with the subindex *i*, which indicates the number of the scenario.

This method is applied to those KPIs whose increase positively affects the ATM network performance, as it is the case of capacity (KPI01) and efficiency (KPI03 and KPI04). For the remaining KPIs, an increase in their value would negatively affect the network: an increase in the overload or in the number of potential conflicts causes a negative impact. Thus, for these two indicators the value of 1 is assigned to the minimum and 0, to the maximum.

Given the fact that the third KPA is represented by only one indicator, this weight should be doubled to have the same importance in the weighted score as the other two areas. Additionally, to highlight the relative importance of safety among efficiency and capacity, an extra 0.5 has been added to this weight, leading to a total weight of 2.5.

As an example of KPI normalization, suppose that the values of KPI05 that have been obtained after six simulations are {1, 3, 2, 6, 4, 1}. The best value (minimum, since it represents the number of potential conflicts) is found to be 1 and 6 the worst case. Assigning the value of the weight (2.5) to the best value and a value of 0 to the worst, the following set of points is obtained: (1, 2.5) and (6, 0), where the X-axis represents the values of the KPI05 and the Y-axis, the weights. The equation of the line defined by these points is calculated as follows:

$$\frac{x-x_1}{x_2-x_1} = \frac{y-y_1}{y_2-y_1} \rightarrow \frac{x-1}{6-1} = \frac{y-2.5}{0-2.5} \rightarrow -2.5x+2.5 = 5y-12.5 \rightarrow y = -0.5x+3, \quad 0 \leq y \leq 2.5 \tag{5.5}$$

By substituting the values of KPI05 for x in Equation 5.5, the values of the normalized KPI05 are: $KPI05_1$=2.5, $KPI05_2$=1.5, $KPI05_3$=2, $KPI05_4$=0, $KPI05_5$=1, $KPI05_6$=2.5.

5.3.1. Conflict Detection

As mentioned before, conflicts are detected when there is an imminent loss of separation (either horizontal or vertical) but not resolved. Thus, the traffic is left unchanged. Conflict detection is not implemented as a functionality of the simulation platform. On the one hand, if this functionality would be implemented, the number of potential conflicts would decrease (some of the actions performed by ATCo could be to change the heading or the FL of one of the conflicting aircraft, depending on the situation). On the other hand, these changes along the three dimensions of the trajectory might also incur in new conflicts arising.

When considering the base scenario (based on real historical data), the "actual traffic" is the real traffic which also takes into account ATCo decisions. However, when simulating mixed traffic with manned and unmanned aircraft, the number of potential conflicts increases and new types of conflicts arise. The increase in the number of potential conflicts is principally due to not only the fact previously mentioned, detected conflicts are not resolved, but also the differences in speed between manned and unmanned traffic.

In order to get an overview of what would happen when integrating RPAS operations in non-segregated airspace, a distinction between three types of conflicts is made for each scenario. These types of conflicts are defined as follows:

- Conflict Type I: between two manned aircraft.
- Conflict Type II: between an unmanned and a manned aircraft.
- Conflict Type III: between two unmanned aircraft.

But, would it be possible to have an increase in the number of potential conflicts of Type I if manned trajectories are not modified? The trajectory simulation functionality is compliant with the constrained route network, regulations, restrictions and performance characteristics of each type of aircraft. Therefore, if capacity would be modified when RPAS are introduced, the entry and occupancy counts change. Even though the trajectories of the remaining manned traffic are left unchanged, their entry time is varied compared to the base scenario, in order to still meet the constraints and requirements of the route network and airspace sector.

For example, consider the entry and occupancy counts (computed in intervals of time of 15 minutes) of the base scenario (see columns 2 and 3 in Table 5.2). There are 65 flights that entered the airspace sector between 10:00 and 11:00 and 10 more flights that entered before 10:00, as traffic demand is 75 flights. Two examples are built based on the same traffic sample, but replacing 10 random flights by RP01 (columns 4 and 5) and by RP02 (columns 6 and 7). The capacity for these examples has been set to 46 AC/h. It can be seen how the entry rates and the occupancy counts vary when applying these changes. In the case of RP01, there are 62 entries in that period of time and 13 flights that entered before 10:00, while for RP02 these values are 64 entries between 10:00 and 11:00 and 11 flights that entered before 10:00. The changes in the number of entries and occupancy counts lead to new potential conflicts between two or more manned aircraft (Type I). This fact illustrates what could happen during the development of the project when RPAS are integrated in non-segregated airspace and capacity is affected.

Table 5.2: Comparison between the entry and occupancy counts for different cases

Interval of time	**Base Scenario**		**Replacing 10 RP01**		**Replacing 10 RP02**	
	Entry count	**Occupancy count**	**Entry count**	**Occupancy count**	**Entry count**	**Occupancy count**
10:00-10:15	17	27	11	12	21	20
10:15-10:30	16	29	24	20	36	31
10:30-10:45	14	24	10	15	27	29
10:45-11:00	8	27	17	17	28	33

The reason why this analysis is not performed for all the stochastic scenarios is because this analysis has to be done manually and per run and per scenario, which would result in thousands of analyses given the expected number of scenarios (around 30) and the order of magnitude of the runs needed for Monte Carlo simulations (hundreds of runs). Since no conclusions are drawn from this breakdown in types of conflicts and the work is very tedious and slow, only the best performing case for each scenario is analysed in detail.

It is important to highlight that care must be taken when comparing the number of potential conflicts with respect to the base scenario (where conflicts have been detected and resolved as the base scenario is based on a real scenario where ATCo decisions have been made). However, the evolution of the number of potential between the different scenarios, either increasing or decreasing the value of this indicator, is key to assess the effect of requiring AS rules and/or minimum performance standards.

In this regard, future work could be related to detect and resolve conflicts and to define different conflict resolution procedures based on who is involved (Type I/II/III).

5.4. Workload

For the en-route sectors, capacity is more restricted by controller workload than by separations [55]. In order to contribute to the assessment of the sector capacity after integrating RPAS operations, it is necessary to define workload and to select one of the methods from literature to compute it.

Controller workload is defined as *"the time spent to process all tasks in an interval of time for one executive controller"* [56]. The simulation duration is one hour, which leads to the use of an interval of time of 15 minutes for workload calculation purposes.

There are two main trends in literature to evaluate workload: microscopic and macroscopic approaches. The first one is based on modelling each task that is derived from each aircraft, while the second approach aggregates different tasks into more generic categories. On the one hand, microscopic methods can provide rich insight about considerations regarding sector design and the causes of the workload, but the results are difficult to validate and interpret. On the other hand, macroscopic methods bring less detailed information but are more appropriate to analyse operational issues. Thus, the macroscopic approach is considered for this project and is based on three main components: transition tasks (number of entries in the sector), monitoring tasks (depending on the time that they spend in the sector) and conflict resolution tasks. The workload is estimated by the following empiric formula that is developed by EUROCONTROL and is implemented in NEST [42, 57].

$$Workload(\%) = Hourly\ Entry\ Rate + Average\ Time\ spent\ in\ sector \times 2 + Number\ of\ potential\ conflicts \times 2 \tag{5.6}$$

The ponderations assigned to each element (1, 2, 2) have been determined based on previous simulation studies [57]. This simplified formula used to estimate controller workload at the macroscopic level is applied due to the lack of further data required for more refined method. However, the units of the terms of the right-hand side of the Equation 5.6 are AC per unit of time, units of time and AC per unit of time respectively. Therefore the units of the equation are not consistent and mathematically, the workload could be higher than 100%. Although in practice this is usually not the case, a more consistent definition of workload is recommended to avoid misunderstandings and to increase the accuracy of the estimation.

This method for evaluating workload, based on three main tasks, reflects one of the key aspects that usually leads to confusion: the same amount of flights may generate different workloads. If the situation is found to be complex, the same number of flights creates a higher workload. To better understand this situation, the spot cloud shown in Figure 5.12 represents the correspondence between the workload values for the date and the time selected for the project and the number of aircraft present in the sector:

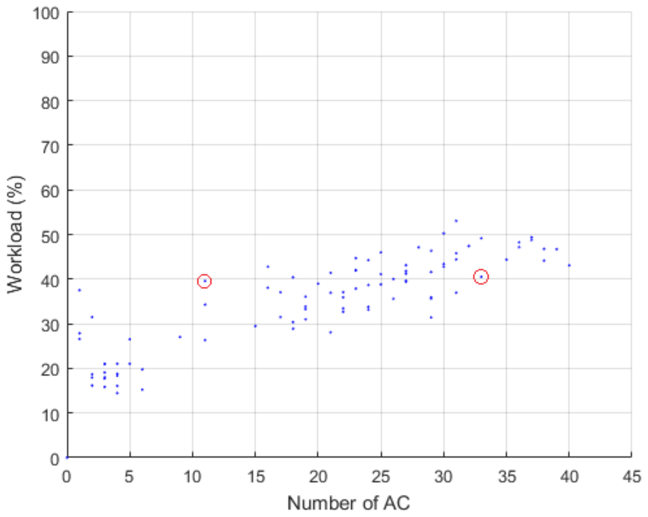


Figure 5.11: Spot cloud corresponding to workload values of the base scenario.

By taking a look at the workload value of 40%, it can be seen that different number of flights can generate this value, ranging from 11 up to 33 (spots marked with a red circle around them). This demonstrates the consequence of complexity variations. As an example, the workload diagram is presented for the base scenario in Figure 5.12. This case will be used as reference when analysing the effect of RPAS in the results section.

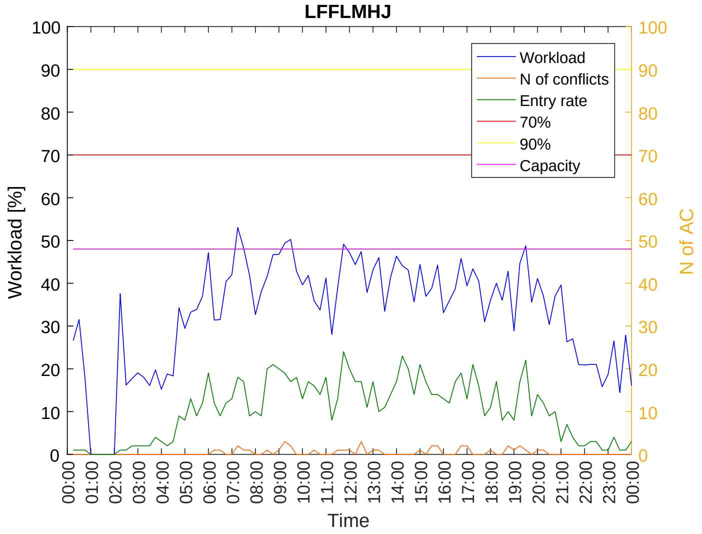


Figure 5.12: Workload distribution for the sector LFFLMHJ.

5.5. CAPAN Regression Method

Although the value of the capacity has been provided by the French ANSP to the Network Manager, the introduction of RPAS with their peculiarities will require modifying the capacity to simulate the effect of a mixed traffic. The CAPAN methodology, developed by EUROCONTROL, is aimed at obtaining theoretical capacities for different sectors. It is used by many European ANSPs such us the UK, Italy or Portugal, either as the final method to estimate capacity or as part of a wider and more complex process [58]. This approach estimates capacity based on controller workload. It establishes different thresholds to interpret the workload value obtained. These thresholds are given in Table 5.3.

Table 5.3: Workload threshold limits defined in [59].

Threshold	Interpretation	Recorded Working Time during 1 hour
70 % or above	Overload	42 minutes +
54 % - 69 %	Heavy Load	32 - 41 minutes
30 % - 53 %	Medium Load	18 - 31 minutes
18 % - 29%	Light Load	11 - 17 minutes
0 % - 17 %	Very Light Load	0 - 10 minutes

Thresholds are based on workload in minutes recorded in one hour, which means that a workload of 15 minutes gives a workload threshold of 25%. Based on its experience with ATCos, EUROCONTROL has agreed that the theoretical capacity corresponds to 42 minutes workload in an hour (70%), since it is the effective measured work per hour. In this project, workload has been calculated in periods of 15 minutes to increase the accuracy of the method by using the macroscopic formula. By plotting this workload (in %) against the traffic demand and applying a regression method -linear regression in this case- the capacity is estimated as the number of aircraft (abscissa) of the intersection between the 70% threshold and the regression line.

Even though there are many other methods and formulas to obtain the workload, most of them involve the number and position of controllers as well as the monitoring tasks. For simplicity, and based on the fact that there are no controllers simulated or involved in the simulation, the macroscopic formula is chosen as the best approximation. In this method, only one controller position is considered (executive controller).

Five different traffic volumes have been analysed in order to find a correlation function for the capacity estimation, between the declared capacity and the capacity obtained after the CAPAN method. An adjustment might be needed to approach the calculated values to the declared capacities and thus, improve the accuracy of the results. The only requirement for their selection is that they were all activated on the chosen day (31^{st} May). They have been selected from different countries and having a wide variety of declared capacities and sizes.

- LFFLMHJ: France. Declared capacity of 48 AC/h.
- LFFOGRT, France. Declared capacity of 28 AC/h.
- EBBUELS1, Belgium. Declared capacity of 39 AC/h.
- EDUDON1D, Germany. Declared capacity of 54 AC/h.
- LECBLGL1, Spain. Declared capacity of 34 AC/h.

In order to calculate and represent their workload, the following data is needed:

- Entry rate, obtained from DDR.
- Occupancy count, gathered from DDR.
- Number of potential conflicts, estimated by using NEST conflict detection module.
- Average time spent in sector, computed from the crossing time data obtained from DDR.

Once the values of the workload are calculated, they are plotted on the Y axis and the number of aircraft (occupancy count) is plotted on the X axis. With these values, two linear regression methods are applied: ordinary least-squares (OLS) and regression through the origin (RTO). The equations and the coefficient of determination for each method and sector are included in Table 5.4.

Table 5.4: Linear regression equations and coefficients of determination per sector.

Traffic Volume	**RTO**		**OLS**	
	Equation	R^2	**Equation**	R^2
LFFLMHJ	y=1.5189x	0.2567	y=0.9042x+16.189	0.7417
LFFOGRT	y=3.6391x	0.4601	y=2.5819x+7.3601	0.6303
EBBUELS1	y=2.2903x	0.0642	y=1.2659x+8.8149	0.4929
EDUDON1D	y=1.6619x	0.0732	y=0.7173x+17.923	0.6308
LECBLGL1	y=2.6843x	0.1654	y=1.6498x+8.153	0.4251

Before continuing with the process it is necessary to make a decision about the method that is going to be employed. In order to select the best model the R^2 statistic is analysed. This coefficient gives an approximation about the goodness of fit of the model to the data, ranging from 0 to 1 (1 indicates that the regression line is found to perfectly match the data). Taking a look at Table 5.4, it can be seen that the values obtained for the OLS model are in all cases higher than the ones from the RTO and closer to 1. For this reason, the regression model selected is OLS.

Having obtained the regression line for each sector, the next step is no other than to calculate the intersection of this line with the 70% threshold. By substituting y=70 in the equations presented in Table 5.4, the result obtained for the x gives the following calculated capacity:

Table 5.5: Calculated (CAPAN) and declared (ANSP) capacity per sector.

Traffic Volume	**Calculated Capacity**	**Declared capacity**
LFFLMHJ	59	48
LFFOGRT	24	28
EBBUELS1	48	39
EDUDON1D	72	54
LECBLGL1	38	34

As was also found in Reference [60], the capacity values obtained through the regression method are usually overestimated. Regarding the values that have been obtained through the CAPAN method and the declared ones provided by the different ANSPs, it is noticeable that a correlation equation is necessary in order to get the best approximation possible to the real (declared) capacity. Based on the results of the comparison made between OLS and ROT, OLS is directly the method used. By plotting the declared capacities on the X axis and the calculated ones on the Y axis, the following equation for the regression line is obtained, having the coefficient of determination, R^2, a value of 0.9889, which indicates that is a very good approximation (value close to 1).

$$\text{Calculated capacity} = 1.7823 \times \text{Declared Capacity} - 23.942 \tag{5.7}$$

This equation is used after applying the CAPAN method. Figures corresponding to the mentioned sectors can be found in Annex B.

5.6. Capacity Estimation

This project is based on an initial traffic sample (75 flights), from which 48 aircraft are cruising. Considering the SJU forecast on RPAS and that the scope is limited to the en-route phase, 20% of the en-route flights are replaced by unmanned aviation (which equals to 10 flights). The objective is to analyse how the introduction of RPAS presenting the same performance as manned aviation affects the actual network when they are allowed to operate in non-segregated airspace.

The main impact is due to the fact that the pilot is outside the cockpit on one hand resulting in a latency in communications which is much bigger than the standards that have been defined so far for IFR flights, and the mix of traffic on the other. Both factors are key in assessing the controllers' workload since they establish the characteristics of the traffic (see Figure 5.13) and thus, the capacity of the sector is affected.

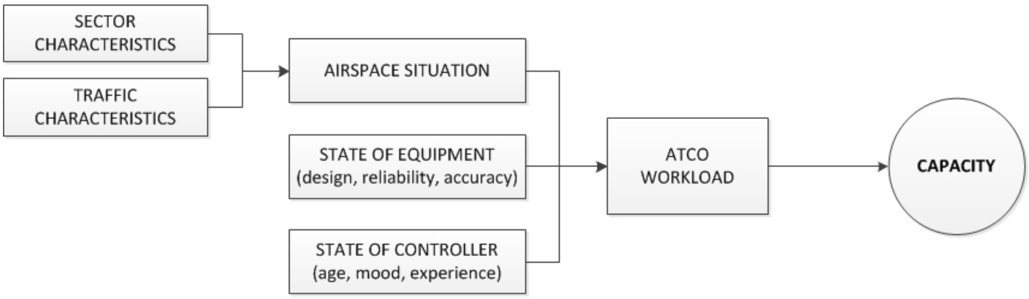


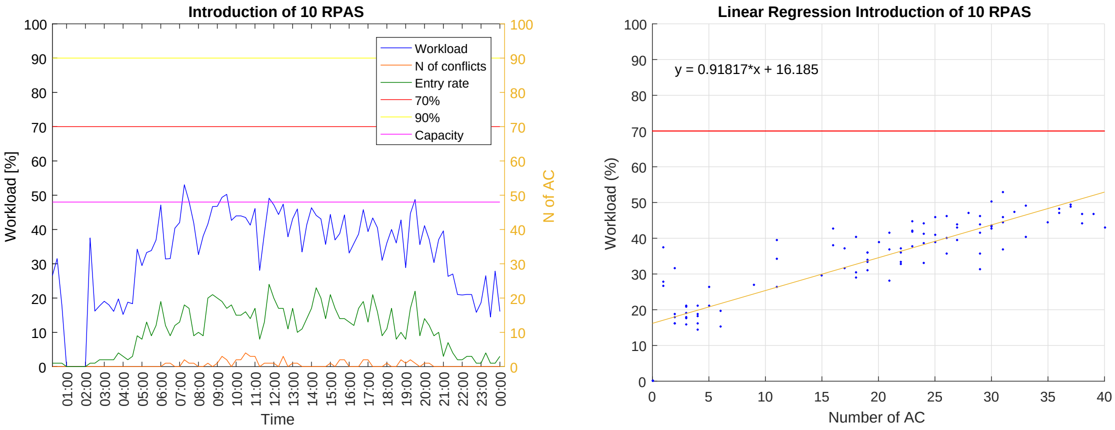
Figure 5.13: Factors affecting controllers' workload, [61].

In order to analyse the impact of RPAS operations on the capacity a two-step approach is conducted:

1. The effect of mixed air traffic on controller workload is estimated following the CAPAN method;
2. Given the capacity calculated in step 1, the Effect of latency in communications between the remote pilot and ATC is computed.

5.6.1. CAPAN Method

The introduction of RPAS will increase the workload since it is dependent on two main factors: the number of potential conflicts and the average time spent in the sector. Capacity can be predicted using workload values. As a first approach, without any further modification in the scenario, the workload is calculated every 15 minutes with ten RP01 introduced in the base scenario.



(a) Workload distribution after introducing 10 RPAS.

(b) Linear regression in the case of integration of 10 RPAS.

Figure 5.14: Workload distribution and linear regression after introducing 10 RPAS in LFFLMHJ.

Comparing this figure with Figure 5.12 for the period of time between 10:00 and 11:00 it can be seen how the workload and the number of potential conflicts increase when introducing RPAS. With these values of workload, the CAPAN method is used to obtain the analytical or calculated capacity as follows:

1. The linear equation obtained after the linear regression of the workload values (see Figure 5.14b) is :

$$y = 0.91817x + 16.185 \longrightarrow x = \frac{70 - 16.185}{0.91817} = 58.6112 \tag{5.8}$$

By substituting y=70 (threshold of 70% of WL) gives a theoretical capacity of 58.6112.

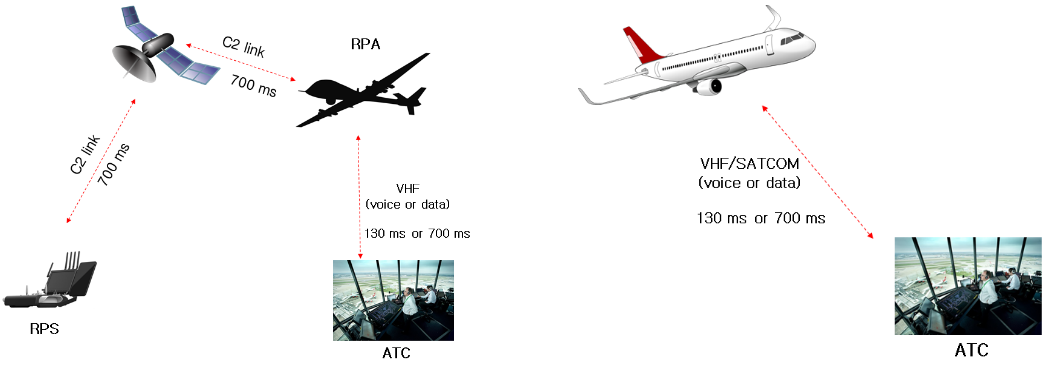
2. By applying the correlation equation explained in Section 5.5, (Equation 5.7), the capacity value obtained for the first step is **46**.

$$\begin{aligned}&\text{Calculated Capacity} = 1.7823 \cdot \text{Declared Capacity} - 23.942\\ &\qquad\longrightarrow \text{Declared Capacity} = \frac{58.6112 + 23.942}{1.7823} = 46.3 \approx 46\end{aligned} \tag{5.9}$$

5.6.2. Latency

Latency in communications vary depending on the type of communication employed. The communication is generally of two types: voice and data. Due to the saturation of voice communications, especially in areas where the traffic density is high, CPDLC (Controller Pilot Data Link Communications) was developed as a system to improve the safety and efficiency of the European ATM by replacing voice communications through a data link between the controller and the pilot. Although the latency in data communications is much higher than in voice communications, the implementation of CPDLC systems will increase the capacity since the radio communications and therewith the voice-frequency load are reduced as well.

However, as it was explained in Section 2.3.2, the latencies expected for RPAS communications are much higher than the current manned data communications. In this case, this causes a reduction of the capacity, contrary to the aim of the CPDLC. In the worst case, in which the RP establishes contact with ATC or vice-versa for BRLOS operations, three paths are needed to accomplish the communication. The difference respect to the architecture corresponding to manned communication is presented in Figure 5.15:



(a) Unmanned communications with the associated latencies.

(b) Manned communications with the associated latencies.

Figure 5.15: ATC communication architectures for manned and unmanned aircraft.

Taking into account the maximum latency values that have been accepted by ICAO (discussed in Section 2.3.2), i.e. 130 ms for continental voice communications, and a typical data delay between 500 and 700 ms, it can be seen that the latency is significantly greater for unmanned operations. This difference has a direct effect on controllers' workload, since two different things might happen:

- The controller is waiting for a reply or a message from the RP for a longer period of time than if the communication would be with a manned aircraft, leaving the other tasks or communications unattended.
- By the time the message arrives to the ATC center, the controller has already forgotten the problem with that RPA, or the RPA might already be in the next sector.

Controllers need to predict and anticipate aircraft trajectory and the individual intentions of each pilot in order to plan the actions that are needed, in time and following the appropriate sequence [62]. Therefore, latency can be considered as detrimental for controllers. Whether latency in communications is too high or too variable, the anticipation and actions planning is notably negatively affected.

To simulate the effect of the increased latency that RPAS operations will introduce, a first assumption is made regarding the percentage of voice and data communications. Since the date chosen is later than the date when CPDLC was implemented in France, and considering the efforts that are being made to get the greatest percentage of data communications as possible[1], 50% of the manned flights are expected to be voice communications, and the remaining 50% via datalink. This percentage will be maintained for RPAS operations but only for the path between the RPA and ATC. The second assumption will be to select the worst latency possible for data communications, 700 ms.

Assuming only one communication between ATCo and the RP (located at the RPS) per flight crossing the sector, the total accumulated latency for a period of time of one hour can be computed. For the base scenario (with 75 flights), the total value of the latency (L) is obtained as follows:

$$L_{BS} = \frac{50}{100} \times 75 \times 130 + \frac{50}{100} \times 75 \times 700 = 31\,125 \text{ ms} \tag{5.10}$$

The introduction of 10 RPAS brings two new possibilities: to have two paths of data and a third one of voice (whith a latency of 700 ms for the first two and 130 ms for the third path), or to have three paths of data communication (in this case with a latency of 700 ms per path). This is reflected in an increase of the total latency as the result of the following equation shows:

$$L_{RPAS} = \frac{50}{100} \times 10 \times (700+700+130) + \frac{50}{100} \times 10 \times (700 \times 3) + \frac{50}{100} \times 65 \times 130 + \frac{50}{100} \times 65 \times 700 = 45\,125 \text{ ms} \tag{5.11}$$

Instead of having 75 flights, now there are 10 unmanned flights (the first two terms in the addition) and 65 manned flights (the other two terms).

A preliminary study carried out by EUROCONTROL [64] and applied to NAS (National Airspace System, term used by FAA to denote the American Airspace System) [65] determines, based on real and fast time simulations, the relationship between the reduction in RT communications and the increase in capacity. This study can be adapted and applied to this project as an estimation of the impact of the latency in capacity (C”), on the basis of the capacity value obtained after step 1 (C’), as follows:

- Comparing the values of the latency after the introduction of RPAS and the base scenario, there is an increase of 44.98% in latency.
- Accounting for the assumption made for the percentage of voice communications (50%), the correspondent increase in latency due to voice communications is 22.49%.
- Applying the relationship obtained in [64], the percentage of capacity gain is -4.47%. The negative sign indicates that there is a loss in capacity since the latency in RT communications has been increased instead of reduced.

$$\text{Capacity Gain (\%)} = 0.189 \cdot \text{Reduced RT comms(\%)} + 0.23 \rightarrow \text{Capacity Gain} = -4.47\% \tag{5.12}$$

- Finally, the value of capacity is computed as follows:

$$C'' = C' - \left(\frac{4.47}{100}\right) \cdot C' = 46 \cdot \left(1 - \frac{4.47}{100}\right) = 43.9 \approx 43 \frac{\text{AC}}{\text{h}} \tag{5.13}$$

It should be notice that the capacity value (C") has been truncated. The result, 43.9 AC/h, is not a possible value of capacity since there are no decimal number of aircraft. Therefore, in order to be conservative, it has been truncated to 43. This increase in latency is reflected in a reduction of the capacity from 46 (value obtained after the first step) to 43.

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[1] One of the European initiatives is the Link 2000+ Programme, aimed to implement CPDLC as the prime means of communications. DSNA has implemented CPDLC IOC services in French continental airspace above FL195 by May 2016, although not all the fleet is ready [63].

PART III

RESULTS AND DISCUSSION

6

Stochastic Model

In order to establish minimum operational and performance requirements for both types of RPAS, Scenario 1A and Scenario 1B, it is necessary to build and analyse a stochastic model where random variations will be applied to the main input, the set of flights that is chosen to be replaced by unmanned aviation. Monte Carlo simulations of the air traffic have been performed in order to come up with the trajectories and traffic data of these varied traffic demands. Only once the statistical analysis of these outputs will be performed conclusions could be drawn. This chapter contains in Section 6.1 an introduction about Monte Carlo simulations and the methodology employed for this project, a brief description of the statistical inference (statistical estimators and hypothesis testing) that is needed for the analysis of the results in Section 6.2, the convergence study that has been performed to determine the number of runs needed (Section 6.3) and the results for scenario A and B in Sections 6.4 and 6.5 respectively.

6.1. Monte Carlo Methodology

Monte Carlo simulation relies on repeated random sampling and the statistical analysis necessary to obtain the results [66], being suitable for analysing uncertainty and providing probabilistic analysis of the different scenarios.

The best performing case is completely dependent on the set of flights that might be chosen, despite the fact that the individual flights to be replaced are randomly selected. It is clear that if the same base scenario (traffic volume, date and time) is maintained but varying the set of flights to be performed by RPAS is varied, the results may differ. Therefore, Monte Carlo simulation is based on the random selection (*n* times) of flights from the original traffic demand file to be replaced by RP01/RP02 (depending on the scenario, 1A or 1B). From the five KPIs that have been defined, only the two corresponding to efficiency (KPI03 and KPI04) and safety (KPI05) are the indicators that will be statistically analysed. The reason for this is that the number of RPAS is kept constant (there are always 10 replacements) and thus, capacity and sector overload (KPI01 and KPI02) are also kept constant.

To this end, a program has been created in Matlab in order to make the changes that are needed. First, it is necessary to generate in a random manner the set of flights that are replaced by RPAS. Secondly, in order to change the AC type in their flight plans it has to be done through the traffic demand file. Finally, when altitude segregations are applicable, FL needs to be changed according to the rules established for their operation: on the one hand, it is necessary to change the FL in the flight plan contained in the traffic demand file to force this flight level to be the actual one; on the other hand, a flight level constraint file has also been created to establish the maximum flight levels per flight in order to make sure that the cruise level corresponds to the one established by the altitude segregation rules. These files are generated as many times as the number of runs that is determined to be needed (*n*). After that, the *n* set of files is imported in NEST together with the base scenario. The base scenario file is needed in order to calculate the trajectory with the functionality of regionalisation activated, which allows to avoid flights to cross different sectors rather than the original one.

In NEST, the possibility exists to design block diagrams (SIM Designer) which run all the functions that are needed to come up with the result files in a loop (n times). These functions are: Retrieve environment (to obtain information about the Network, TV, airports, waypoints, etc); 2D traffic, 4D trajectory simulation and airspace/traffic intersection. Finally, once the trajectories have been simulated, the detection of possible conflicts between aircraft is done through Conflict Analysis. As a result, two types of files are generated: a file that contains the information of each flight per subsector that it crosses, and a file that collects the statistics about the number of potential conflicts.

Since after all the simulations there are n instances of these files, it is also necessary to create another program to process the results. Due to the format of each type of file, airspace/traffic intersection files are processed in Matlab to generate the statistics needed for KPI03 and KPI04, and a macro in excel has been implemented to gather the data regarding the number of potential conflicts and to calculate its corresponding statistics for KPI05. The pseudo-code for the random generation of the set of flights and the analysis of KPI03 and KPI04 are included in Annex C. Further details about the block diagram developed in SIM Designer to perform Monte Carlo simulations are also presented in Annex C.

A simplified diagram is presented in Figure 6.1. The complete block diagram and the code for each processing program are included in Annex C.

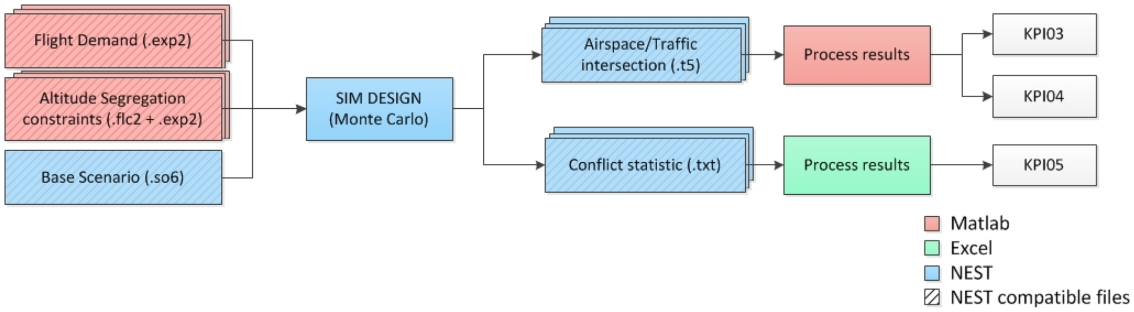


Figure 6.1: Simplified breakdown structure of the Monte Carlo simulation.

6.2. Statistical Inference

The outcome of the stochastic model needs to be statistically analysed in order to obtain manageable and concise results, avoiding having to deal with hundreds of raw results. This section presents an overview of the statistical inference aimed at making decisions or drawing conclusions about a population or, in this case, an experimental project. Several cruise speeds and ROCs are analysed to see which combination of performance requirements would result in the best performing case (according to Equation 5.4) to reduce the impact on the ATM Network, with or without operational requirements. For that reason, estimators for the statistical analysis are defined in Section 6.2.1, which is one of the two major areas of the statistical inference. However, mean differences of the indicators also need to be analysed in order to obtain more accurate conclusions and to see the effect of different constraints on the outcome. Section 6.2.2 introduces the basic principles for hypothesis testing for the equality of the mean and the variance. Statistical inference analysis is carried out using IBM SPSS software.

6.2.1. Estimators for the Statistical Analysis

According to the central limit theorem, *"as the sample size, n, gets larger, the sampling distribution of the sample means tends to follow a normal probability distribution with a mean equal to the true population mean, μ, and standard error, σ"* [67]. This is applicable regardless of the original population distribution or shape. A sample is considered large enough if $n \geq 30$ [68]. Although the uncertainty study has not been carried out yet (it is presented in the following sections), it is expected that the order of magnitude of the number of runs will be of at least one hundred. Therefore, the sampling distribution can be considered normally distributed.

The following sample statistics (or estimators) are used in the statistical analysis [69]:

- Mean, $\overline{x}$:

$$\overline{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{6.1}$$

- Standard Deviation, σ_x:

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2}. \tag{6.2}$$

These statistics are useful to provide, for a given level of significance α, an estimation of the variable under analysis by means of confidence intervals based on the mean of the population:

$$CI(95\%) = \mu_{\overline{x}} \pm Z_{\frac{\alpha}{2}} \cdot \sigma_{\overline{x}} = \overline{x} \pm Z_{\frac{\alpha}{2}} \cdot \frac{\sigma_x}{\sqrt{n}}. \tag{6.3}$$

If the confidence interval (CI) is set to 95%, then the confidence level is the difference between 100% and the CI (in %): $100 - 95 = 5\%$. The value of $z_{\frac{\alpha}{2}}$ (or critical z-value based on the confidence level) can be found in the standardised Z-tables, which for this case is 1.96 [68].

Finally, it is also necessary to take a look at margin of error (MOE) since every estimation is subject to random sampling error. This value gives an indication of the precision of the estimation. Although it is contained in the CI formula, its value will be indicated separately to see how it changes with the number of iterations.

$$MOE = \frac{CI_{\text{UpperBound}} - CI_{\text{LowerBound}}}{2} = Z_{\frac{\alpha}{2}} \cdot \frac{\sigma_x}{\sqrt{n}} \tag{6.4}$$

From this estimator, SEM or Standard Error of the Mean can be derived as the relationship between the standard deviation of the sampling distribution of the mean. This error is commonly used when creating error bars.

$$SE_{\overline{x}} = \frac{\sigma_x}{\sqrt{n}} \tag{6.5}$$

6.2.2. Hypothesis Testing

The statistical estimators defined in Section 6.2.1 will be used to obtain the means of the KPIs which are then normalized to compute the weighted score. This procedure leads to the selection of the best candidate amongst the cases analysed. But apart from selecting the best performing case, analysing the effect of the different constraints applied to each scenario is also of interest (i.e. the effect of altitude segregation or the influence of the different cruise speeds on the indicators). As an example, consider that KPI03 for scenarios 1A_1 and 1A_2 has values of -300 and -305 seconds respectively. How could it be determined if there is an influence of AS rules on KPI03 if both means are very similar? For this, it is also necessary to analyse the statistical difference between the mean of each case.

To that end, ANOVA test (analysis of variance) has been developed in order to analyse the difference within (and between) group means, indicating whether or not the means are different for a given level of significance [70]. Its simplest form is a one-way ANOVA test, which is based on the following assumptions [71]:

- Homogeneity in variances.
- The dependent variable, which is the indicator that is analysed in each case, is normally distributed. This assumption is met as it has been explained in Section 6.2.1 (based on the central limit theorem).
- The observations are independent. This assumption is verified since each run is set and simulated independently.

One-way ANOVA tests the null hypothesis that the means are equal. The hypothesis can be formulated as follows:

$$H_0 : \mu_1 = \mu_2 = \mu_3 = \ldots = \mu_k$$
$$H_1 : \text{at least one of the means is different}$$

The results of the ANOVA tests will be reported according to the APA format: [F(df_B, df_W= F_ratio, p=p-value)], where the degrees of freedom (df_B for the value between groups and df_W within groups), F value (F_ratio) and the significance or p-value are indicated.

In order to accept or reject H_0, there is a significant output that must be analysed: the p-value. P-value is defined as the smallest level of significance that would force to reject the null hypothesis [68]. If p-value is larger than the level of significance (in this case, α=0.05) then the null hypothesis is accepted and conclusions can be drawn. However, if p-value is smaller than 0.05, H_0 is rejected: at least one of the means is different.

ANOVA test compares more than two groups which means that no directional hypothesis can be made. Directional hypothesis are related to one-tailed tests and aimed at knowing whether one mean equals a predetermined value or is greater than the other mean. A two-tailed model is selected because the aim of this test is to know whether they are different (two-tailed) [68].

One of the outputs of this test is the statistic F, or F_ratio, which provides information whether the group means are different. It is defined as the ratio of the variation between sample means and the variation within the sample. In other words, it expresses the ratio of the experimental effect to the individual differences in performance. For values larger than 1, it can be affirmed that there is an effect and thus the means differ; for values smaller than 1, there is no significant effect and the means are roughly the same [71].

The remaining outputs are df_B and df_W. The degrees of freedom between groups is *k-1*, as *k* is the total number of groups. The degrees of freedom within groups equals the total number of individual degrees of freedom per scenario (n) minus k, as there each sample has one degree of freedom less than the sample size and there are k samples: $df_\text{W} = n - k$.

The procedure to calculate the F_ratio is described based on the following steps [71, 72]:

- Variances between groups are due to the treatment or experimental effect. Apart from the degrees of freedom between groups, the other main parameter is the sum of squares between groups (SSB)

$$\text{SSB} = \sum_k n_k(\overline{x}_k - \overline{X})^2, \tag{6.6}$$

  where n_k is the sample size of each group, $\overline{x}_k$ the mean of each group, and $\overline{X}$ the mean of the means.

- Variances within groups are because of the error or the individual differences in performance. The correspondent parameter that is required besides the degrees of freedom within groups is the sum of squares within groups (SSW):

$$\text{SSW} = \sum_k s_k^2(n_k - 1), \tag{6.7}$$

  where s_k is the variance each group.

- The mean square between groups (MSB) is defined as:

$$\text{MSB} = \frac{SSB}{df_\text{B}} \tag{6.8}$$

- The mean square within groups (MSW) is computed by means of the following formula:

$$\text{MSW} = \frac{SSW}{df_\text{W}} \tag{6.9}$$

- Finally, the F_ratio is obtained as follows:

$$F_\text{ratio} = \frac{MSB}{MSW} \tag{6.10}$$

In order to compute the p-value, it is necessary to compare the value obtained for the F to an F distribution. With this approach, the probability of observing an F-value that is at least as high as the value obtained is assessed. This probability is the p-value for accepting or not the null hypothesis.

So far, the violation of the assumption in homogeneity in variances has not been addressed. If variances are not homogeneous, one-way ANOVA test cannot be performed. This assumption can be tested through a Levene's test. It tests the null hypothesis that variances of a group are the same [71].

$$H_0 : \sigma_1 = \sigma_2 = \sigma_3 = ... = \sigma_k$$
$$H_1 : \sigma_1 \neq \sigma_2 \neq \sigma_3 \neq ... \neq \sigma_k$$

This test is a simple one-way ANOVA on the absolute difference between each result and the mean of the group where it belongs. Therefore, the main outcome to take into account is the p-value. If the result of Levene's test is significant (i.e. p<0.05) the assumption of homogeneity of variances is violated and there is a significant difference in variances.

If Levene's test results in a significant value (p<0.05) a corrected version of the one-way ANOVA can be carried out: Welch's ANOVA [73]. This method has as assumptions the normality of the dependent variable and the independence of samples. But Welch's ANOVA should be run when variances are not homogeneous. This test is robust for unequal sizes [71]. For those cases where this test is run, the p-value replaces the regular ANOVA p-value.

ANOVA test does not provide information about which of the specific group means differ. A post-hoc test on the data is necessary to investigate which means are different from the others. Post-hoc tests consist of pairwise comparisons designed to compare all the different possible combinations of groups. In case ANOVA shows that for a specific group of scenarios the means are equal (null hypothesis accepted), no further analysis is needed.

The selection of the appropriate post-hoc test depends on the homogeneity of the variances. Depending on the outcome of Levene's test, a different post-hoc test should be performed: Tukey HSD (Honestly Significant Difference), when there is homogeneity in variances, and Games-Howell otherwise. Tukey's test has been selected over the different options because it is able to control Type 1 error for large number of means. This method uses the studentized range distribution. The differences in mean and the standard error of the mean are used to obtain q. P-value can be obtained from the tables of the studentized range distribution based on the q value previously obtained. This p-value is compared with the level of significance α in order to conclude whether the means are equal or not [74].

For non-homogeneous variances, Games-Howell is found to be robust for different sample sizes, which might be the case after removing the outliers [71]. This test is also based on Tukey's studentized range distribution whose statistic q is used to compute the p-value.

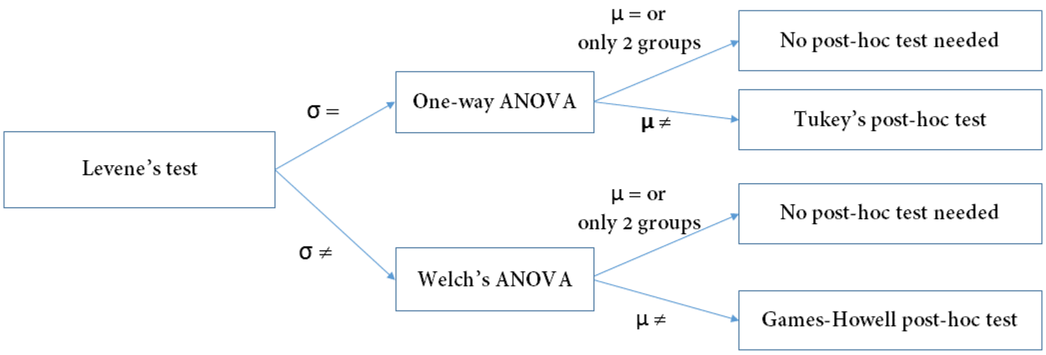


Figure 6.2: Overview of the steps for hypothesis testing. Created by the author based on [71].

Figure 6.2 shows an overview of the steps required for the hypothesis testing procedure.

6.3. Convergence Study

The first aspect that needs to be verified prior to any simulation or analysis is the number of runs that are needed in order for the results to be accurate enough. On the one hand, if the number of runs is small, the output is usually inaccurate and the data reflected in the histogram is very poor. On the other hand, if the number of runs is too large, the simulation and processing time will make impossible to run many different scenarios due to time constrains or processing capability. It is clear that there is a need for a trade-off between the number of runs and the desired accuracy of the output.

Ideally, Monte Carlo simulations are based on thousands of runs (starting from 1,000 runs). Each iteration takes 2 minutes only to run the Monte Carlo part in NEST (without considering processing and analysing times), which means that the minimum of 1,000 runs will take one day and a half per scenario. Taking into account the number of scenarios (around 30), the stochastic part alone would take around 2 months. Thus, it is not possible to carry out 1,000 runs per scenario. However, if the results do not converge after 1,000 runs, they will be invalid and more iterations will be needed.

To start with, 1,000 iterations are run for the first scenario (Scenario 1A_1), and the convergence is analysed in steps of 10. But prior to any analysis, it is necessary to identify the possible outliers. The presence of outliers might lead to error and inaccurate results. They have been defined by many authors as data points that deviate from the norm of a variable. They can arise for different reasons [75], but for this project, the main causes are the sampling and software errors. Regarding the sampling error, it is possible that within a set of flights, few of them have been selected in such a way that the RPAS are crossing the sector for just a few seconds (skipping in/out) which would make this scenario different from the desired one, where 10 RPAS are needed to operate in the airspace sector for longer periods than a few seconds. Apart from that, there might be the case that the software has some unidentified bugs (especially when running trajectory simulations). Therefore, the outliers have to be identified in order to removed them from the statistical analysis.

6.3.1. Identification of Outliers

From the different techniques to determine the outliers that are described in literature [76–78], Tukey's test has been chosen for two main reasons: it does not make distributional assumptions and the method is not dependent on the mean or the standard deviation; instead, is purely dependent on the data obtained. The method comprises the following steps:

1. Calculate first and third quartiles of the data, named Q1 and Q3. The location of the quartile is obtained as follows:

$$Q_k = \frac{n \cdot k}{4} \tag{6.11}$$

2. Calculate the interquartile, IQR, by subtracting the first quartile from the third:

$$IQR = Q3 - Q1 \tag{6.12}$$

3. Determine the upper and lower bounds as follows [79]:

$$UB = Q3 + 1.5IQR \tag{6.13}$$

$$LB = Q1 - 1.5IQR \tag{6.14}$$

4. For each data point, check if it belongs to the interval defined as (LB,UB). Otherwise, it is an outlier.

This procedure is used not only for the convergence study but also in all the following statistical analyses.

6.3.2. Convergence Analysis for Scenario 1A_1

The case selected for this study is Scenario 1A_1. The number of runs has been increased progressively, as shown in Table 6.1. As indicated before, the three indicators that are going to be analysed are KPI03, KPI04 and KPI05. This scenario is based on replacement, but without further requirements implemented. The efficiency in terms of flight path extension does not vary since the trajectory is the same as it was in the base scenario. This indicator does not change its value when increasing the number of runs and therefore is not considered in this study.

Taking a look at the first and last columns of KPI03 (mean and margin of error, MOE, respectively) it can be seen that with 300 runs the margin of error is below 1 (measured in seconds) and the mean seems to get stabilized around -124.4 s (with variations of the order of 0.1 seconds which can be considered negligible respect to a period of time of one hour, 3600 s).

A good practise in establishing the number of runs is by looking at the standard deviation: the lower its value the more accurate the results are. However, the value does not get lower when increasing the number of iterations but it stabilizes around 8.61, which can also be considered an indication of convergence. However, the number of necessary runs has to be the same for all the KPIs, so KPI05 is also examined. In this case, the margin of error is already below 1 for 50 runs, but since this indicator refers to the number of potential conflicts, it is necessary to improve this value. Moreover, at 50 runs, the value has not converged yet. Thus, looking at the values around 250-400 runs, the mean tends to converge to 14.82 potential conflicts per hour and thus the results can be considered accurate enough (the confidence interval does not change the integer value of the conflicts if the result is rounded up since there cannot be decimal values for conflicts).

Table 6.1: Scenario 1A_1 statistic results for different numbers of iterations.

Runs	**KPI03**					**KPI05**				
	Mean	σ_x	**LB_CI**	**UB_CI**	**MOE**	**Mean**	σ_x	**LB_CI**	**UB_CI**	**MOE**
1	-117.90	-	-	-	-	16.00	-	-	-	-
10	-130.91	7.85	-135.77	-126.04	4.86	16.20	1.93	15.00	17.40	1.20
50	-124.20	8.69	-126.60	-121.79	2.41	15.16	2.16	14.56	15.76	0.60
100	-123.85	8.28	-125.47	-122.23	1.62	14.91	2.12	14.49	15.33	0.42
150	-124.10	8.45	-125.45	-122.75	1.35	14.93	2.10	14.59	15.26	0.34
200	-124.34	8.61	-125.53	-123.15	1.19	14.84	2.38	14.50	15.17	0.33
250	-124.44	8.49	-125.49	-123.38	1.05	14.80	2.33	14.52	15.09	0.29
300	-124.39	8.62	-125.36	-123.41	0.97	14.82	2.26	14.56	15.07	0.26
350	-124.41	8.61	-125.31	-123.51	0.90	14.82	2.25	14.58	15.05	0.24
400	-124.40	8.62	-125.24	-123.56	0.84	14.82	2.23	14.60	15.04	0.22

As a first approach, 300 is set as the candidate for the number of runs. This must be double-checked with at least one more scenario, and if both converge at the same number of iterations, it will be assumed that it is also the case for the remaining scenarios. The number of runs would be established to 300. If not, more scenarios will be required. As was explained, it is not feasible to check all the scenarios for thousands of simulations due to the computational time it takes to run Monte Carlo simulations.

It should be noticed that KPI01 and KPI02 are not analysed due to their constant value for the different scenarios. Looking at KPI04, its value for Scenario 1A_1 does not change when increasing the number of runs, as altitude segregation has not been implemented yet. Therefore, as the flight path is always the same in Scenario 1A_1, the results have not been included in this section.

6.3.3. Convergence Analysis for Scenario 1A_2

The next scenario that is analysed is Scenario 1A_2. Again, starting from 1 until 400 runs, the average value for the indicators is calculated. It is necessary to examine if for 300 runs convergence or not is achieved (and if the margin of error decreases when increasing the number of runs). The results are presented in Table 6.2.

Table 6.2: Scenario 1A_2 statistic results for different numbers of iterations.

Runs	**KPI03**					**KPI04**					**KPI05**				
	Mean	σ_x	**LB_CI**	**UB_CI**	**MOE**	**Mean**	σ_x	**LB_CI**	**UB_CI**	**MOE**	**Mean**	σ_x	**LB_CI**	**UB_CI**	**MOE**
1	-224.93	-	-	-	-	-21.89	-	-	-	-	13.00	-	-	-	-
10	-193.16	43.23	-219.95	-166.36	53.59	-22.41	5.31	-25.70	-19.12	6.58	11.50	3.03	9.62	13.38	3.75
50	-220.36	20.76	-226.43	-214.30	12.13	-21.27	2.62	-22.03	-20.50	1.53	12.51	2.24	11.88	13.14	1.25
100	-230.95	26.10	-236.17	-225.73	10.44	-22.41	2.96	-23.00	-21.82	1.19	12.48	2.13	12.06	12.90	0.84
150	-231.67	24.62	-235.66	-227.69	7.97	-22.42	2.74	-22.87	-21.98	0.89	12.21	2.06	11.88	12.55	0.66
200	-234.56	24.62	-238.01	-231.11	6.89	-22.81	2.82	-23.21	-22.42	0.79	12.19	2.07	11.90	12.47	0.58
250	-234.42	24.23	-237.45	-231.39	6.06	-22.84	2.81	-23.19	-22.38	0.81	12.17	2.04	11.92	12.42	0.51
300	-233.66	24.64	-236.47	-230.85	5.62	-22.75	2.79	-23.07	-22.44	0.64	12.21	2.07	11.97	12.44	0.47
350	-233.72	24.63	-236.32	-231.12	5.20	-22.75	2.77	-23.04	-22.46	0.58	12.20	2.04	11.99	12.41	0.43
400	-233.66	24.62	-236.09	-231.23	4.86	-22.75	2.76	-23.02	-22.48	0.54	12.19	2.06	11.99	12.39	0.40

From Table 6.2, it can be seen that:

- KPI03 converges at 300 runs, with a the margin of error around 5 seconds. Since the true period of time covered by the simulations is one hour, five seconds can be considered as an acceptable value for the error. The mean barely changes with the successive number of iterations (on the order of 0.1 seconds).
- KPI04 also shows a convergence of the value around 300 runs (with more runs the value does not change and the margin of error decreases in the order of 0.01 NM).
- KPI05 tends to be stable around 12.2, from 150 runs onwards. The margin of error improves its value with increasing number of runs, but only in the order of tenths of conflicts, which does not change the overall result.

Therefore, for the following scenarios, it is concluded that the number of runs required to get accurate results is 300.

6.4. Results for Scenario 1A

After performing 300 independent runs for each scenario and carrying out the statistical analysis in order to remove the outliers (following the procedure explained in Section 6.3.1), the remaining results are further processed: the mean, the standard deviation and the confidence interval are computed (see Annex D). The outcome of the Monte Carlo simulations for Scenario 1A is presented in Table 6.3.

Table 6.3: Results of the stochastic model of Scenario 1A (average values).

Scenario	**Change**	**KPI01**	**KPI02**	**KPI03**	**KPI04**	**KPI05**	**Weighted Score**
BS	-	48	17	-131.24	-16.88	1	-
1A_1	Replacement	43	22	-124.30	-10.14	14.82	3.82
1A_2	AS	43	22	-233.50	-22.73	12.21	4.28
1A_3_1	350 kts + AS	43	22	-226.17	-22.75	12.29	4.27
1A_3_2	360 kts + AS	43	22	-222.49	-22.75	12.20	4.37
1A_3_3	370 kts + AS	43	22	-218.25	-22.75	12.04	4.54
1A_3_4	380 kts + AS	43	22	-214.23	-22.75	12.18	4.45
1A_3_5	**390 kts + AS**	**43**	**22**	**-210.35**	**-22.75**	**11.96**	**4.67**
1A_3_6	400 kts + AS	43	22	-206.39	-22.75	12.33	4.38
1A_3_7	**400 kts**	**43**	**22**	**-99.62**	**-10.14**	**13.87**	**4.83**
1A_3_8	390 kts	43	22	-103.14	-10.14	14.55	4.21

The best candidate is Scenario 1A_3_7, based on a minimum cruise speed of 400 kts required for unmanned aviation. RPAS are generally replacing flights whose cruise speed was lower than 400 kts and, therefore, time efficiency is showing a significant improvement, which outweighs the increase in the number of potential conflicts. Moreover, since RPAS do not need to recalculate the trajectory because of the non required altitude segregation rules, flight path extension is also improved, as they are flying routes closer to the optimal. However, from a practical point of view, this result should be discarded. The reason for this is the following: having RPAS flying in the busiest part of the airspace (with no AS rules) and in a CTA that is one of the most congested in Europe will incur in a greater negative impact if a contingency issue occurs. If they operate outside the busiest part of the airspace, any problem (especially those related to specific RPAS issues) would be solved more efficiently since they would have less traffic in their surroundings that would be affected.

The second best candidate is a combination of altitude segregation rules and a minimum cruise speed of 390 kts, which due to the implementation of operational requirements seems to be more realistic. If something similar would happen in the future, the final decision during the selection of the minimum requirements (performance and operational) must be made by the correspondent ANSP, accounting for the characteristics of the airspace sector and the traffic.

Regarding the number of potential conflicts obtained in Scenario 1A_3_5 (see Table 6.3), further analysis is performed in order to see the proportion of the different types of conflicts defined in Section 5.3.1. The average values of each type of conflicts have been computed, begin the resulting percentages: 89.35% Type I (manned/manned), 8.99% Type II (manned/unmanned) and 1.66% Type III (unmanned/unmanned). Most of the potential conflicts are of type I. In this type of conflicts RPAS are not directly involved in any of the potential conflicts, but they can be considered as one of the reasons or the cause of this increase, as a result of different causes: the reduction of capacity derived from their presence, differences in cruise speed (although this difference has been reduced when requiring a minimum of 390 kts). Conflicts of type II are either between cruising RPAS and climbing manned AC or between two cruising AC (one of them manned and the other one unmanned). Conflicts of type III are between RPAS flying at FL420 which now, after requiring AS rules, turns to be busier than before.

Nevertheless, it is necessary to analyse the statistical difference between these means in order to understand and to see the effect of the different constraints on the indicators, in an individual manner. To that end, a statistical inference analysis is carried out.

The following consideration must be taken into account beforehand: not all the scenarios have been built under the same constraints (the applicability of operational requirements and different performance requirements varies among the scenarios). By splitting the scenarios into different models (regarding the type of requirements, if any, that is in place for each of them) the following classification can be obtained:

- Model 1: Only replacement, which corresponds to Scenario 1A_1.
- Model 2: Only altitude segregation rules are required, as is the case of Scenario 1A_2.
- Model 3: Altitude segregation rules and minimum cruise speed requirement, which includes scenarios 1A_3_1 to 1A_3_6.
- Model 4: Only minimum cruise speed requirement, that is present in scenarios 1A_3_7 and 1A_3_8.

This classification is needed in order to properly compute the differences in means, since different constraints have been imposed for each type of models. It is very improbable that all the scenarios have the same mean. Therefore, performing an ANOVA test to all of them at the same time makes no sense. A breakdown into different analysis is needed in order to draw strong conclusions by answering the following questions:

A) Do AS rules have an influence on the specific KPI under analysis when no minimum performance standards are required? Compare Model 1 with Model 2, where replacement and altitude segregation rules are respectively implemented.

B) Does a different minimum cruise speed have an influence on the specific KPI under analysis? Comparison within Model 3, where different cruise speeds are analysed.

C) Do AS rules have an effect on the specific KPI under analysis if minimum performance requirements are implemented? Compare Model 3 and Model 4, where given minimum cruise speed, altitude segregation is applied (Model 4) or not (Model 3).

D) Does the minimum cruise speed influence the specific KPI under analysis when no operational requirements are in place? Compare Model 1 and Model 4, where only replacement and minimum cruise speed are respectively required.

E) Does the combination of performance and operational requirements have an influence with respect to the other options where only replacement or altitude segregation are in place? Compare Model 1, 2 and 3.

This post-analysis on the equality of means could be of great relevance if, after applying this methodology, two or more best performing cases are obtained. Under these circumstances, the ANSP would be able to take a look at the equality of means to analyse the influence of each constraint. Depending on their own interest and the KPA or KPI that would be prioritized, decisions about the minimum performance and operational requirements can be made.

6.4.1. KPI03 Analysis

The first indicator analysed is KPI03 (flight time efficiency). The individual effects of the different constraints are analysed through the analyses defined in Section 6.4. Table 6.4 shows the results of both the Levene and ANOVA tests performed.

Table 6.4: Results of Levene and ANOVA tests for KPI03 - Scenario A.

Analysis	Models	Levene's significance	Post-hoc test	ANOVA	H_0 rejected?	Post-hoc needed
A	1 & 2	0.00	G-H	[F(1, 594)=5211.97, *p*=0]	Rejected	No
B	3	0.97	Tukey	[F(5, 1788)=32.65, *p*=0]	Rejected	Yes
C	3 & 4	0.00	G-H	[F(7, 2386)=2204.88, *p*=0]	Rejected	Yes
D	1 & 4	0.00	G-H	[F(2, 896)=1081.67, *p*=0]	Rejected	Yes
E	1, 2 & 3	0.00	G-H	[F(7, 2382)=763.19, *p*=0]	Rejected	Yes

- **Analysis A:** As there are only two models with one scenario each (Model 1 and 2 are formed by scenarios 1A_1 and 1A_2 respectively), post-hoc analysis are not necessary since conclusions can be obtained directly form the ANOVA results. Applying the rejection criterion to this case, i.e. $p < 0.05$, null hypothesis is rejected, which indicates that there is a significant effect of AS rules on KPI03. When implementing operational requirements, RPAS need to modify their original FL (as filed in the flight plan) to be compliant with AS rules. This modification of FL also affects time efficiency: means have been found to be different as demonstrated by ANOVA test.

- **Analysis B:** The scenarios present in Model 3 do not violate the assumption of homogeneity in variances (Levene's test p=0.97). Therefore, this is the only case for KPI03 where Tukey's test has been performed. Post-hoc is necessary since ANOVA's H_0 is rejected (p<0.05). Table 6.5 indicates the pairs with the same mean. As can be seen, means are only considered as equal for consecutive pairs of cruise speeds, as their values barely differ. However, comparing 1A_3_1 and 1A_3_6 the difference is 20 seconds, which is not negligible any more. P-values are included in the tables of pairs of means as they indicate the significance of each equality.

Table 6.5: Tukey's test result for Analysis B of KPI03 - Scenario A.

Scenario	**Pair 1**	**Pair 2**	**Pair 3**	**Pair 4**	**Pair 5**
1A_3_1	-226.17				
1A_3_2	-222.49	-222.49			
1A_3_3		-218.25	-218.25		
1A_3_4			-214.23	-214.23	
1A_3_5				-210.35	-210.35
1A_3_6					-206.39
p-value	0.35	0.19	0.25	0.29	0.26

- **Analysis C:** Levene's test result forces to use a Games-Howell post-hoc analysis. There is a significant effect of altitude segregation rules on KPI03 at the $p<0.05$ level. Post-hoc comparisons show that the means of Model 3 and Model 4 are significantly different, as the only pairs of equal means have been found within Model 3 (as Analysis B already indicated).
- **Analysis D:** H_0 for ANOVA test has been rejected at the $p<0.05$ level, as row D in Table 6.4 indicates. The post-hoc analysis, Games-Howell, has not provided any pair of scenarios that have equal mean, which indicates that cruise speed does have a significant impact on KPI03 when no altitude segregation rules are required. This conclusion is logical since the faster RPAS are allowed to fly, the less time they spend in the sector and the better the flight time efficiency becomes. In this case, three different cruise speeds have been analysed: 335 kts (Model 1), 390 and 400 kts (Model 4). The best result (lowest mean value) corresponds to the greatest cruise speed, 400 kts (see Table 6.3 to compare the KPI03 values for scenarios 1A_1, 1A_3_7 and 1A_3_8).
- **Analysis E:** The combination of AS rules and minimum cruise speed requirements has been proved to have an effect on KPI03 since the means of Models 1, 2 and 3 are different, since p=0. Therefore, H_0 has been rejected ($p<0.05$) and the Games-Howell post-hoc analysis is applied. The results show that there is a difference between the three models ($\overline{x}_1 \neq \overline{x}_2 \neq \overline{x}_3$) although there are equalities within Model 3, providing the same pairs for Model 3 as in Analysis B.

From these analyses it can be concluded that every set of constraints that has been added or removed for the different models has an effect on KPI03, flight time efficiency.

6.4.2. KPI04 Analysis

The same procedure followed for KPI03 is applied to KPI04 (flight path efficiency). An ANOVA test has been conducted to see the effect of the different requirements on KPI04. The results are shown in Table 6.6.

Table 6.6: Results of Levene and ANOVA tests for KPI04 - Scenario A.

Analysis	**Models**	**Levene's test significance**	**Post-hoc test**	**ANOVA**	**H_0 rejected?**	**Post-hoc needed**
A	1 & 2	0.00	G-H	[F(1, 594)=5941.92, p=0]	Rejected	No
B	3	1.00	Tukey	[F(5, 1788)=0.01, p=1]	Accepted	No
C	3 & 4	0.00	G-H	[F(7, 2386)=1848.9, p=0]	Rejected	Yes
D	1 & 4	1.00	Tukey	[F(2, 896)=0, p=1]	Accepted	No
E	1, 2 & 3	0.00	G-H	[F(7, 2382)=913.01, p=0]	Rejected	Yes

- **Analysis A:** Variances of Model 1 and 2 are not homogeneous, as Levene's p-value is 0. Looking at the ANOVA results, as p=0, the null hypothesis is rejected and, therefore, it can be concluded that both means are different. There is a significant difference between applying altitude segregation rules (Model 2) or not (Model 1).
- **Analysis B:** When analysing different minimum cruise speeds, is found that there is no significant effect of the different values on KPI04. The rejection criterion is not met ($p>0.05$) which indicates that the means are all equal. Cruise speed does not affect flight path efficiency.

- **Analysis C:** Altitude segregation rules have a significant effect on KPI04, as the results of this analysis show in Table 6.7. The rejection criterion is met (p<0.05) and, therefore, a post-hoc analysis must be conducted. Since Levene's test is significant and variances are not homogeneous, a Games-Howell post-hoc test has been conducted. Results are presented in Table 6.7. It can be seen that there is no no difference between the different speeds within the same model, as they form two different pairs with the same mean, Pair 1 and 2 correspond to Model 3 and 4 respectively. For the first case, Model 3, the "pair" includes more than two scenarios as they all have the same mean. Since $\overline{x}_3 \neq \overline{x}_4$ it can be concluded that AS rules affect KPI04.

Table 6.7: Games-Howell test result for Analysis C of KPI04 - Scenario A.

Scenario	**Pair 1**	**Pair 2**
1A_3_1	-22.75	
1A_3_2	-22.75	
1A_3_3	-22.75	
1A_3_4	-22.75	
1A_3_5	-22.75	
1A_3_6	-22.75	
1A_3_7		-10.14
1A_3_8		-10.14
p-value	1.00	1.00

- **Analysis D:** As shown in Analysis B, cruise speed does not influence KPI04 although in analysis B has been verified independently of the operational requirements. The p-value is larger than 0.05 (see row D of ANOVA column in Table 6.6) which allows concluding that the means for KPI04 are equal for the three cruise speeds considered: 335, 390 and 400 kts (1A_1, 1A_3_8 and 1A_3_7 respectively).
- **Analysis E:** This last analysis of KPI04 shows that, as was found in Analysis A, AS rules do have an effect on KPI04. Because the p-value of the ANOVA test is 0, less than 0.05, the null hypothesis is rejected. However, the interesting finding in this analysis is that requiring minimum cruise speed or not in combination with AS rules does not affect KPI04: Model 2 and 3 have equal means (see Table 6.3).

It can be concluded that the main effect on KPI04 is the implementation or not of AS rules. Models 1 and 4 (where only different cruise speeds are analysed) have equal means, as is also the case for Models 2 and 3 (where the difference is also in the cruise speed). However, these means ($\overline{x}_{1,4}$ and $\overline{x}_{2,3}$) are different, which supports the conclusion on the effect of AS rules.

6.4.3. KPI05 Analysis

Finally, the last indicator to analyse for Scenario 1A is KPI05 (number of potential conflicts). An ANOVA test has been conducted to analyse whether the different constraints imposed for each model affect the total number of potential conflicts. The outcome of the Levene's test for the homogeneity of variances and the ANOVA test for the variance of the means is provided in Table 6.8.

Table 6.8: Results of Levene and ANOVA tests for KPI05 - Scenario A.

Analysis	**Models**	**Levene's test significance**	**Post-hoc test**	**ANOVA**	**H_0 rejected?**	**Post-hoc needed**
A	1 & 2	0.35	Tukey	[F(1, 595)=216.49, p=0]	Rejected	No
B	3	0.53	Tukey	[F(5, 1791)=1.39, p=0.22]	Accepted	No
C	3 & 4	0.76	Tukey	[F(7, 2383)=62.33, p=0]	Rejected	Yes
D	1 & 4	0.59	Tukey	[F(2, 890)=14.93, p=0]	Rejected	Yes
E	1, 2 & 3	0.64	Tukey	[F(7, 2386)=58.76, p=0]	Rejected	Yes

- **Analysis A:** When AS rules are required, for the given nominal cruise speed, there is an effect of these operational requirements on the number of potential conflicts detected: p-value is greater than the level of significance which forces to reject H_0 and to conclude that the means are different. This outcome was expected, since when RPAS are flying outside the busiest airspace zone they are involved in or cause less potential conflicts ($\overline{x}_1$ =14.82 AC/h while after AS rules, $\overline{x}_2$ =12.21 AC/h). Therefore, requiring AS rules does influence the number of potential conflicts.

- **Analysis B:** According to ANOVA results (row B in Table 6.8), for a given set of AS rules, different cruise speeds do not have a significant influence on KPI05, at the $p<0.05$ level (as p-value is 0.22, greater than the level of significance). The means are roughly equal and no post-hoc analysis is needed.

- **Analysis C:** When assessing the effect of AS rules in Analysis A, it is found to have a significant effect on KPI05. This also applies when comparing Model 3 (where both requirements minimum cruise speeds and AS rules are taken into account) and Model 4 (where only a minimum cruise speed is required). The outcome of Tukey's post-hoc analysis shows that only the scenarios that form Model 3 have the same mean, while it is not the case between the means of Model 3 and Model 4. Moreover, even between different cruise speeds with no AS rules in place, means are not equal ($\overline{x}_{3\_7} \neq \overline{x}_{3\_8}$). This can be easily deduced from Figure 6.3. Although it might be difficult to assess the meaningful of the differences in means by just looking at the figure, it has been statistically verified through a Games-Howell test.

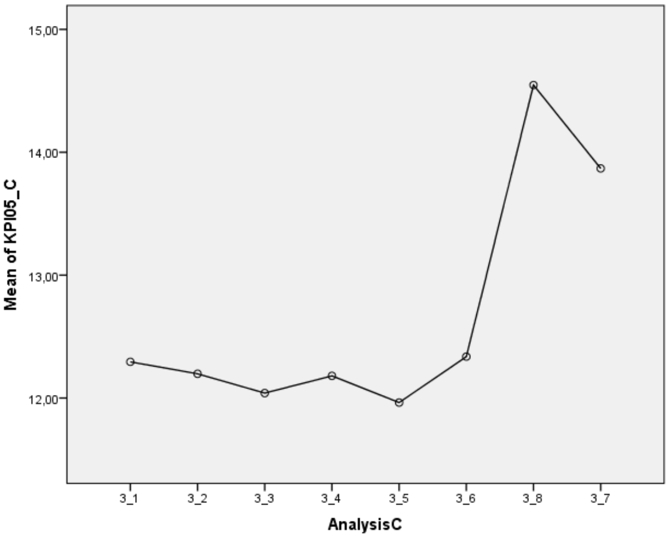


Figure 6.3: Mean values of the different scenarios in Model 3 and Model 4 - Scenario A.

- **Analysis D:** As found in Analysis B, when AS rules are required, minimum cruise speed has no effect on KPI05. However, the influence of cruise speed in KPI05 when no AS rules are required (Model 1 and Model 4) might be significant depending on the pair of minimum cruise speeds under analysis: between Scenario 1A_1 (Model 1, $\overline{x}_1$ = 14.82 AC/h) and Scenario 1A_3_8 (Model 4, $\overline{x}_{3\_8}$ = 14.55 AC/h) it can be assumed that means are equal, while this mean is different from the case 1A_3_7 (400kts, $\overline{x}_{3\_7}$ = 13.87AC/h).

- **Analysis E:** The null hypothesis is rejected because the p-value is less than 0.05. Some of the scenarios have different means (some constraints do have an effect on KPI05). Tukey's outcome shows that the means obtained for Model 2 and Model 3 are equal, which means that cruise speed (the main difference between these models) does not have an effect on KPI05. However, Model 2 and 3 do not have the same mean as Model 4, which indicates that AS rules do affect KPI05. This leads to the same conclusion as in Analysis A and B: different cruise speed do not have an influence on KPI05 if AS rules are applied (Model 2 and 3 have equal means) while AS has an effect on KPI05 ($\overline{x}_1 \neq \overline{x}_{2,3}$).

Table 6.9: Tukey's test result for Analysis E of KPI05 - Scenario A.

Scenario	Pair 1
1A_2	12.21
1A_3_1	12.29
1A_3_2	12.20
1A_3_3	12.04
1A_3_4	12.18
1A_3_5	11.96
1A_3_6	12.34
p-value	0.38

To conclude, the main factor affecting KPI05 is AS rules. When these operational requirements are implemented, the different values of cruise speed do not affect the number of potential conflicts. When no AS is required, the specific value of the cruise speed might have (or not) an effect on KPI05 as the means within Model 1 and 4 have not formed an unique pair.

6.5. Results for Scenario 1B

Results of Monte Carlo simulations for Scenario 1B are processed by following the same steps as for Scenario 1A: the statistical estimators (mean and standard deviation) are calculated for each case investigated once the outliers have been identified and removed. The mean values are gathered in Table 6.10:

Table 6.10: Results of the stochastic model of Scenario 1B (average values).

Scenario	Change	KPI01	KPI02	KPI03	KPI04	KPI05	WS
BS	-	48	17	-131.24	-16.88	1	-
1B_1	Replacement	43	22	-275.91	-23.75	13.06	5.29
1B_2	AS	43	22	-344.92	-24.01	13.68	3.15
1B_3_1	210 kts + AS	43	22	-315.21	-22.02	13.63	4.51
1B_3_2	220 kts + AS	43	22	-302.65	-22.01	13.34	5.27
1B_3_3	230 kts + AS	43	22	-292.12	-22.01	13.41	5.22
1B_3_4	240 kts + AS	43	22	-282.29	-22.02	13.66	4.75
1B_3_5	250 kts + AS	43	22	-274.30	-22.02	13.67	4.82
1B_3_6	260 kts + AS	43	22	-265.45	-22.02	13.54	5.18
1B_3_7	270 kts + AS	43	22	-257.68	-22.02	13.54	5.26
1B_3_8	**280 kts + AS**	**43**	**22**	**-250.22**	**-22.02**	**13.53**	**5.33**
1B_3_9	290 kts + AS	43	22	-245.80	-22.35	13.89	4.44
1B_3_10	300 kts + AS	43	22	-239.31	-22.35	14.29	3.84
1B_2_A	AS + 250 fpm	43	22	-293.63	-23.74	13.54	4.19
1B_2_B	AS + 500 fpm	43	22	-293.65	-23.74	13.57	4.14
1B_2_C	AS + 750 fpm	43	22	-293.17	-23.74	12.72	5.52
1B_2_D	AS + 1,000 fpm	43	22	-293.63	-23.74	12.73	5.49
1B_3_7_A	AS + 270 kts + 250 fpm	43	22	-247.30	-23.74	13.90	4.50
1B_3_7_B	AS + 270 kts + 500 fpm	43	22	-247.21	-23.74	14.12	4.15
1B_3_7_C	AS + 270 kts + 750 fpm	43	22	-246.82	-23.74	13.95	4.43
1B_3_7_D	AS + 270 kts + 1,000 fpm	43	22	-246.85	-23.74	13.21	5.54
1B_3_8_A	AS + 280 kts + 250 fpm	43	22	-242.42	-23.74	13.81	4.74
1B_3_8_B	AS + 280 kts + 500 fpm	43	22	-242.34	-23.74	14.27	4.00
1B_3_8_C	AS + 280 kts + 750 fpm	43	22	-241.93	-23.74	13.08	5.93
1B_3_8_D	**AS + 280 kts + 1000 fpm**	**43**	**22**	**-241.97**	**-23.74**	**13.03**	**6.01**

Table 6.10 is divided into two main parts: the top part presents the indicators and the weighted score for the sub-scenarios where only minimum cruise speed is required. Among them, the combination of 280 kts to-

gether with operational requirements based on altitude segregation rules results in the best performing case. But since RPAS might need to climb during their cruise phase, it is necessary to establish the minimum value of ROC which reduces the impact. To that end, the bottom half of the table includes different combinations of minimum cruise speed and ROC. On the one hand, the cruise speeds selected are the nominal and the best two candidates found in the previous analysis, presented in the top part of the table. On the other hand, the values of ROC analysed go from 250 fpm (nominal value for RP02) up to 1,000 fpm. Within all the possible combinations, the best candidate is the combination of altitude segregation rules, 280 kts and 1,000 fpm.

Looking at the value of KPI05 for Scenario 1B_3_8, 13.53 AC/h, it is further divided into different types of conflicts: 84.12% are Type I, 15.73% Type II and 0.02% Type III. As was found for Scenario A, the majority of conflicts do not involve RPAS, although they can be pointed as one of the causes. Conflicts of type II are mostly between climbing manned AC and a cruising unmanned AC. Low-performance RPAS are operating in the lower part of the airspace (below or at FL300) and this incurs in conflicts with manned aircraft that are climbing when crossing the airspace sector. Conflicts of type III are between RPAS flying below FL300. This part of the airspace has now more users operating in it, which incurs in potential conflicts between these users.

Moving to the statistical analysis, for this scenario, the following models are defined:

- Models 1, 2 and 3: defined as for Scenario A (replacement, AS, combination of AS and minimum cruise speed requirement).
- Model 4: combination of AS, minimum cruise speed and minimum ROC required.

The breakdown into different analysis that was defined for Scenario 1A is maintained, accounting for the following changes:

- Analysis C is modified: comparing Models 3 and 4 makes no sense for Scenario B, since for Model 4 the trajectories have been modified to force the RPA to climb when crossing the airspace sector that is being considered. Therefore, analysis C will analyse only Model 4 to see the effect of the different combinations of minimum cruise speed and ROC requirement on the indicators (when AS rules are in place).
- Analysis D is removed. Model 1 and Model 4 are based on different constraints for the trajectory definition (with and without climbing inside the sector). Instead, Analysis E will be denoted as Analysis D.

6.5.1. KPI03 Analysis

The first indicator that is analysed for Scenario 1B is KPI03, which represents flight time efficiency. Levene's test, ANOVA test and post-hoc analysis are the three main steps followed in this analysis. The results are summarised in Table 6.11.

Table 6.11: Results of Levene and ANOVA tests for KPI03 - Scenario B.

Analysis	**Models**	**Levene's test significance**	**Post-hoc test**	**ANOVA**	**H_0 rejected?**	**Post-hoc needed**
A	1 & 2	0.86	Tukey	[F(1, 589)=575.41, p=0]	Rejected	No
B	3	0.14	Tukey	[F(9, 2950)=237.69, p=0]	Rejected	Yes
C	4	0.03	G-H	[F(11, 3551)=124.34, p=0]	Rejected	Yes
D	1, 2 & 3	0.00	G-H	[F(11, 3539)=326.08, p=0]	Rejected	Yes

- **Analysis A:** The ANOVA test carried out for Models 1 and 2 shows that the effect of AS rules on KPI03 is significant: $p<0.05$, which implies that $\overline{x}_1 \neq \overline{x}_2$. Post-hoc analysis is not necessary since each model is formed by only one scenario.

- **Analysis B:** As Levene's test is not significant (p-value larger than 0.05), variances are homogeneous. H_0 is rejected according to the results of the ANOVA test (p=0). Therefore, a Tukey's test is performed to find in which cases the means coincide. Table 6.12 shows the pairs of scenarios that have equal means. It can be concluded that different cruise speed do have an effect on KPI03, as not all the means have been found to be equal.

Table 6.12: Tukey's test result for Analysis B of KPI03 - Scenario B.

Scenario	Pair 1	Pair 2
1B_3_8	-250.22	
1B_3_9	-245.80	-245.80
1B_3_10		-239.31
p-value	0.46	0.15

- **Analysis C:** The assumption of homogeneity in variances is violated, as Levene's test reveals (p=0.03). Looking at the results of the ANOVA test (row C in Table 6.11), the different combinations of minimum cruise speed and ROC do have an influence on KPI03. Results obtained after Games-Howell test are shown in Figure 6.4: for a given cruise speed (200 kts, scenario 2_X), the means are equal and there is no effect of imposing different ROC on KPI03. However, for greater cruise speeds (280 and 270 kts, denoted as 3_8 _X and 3_7_X respectively) there is no effect of the different combinations on KPI03: means are roughly equal for all the combinations between 3_8_X and 3_7_X. Further details about these results and p-values can be found in Annex D (Table D.5).

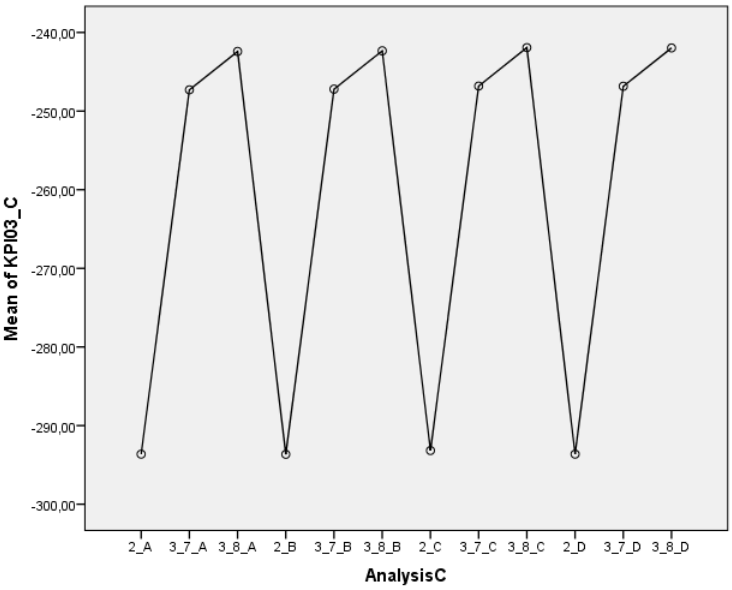


Figure 6.4: Mean values of the KPI03 Analysis C - Scenario B.

- **Analysis D:** Finally, this analysis aims at investigating the effect of the combination of AS rules and minimum cruise speed on KPI03 compared to Model 1, where there are no requirements, and Model 2, where there are only AS rules. Since the assumption of homogeneity in variances is violated and the ANOVA test results forces to reject H_0, a Games-Howell test has been carried out. The resulting pairs with equal means are summarised in Table 6.13.

Table 6.13: Games-Howell test result for Analysis D of KPI03 - Scenario B.

Scenario	Pair 1	Pair 2	Pair 3	Pair 4
1B_1	-275.91	-275.91		
1B_3_4	-282.29			
1B_3_5		-274.30		
1B_3_8			-250.22	
1B_3_9			-245.8	-245.8
1B_3_10				-239.31
p-value	0.37	1.00	0.47	0.13

In closing, there is a significant effect of the combination of operational and performance requirements on KPI03 since only singular events have been found to have equal means and no general rules or patterns are driven. When adding to the previous combination ROC requirements, there is no significant effect on the different ROC assessed on KPI03 while considering low cruise speed (Scenario 2) or higher cruise speed (1B_3_7 and 1B_3_8) in combination with minimum ROC and AS rules, does influence KPI03 (as demonstrated in Analysis C).

6.5.2. KPI04 Analysis

The results of KPI04 are shown in Table 6.10. Even though they are very clear in terms of equality of means, the same procedure (Levene's test followed by ANOVA test and, if necessary, post-hoc analysis) is followed for KPI04. The results of this procedure are presented in Table 6.14.

Table 6.14: Results of Levene and ANOVA tests for KPI04 - Scenario B.

Analysis	Models	Levene's test significance	Post-hoc test	ANOVA	H_0 rejected?	Post-hoc needed
A	1 & 2	0.88	Tukey	[F(1, 596)=0.701, p=0.40]	Accepted	No
B	3	0.73	Tukey	[F(9, 2974)=0.29, p=0.98]	Accepted	No
C	4	1.00	Tukey	[F(11, 3563)=0.00, p=1]	Accepted	No
D	1, 2 & 3	0.02	G-H	[F(11, 3570)=13.37, p=0]	Rejected	Yes

- **Analysis A:** The analysis of homogeneity in variances provided a p-value for the Levene's test of 0.88 which, compared to the level of significance, accepts Levene's null hypothesis: variances are the same. Analysis of variance shows that there is no significant effect on KPI04 when operational requirements are in place: ANOVA test provided a p-value of p=0.40>0.05, which indicates that the means are equal.

- **Analysis B:** The comparison of the variances between the different scenarios within Model 3 shows a non-significant Levene's test, whose p-value is 0.73. Therefore, variances are roughly equal and the post-hoc analysis is based on a Tukey's test. But prior to the post-hoc analysis, it is necessary to take a look at the ANOVA results (row B in Table 6.14). The p-value is 0.98, which forces to accept the null hypothesis which implies that the means of the scenarios of Model 3 are all equal. This equality of means shows that there is no effect of different values of cruise speed on KPI04, as was the case for same-performance RPAS (Scenario 1A).

- **Analysis C:** The analysis of the homogeneity in variances in Model 4 shows that this assumption is not violated (p-value of Levene's test is 1.00). Analysis of variance (ANOVA) shows that there is no effect of different combinations of minimum cruise speed and ROC requirements in KPI04, as the p-value of this ANOVA test is 1.00 (H_0 is accepted): all the means within Model 4 are equal.

- **Analysis D:** Finally, the last analysis of flight path efficiency is performed between Models 1, 2 and 3. Levene's test is significant as it obtains a p-value of 0.02, which indicates that the assumption of equal variances is violated. Post-hoc analysis will be based on Games-Howell method. The Welch's ANOVA test shows that there is a significant effect of the combination of AS rules and minimum cruise speed requirement on KPI04 with respect to the cases where either no requirements or only AS rules are implemented (p=0). This indicates that at least one of the means is different. This difference was found in the post-hoc analysis: Model 1 and Model 2 have equal mean (as Analysis A already proved), but this mean is different from Model 3. The previous fact verifies the significant effect of the combination of operational and performance requirements over the other options implied in Models 1 and 2.

In conclusion, the combination of operational and performance requirements has a significance impact on KPI04 but without distinction between different cruise speeds. The same applies to Model 4: different combinations of cruise speed and ROC do not affect KPI04, as all the means of the scenarios within Model 4 are equal.

6.5.3. KPI05 Analysis

The last analysis for low-performance RPAS (Scenario 1B) focuses on the number of potential conflicts (KPI05). Homogeneity of variances is first tested through Levene's test in order to select the best option for the post-hoc analysis. After analysing the homogeneity of variances, a ANOVA is carried out find the differences in means. Table 6.15 summarizes the results of both tests, Levene and ANOVA:

Table 6.15: Results of Levene and ANOVA tests for KPI05 - Scenario B.

Analysis	**Models**	**Levene's test significance**	**Post-hoc test**	**ANOVA**	**H_0 rejected?**	**Post-hoc needed**
A	1 & 2	0.00	G-H	[F(1, 584)=11.93, p=0]	Rejected	No
B	3	0.60	Tukey	[F(9, 2966)=4.24, p=0]	Rejected	Yes
C	4	0.00	G-H	[F(11, 3553)=15.65, p=0]	Rejected	Yes
D	1, 2 & 3	0.04	G-H	[F(11, 3550)=5.25, p=0]	Rejected	Yes

- **Analysis A:** The effect of AS rules on KPI05 is found to be significant (as was expected): the output of the ANOVA test provided a p-value of 0, which rejects the null hypothesis on equality of means. Since there are only two models of one scenario each, it can be directly concluded that both means are unequal ($\overline{x}_1$ = 13.06 AC/h and $\overline{x}_2$ = 13.66 AC/h). It s logical to think that once they are separated from the busiest airspace region (by requiring AS rules), the number of potential conflicts would decrease. However, when forcing them to fly below this altitude and above this busiest region (considering that in this case since there are only low-performance RPAS that will fly only below due to their ceiling) the number of airspace users in this region is increased (now the 10 low-performance RPAS are operating there while for the base scenario, the original flights could have been taken place in the whole airspace sector, without). But the increase in the number of potential conflicts is not only a consequence of having more users in the same region, but also that they are flying much slower (at 200 kts) than the rest of aircraft. The effect of the minimum cruise speed requirement is analysed next and will be compared with these two models in Analysis D.
- **Analysis B:** Since the assumption of homogeneous variances is not violated, as indicated through the p-value of Levene's test (equal to 0.60), the post-hoc analysis that has been performed is a Tukey's test. Analysis of variance (ANOVA) shows that there is a significant effect of minimum cruise speed on KPI05. There are two pairs that have equal means. One of the pairs is formed by the majority of the cruise speeds analysed except for the highest one, while the other pair is only based on the two highest cruise speeds (see Table 6.16). Therefore, the effect is mainly significant when considering higher cruise speeds. The reason behind this fact is that they are operating at low altitude. In that region, cruise speeds are typically not that high (between 250 and 290 kts in general). By requiring a minimum cruise speed of 300 kts for unmanned aviation, conflicts arise as there are differences in cruise speed (although now unmanned aircraft are the fastest in that region).

Table 6.16: Tukey's test result for Analysis B of KPI05 - Scenario B.

Scenario	Pair 1	Pair 2
1B_3_2	13.34	
1B_3_3	13.42	
1B_3_7	13.54	
1B_3_6	13.54	
1B_3_8	13.57	
1B_3_1	13.63	
1B_3_4	13.66	
1B_3_5	13.67	
1B_3_9	13.89	13.89
1B_3_10		14.29
p-value	0.08	0.50

- **Analysis C:** Levene's test proved that the variances of Model 4 are not equal, seeing as p=0. Therefore, to analyse the significance of the effect of different combinations of minimum cruise speed and ROC requirements, a Games-Howell test is chosen. This post-hoc test is needed since the ANOVA's null hypothesis has been rejected (p<0.05). Given that there are multiple combinations of pairs of scenarios with equal means, Figure 6.5 shows the means of this indicator for the scenarios in Model 4, which is of help to assess the pairs. The complete table can be found in Annex D (Table D.6). As an example, scenarios 1B_2_C, 1B_2_D, 1B_3_8_C and 1B_3_7_D have equal means.

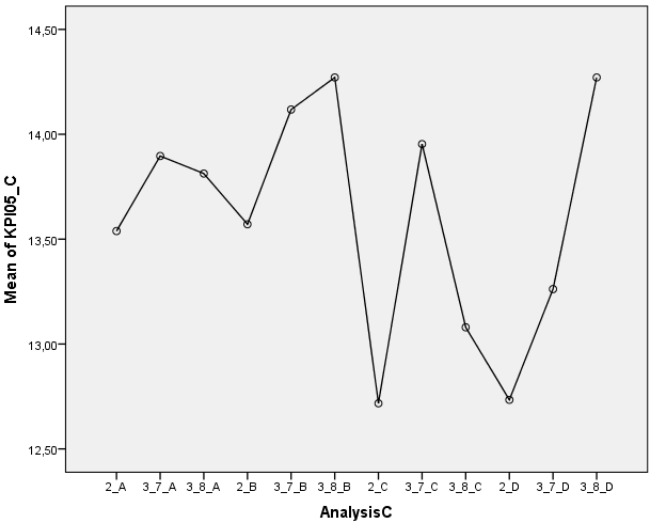


Figure 6.5: Analysis C means plot for KPI05 - Scenario B.

- **Analysis D:**Finally, as introduced in Analysis A, the influence of minimum cruise speed requirements (in combination with AS rules) on KPI05 is assessed through an ANOVA test. Levene's test has resulted in a significant difference in variances, which implies that the post-hoc analysis should be a Games-Howell test. This test is necessary as ANOVA's null hypothesis about equality of means is rejected (p=0). The different pair combinations with equal mean are presented in Annex D (Table D.7) but not general conclusion than the existence of an influence can be draw. Pairs are formed between mean closer values with no predefined trend regarding the constraints imposed on each case. For example, Scenario 1B_1 forms a pair with 1B_3_2, 1B_3_3, 1B_3_6, 1B_3_7, 1B_3_8 which does not follow any pattern.

It can be concluded that for low-performance RPAS , the introduction of AS rules does not improve the number of potential conflicts. Since their ceiling is FL310, they are already avoiding the majority of the busiest airspace region. When requiring altitude segregation rules, the number of available FLs for them to operate is reduced (upper limit of the allowed region changes from FL310 to FL300), which implies that there is less airspace available for a greater number of airspace users than before. This leads to an unavoidable increase in the number of potential conflicts that will affect not only aircraft flying at low altitudes but also aircraft climbing or descending.

A possible solution to avoid this effect of AS rules on KPI05 could be to raise the upper limit of the allowed region (to FL310 or FL320) in order for low-altitude operations to have a bigger volume of airspace. But this solution might not be feasible for some sectors that are already saturated and cannot restrict commercial aircraft operations to a smaller airspace region. A trade-off between available airspace for manned operations and the potential number of potential conflicts should be performed by each ANSP.

In general, minimum cruise speed requirements barely affect the number of potential conflicts detected, as has been shown in Analysis B. Speeds greater than 290 kts have an influence on KPI05, as aircraft operating in the lower airspace are normally slower, with typical cruise speeds below 300 kts.

7

Sensitivity Analysis

Mathematical models have been used in many fields for simulation purposes, when experiments are found to be expensive or infeasible, as well as for prediction purposes. For this project, assessing the impact of integrated RPAS operations and the definition of minimum operational and performance requirements cannot be performed in practice due to the inherent risk for the other airspace users that this would cause. After these minimum requirements are defined by means of Monte Carlo simulations, an analysis on the sensitivity of the resulting KPIs is necessary since they are dependent on different scenario parameters. The main question to answer is: *"Will the results change if the scenario parameters are randomly changed?"*. To test the robustness of the outcome, three different sensitivity analyses are performed individually, aimed at varying different scenario parameters:

1. **Flight Level Allocation**: Traffic demand has kept the flight level as filed in the flight plan, also known as requested flight level (RFL). For this study, flight level is randomly allocated to avoid flights with similar characteristics (same origin and destination) on the same level and to analyse how sensitive the efficiency is with respect to the RFL. As an intrinsic function of the 4D trajectory functionality in NEST, this variable has four different possible values: none (used until now in the project), narrow, medium and wide. They differ in the amount of flights that are randomly varied. The option selected for this analysis is *wide*, which keeps 50% of flights on the same FL, 30% of flights in ± 1 FL, 16% of flights in ± 2 FL and 4% of flights in ± 3 FL.

2. **Weights of the WS for the KPIs**: For this project, a fixed set of weights for the KPIs has been used when evaluating the best candidate for each scenario. However, it is also necessary to analyse how sensitive the outcome is (i.e. the best performing case) when changing these weights. This sensitivity analysis would have made more sense if it would have been performed when selecting the weights, but results were not available yet. Weights are varied independently (one weight at a time) to see the independent effect of each indicator when selecting the best case. Four different variations are investigated (per KPI and per Scenario, 1A and 1B): ± 0.5 and ±1. The weights associated to KPI01 and KPI02 are not investigated. Both have the same value for all the scenarios and, therefore, variations in these weights will affect to all the scenarios equally (with would not change the resulting best performing case).

7.1. Scenario 1A

In this section, the sensitivity analysis for scenario 1A is presented following the guidelines presented in the previous section. Sensitivity analysis is applied to the best performing case and from which the operational and performance requirements are derived (Scenario 1A_3 _5, see table 6.3), which is based on a combination of applying altitude segregation rules and requiring a minimum cruise speed of 390 kts. For each case defined for the sensitivity analysis, different set-ups are needed and are explained in the following subsections. A comparison between the results obtained from Monte Carlo simulations and those from the sensitivity analysis will be provided based on ANOVA tests, to determine whether the means are statistically different.

7.1.1. Variation of the FL Allocation

The sensitivity of the efficiency with regards to the FL allocation is analysed by varying the *wide* option the traffic files used for Monte Carlo simulations accordingly, and by using the performance files corresponding to the best performing case, 1A_3_5 (hereafter denoted as the *Original* case). Since there are two different means to be compared in order to analyse the sensitivity of the indicators respect to the FL allocation, the procedure described in Chapter 7 is used: Levene's, ANOVA and post-hoc test. Scenario modified under the *wide* option is denoted as *Modified* case.

Table 7.1 presents the results of the statistical estimators for each of the indicators considered:

Table 7.1: KPI03, KPI04 and KPI05 statistical estimators for variations in FL allocation - Scenario A.

	KPI03		**KPI04**		**KPI05**	
	Mean	σ_x	**Mean**	σ_x	**Mean**	σ_x
Original	-210.35	22.20	-22.78	2.70	11.96	1.95
Modified	-207.89	22.44	-22.57	2.78	12.24	1.91

Regarding the sensitivity of time efficiency (KPI03), Levene's test outcome is not significant (p=1.00 > 0.05) which implies that the variances are equal and that the post-hoc analysis should be a Tukey's test. One-way ANOVA outcome [F(3, 1198)=0.90, p=0.44] accepts the null hypothesis about the equality of means. Therefore, for same-performance RPAS, time efficiency is not sensitive to FL allocation.

Regarding the flight path efficiency (KPI04), the statistical estimators are presented in columns 4 and 5 in Table 7.1. Although conclusions about the sensitivity of KPI04 for a variation in FL allocation might be drawn directly from these results (mean values are very close), it is confirmed after the ANOVA test: [F(3, 1192)=0.44, p=0.72]. As p-value is greater than the level of significance, the null hypothesis is accepted. In conclusion, since means have been found to be equal, flight path efficiency is not sensitive to FL allocation.

To conclude this analysis, the effect of FL allocation on the number of potential conflicts is analysed. The estimators are included in the last two columns of Table 7.1. In this case, mean values seems to be different but it is necessary to verify the statistical significance of this difference. Homogeneity in variance can be affirmed as Levene's test is not significant (p=0.99). ANOVA test results, [F(3, 1196)=2.07, p=0.13] allows to confirm that there is no influence of FL allocation in KPI05 (for same-performance RPAS), at the p<0.05 level.

It can be concluded that the best performing case for same-performance RPAS is not sensitive to FL allocation, as demonstrated by three independent analysis: effect on KPI03, KPI04 and KPI05. All of them have been found to be not sensitive to changes in FL allocation defined by the *wide* option as the difference between the means of the original and modified scenarios are found to be equal for each indicator. Same-performance RPAS are not allowed to enter the most congested area, which means that even if they change their FL they will still fly above or below this congested area. Although manned aircraft are changing their FL, these changes are not so radical (the maximum value is of ±3FL) which keeps commercial aviation within the most occupied region of the airspace.

7.1.2. Variation of the Weights of the KPIs

The selection of the best performing case has been based on the computed weighted score. This result depends on the weights that have been associated to each indicator (see Equation 5.4): KPI01, KPI02, KPI03 and KPI04 have an assigned weight of 1 while KPI05 has been assigned to a weight of 2.5. It would have been a good practise to analyse the sensitivity of the selection of the best performing case when varying these weights. However, the decision of the different weights was made before any result was obtained. Therefore, once the project has been developed and the results have been obtained, this sensitivity of the selection of the best performing case with respect to the weights associated do the KPIs is analysed.

For Scenario 1A, Table 7.2 presents the different combinations of weights that have been researched and, based on these new weights, the resulting best performing case is established.

Table 7.2: Variation of weights associated with the KPIs - Scenario A.

Variation	WKPI03	WKPI04	WKPI05	Best case
+1	2	1	2.5	1A_3_7
	1	2	2.5	1A_3_7
	1	1	3.5	1A_3_5
-1	0	1	2.5	1A_3_5
	1	0	2.5	1A_3_5
	1	1	1.5	1A_3_7
+0.5	1.5	1	2.5	1A_3_7
	1	1.5	2.5	1A_3_7
	1	1	3	1A_3_5
-0.5	0.5	1	2.5	1A_3_5
	1	0.5	2.5	1A_3_5
	1	1	2	1A_3_7

The effect of variations in weights is clear as two main trends can be observed:

- When reducing the weight of any of the efficiency indicators (KPI03 or KPI04) or increasing the weight of KPI05, the best performing case is in all cases 1A_3_5. This scenario has the lowest number of potential conflicts (11.96 AC/h) and, thus, if safety is prioritized, this scenario results in the best case.
- For the rest of the combinations of weights, the best performing case is 1A_3_7. This scenario has the best efficiency indicators (KPI03=-99.62 s and KPI04=-10.14 NM). In all cases where safety is not prioritized, this scenario turns to be the best performing case.

Table 7.3 presents the weighted score associated to each scenario and to each variation in the weights of the KPIs.

Table 7.3: Weighted score obtained after varying the weights of the KPIs - Scenario A.

Scenario	No Variation	Variation of +1			Variation of -1			Variation of -0.5			Variation of +0.5		
		WKPI03	WKPI04	WKPI05	WKPI03	WKPI04	WKPI05	WKPI03	WKPI04	WKPI05	WKPI03	WKPI04	WKPI05
1A_1	3.82	4.63	4.82	3.82	3.00	2.82	3.82	3.41	3.32	3.82	4.22	4.32	3.82
1A_2	4.28	4.28	4.28	5.20	4.28	4.28	3.37	4.28	4.28	3.83	4.28	4.28	4.74
1A_3_1	4.27	4.32	4.27	5.15	4.21	4.27	3.38	4.24	4.27	3.82	4.29	4.27	4.71
1A_3_2	4.37	4.45	4.37	5.29	4.29	4.37	3.46	4.33	4.37	3.91	4.41	4.37	4.83
1A_3_3	4.54	4.66	4.54	5.52	4.43	4.54	3.57	4.49	4.54	4.06	4.60	4.54	5.03
1A_3_4	4.45	4.60	4.45	5.37	4.31	4.45	3.53	4.38	4.45	3.99	4.52	4.45	4.91
1A_3_5	4.67	4.85	4.67	**5.67**	**4.50**	**4.67**	3.67	**4.59**	**4.67**	4.17	4.76	4.67	**5.17**
1A_3_6	4.38	4.58	4.38	5.25	4.18	4.38	3.51	4.28	4.38	3.94	4.48	4.38	4.81
1A_3_7	**4.83**	**5.83**	**5.83**	5.16	3.83	3.83	**4.50**	4.33	4.33	**4.66**	**5.33**	**5.33**	5.00
1A_3_8	4.21	5.18	4.21	4.30	3.24	4.21	4.12	3.72	4.21	4.16	4.70	4.21	4.26

It should be noted that these two scenarios, 1A_3_5 and 1A_3_7, coincide with the best two performing cases for Scenario 1A. Thus, it can be concluded there is a high sensitivity regarding the variation of weights (in order to prioritize either efficiency or safety). This highlights the importance of applying this methodology to each sector, and to not generalize the results obtained in this project. Depending on the desired trade-off between efficiency and capacity, a different combination of performance and operational requirements for same-performance RPAS is needed.

7.2. Scenario 1B

To analyse the sensitivity of the outcome of Scenario 1B to variations of different scenario parameters, the traffic demand files used in the simulations correspond to scenario 1B_3_8, in which case RPAS are flying at a constant cruise level (and not forcing them to climb, as has been the case of the minimum ROC assessment). The analysis is thus performed in the same manner as for Scenario 1A: variation of the FL allocation. variation of the take-off time and variation of the weights associated to each KPI.

7.2.1. Variation of the FL Allocation

After randomly varying the RFL according to the FL allocation option defined as *wide*, efficiency and number of potential conflicts are investigated to see if for low-performance RPAS, these indicators are sensitive or not to FL allocation. Again, Levene's, ANOVA and post-hoc tests are carried out to come up with the statistical significance of the difference in means. The first indicator that is analysed is flight time efficiency. The mean and standard deviation values are gathered in Table 7.4.

Table 7.4: KPI03, KPI04 and KPI05 statistical estimators for variations in FL allocation - Scenario B.

	KPI03		**KPI04**		**KPI05**	
	Mean	σ_x	**Mean**	σ_x	**Mean**	σ_x
Original	-210.35	22.20	-22.02	3.32	13.57	2.25
Modified	-210.35	22.20	-22.02	3.32	13.51	2.17

The effect of FL allocation on KPI03 is clear: flight time efficiency is not sensitive to the different options of FL allocation. This is also the case of flight path efficiency (see columns 4 and 5 in Table 7.4): since means are equal, for low-performance RPAS, KPI04 is not sensitive to FL allocation. However, means are not equal for KPI05. Further analysis is required to conclude whether FL allocation affects KPI05. The significance of Levene's test (p=0.99) indicates that variances are homogeneous. In order to analyse the differences in means, ANOVA test is carried out: [F(3, 1184)=0.08, p=0.93]. The significance obtained from this test does not meet the rejection criterion and, thus, the null hypothesis is accepted. The number of potential conflicts for low-performance RPAS is not sensitive to FL allocation.

It can be concluded that for low-performance RPAS, the best performing case (AS + 280 kts) is not sensitive to FL allocation, as has been proven for KPI03, KPI04 and KPI05. Low-performance RPAS are allowed to operate below the most occupied region of the airspace. FL allocation has been performed within the range [-3FL, +3FL] which implies that manned aviation still operates in this saturated region while unmanned aviation is below this region.

7.2.2. Variation of the Weights of the KPIs

The variation of the weights and the resulting best performing case has been carried out int two different phases: a first phase for the scenarios where only AS rules and minimum cruise speed requirement are considered (CS) and a second phase for the scenarios with combinations of AS rules, minimum cruise speed and ROC requirements. The reason this distinction is made is because of the different scenario that was required when assessing ROC. Both cases are included in Table 7.5.

Table 7.5: Variation of weights associated with the KPIs - Scenario B.

Variation	KPI03	KPI04	KPI05	Best case - CS	Best case - ROC
+1	2	1	2.5	1B_3_8	1B_3_8_D
	1	2	2.5	1B_3_8	1B_3_8_D
	1	1	3.5	1B_1	1B_3_8_D
-1	0	1	2.5	1B_3_2	1B_3_8_D
	1	0	2.5	1B_1	1B_3_8_D
	1	1	1.5	1B_3_8	1B_3_8_D
+0.5	1.5	1	2.5	1B_3_8	1B_3_8_D
	1	1.5	2.5	1B_3_8	1B_3_8_D
	1	1	3	1B_1	1B_3_8_D
-0.5	0.5	1	2.5	1B_3_2	1B_3_8_D
	1	0.5	2.5	1B_1	1B_3_8_D
	1	1	2	1B_3_8	1B_3_8_D

On the one hand, the variations in weights do not affect the best performing case when assessing the combination of AS rules, minimum cruise speed and ROC requirements (see column 6 in Table 7.5). On the other hand, as happened also with same-performance RPAS, variations in weights for the combination of AS rules and minimum cruise speed follows the following patterns:

- When reducing the weight of efficiency (KPI03 or KPI04) or increasing the weight of safety (KPI05), the best performing case changes.
- In case of a reduction in the weight associated to KPI04 or an increase in the weight of KPI05, the best performing case turns out to be scenario 1B_1 (replacement). KPI04 presents a similar value for all the scenarios except for 1B_1 (worst value). However, this scenario has the best value for KPI05. Therefore, by reducing the importance of KPI04 or by increasing the importance of KPI05, this scenario 1B_1 results in the best performing case.
- In case the reduction is applied to the weight of KPI03, the best performing case is 1B_3_2, as is the scenario with the second best value of KPI05. By reducing the importance of KPI03, safety becomes more important (for similar values of KPI04) and, therefore, the best performing case is 1B_3_2.

The weighted scores for each variation of the weights associated to the KPIs is summarised in Table 7.6.

Table 7.6: Weighted score obtained after varying the weights of the KPIs - Scenario B.

Scenario	No Variation	Variation of +1			Variation of -1			Variation of -0.5			Variation of +0.5		
		WKPI03	WKPI04	WKPI05	WKPI03	WKPI04	WKPI05	WKPI03	WKPI04	WKPI05	WKPI03	WKPI04	WKPI05
1B_1	5.29	5.94	5.41	**6.28**	4.63	**5.15**	4.28	4.96	**5.22**	4.78	5.61	5.35	**5.78**
1B_2	3.15	3.12	3.12	3.57	3.12	3.12	2.67	3.12	3.12	2.90	3.12	3.12	3.35
1B_3_1	4.51	4.79	5.50	5.00	4.23	3.51	4.02	4.37	4.01	4.26	4.65	5.01	4.76
1B_3_2	5.27	5.67	6.26	6.02	**4.87**	4.27	4.52	**5.07**	4.77	4.89	5.47	5.76	5.64
1B_3_3	5.22	5.72	6.22	5.91	4.72	4.22	4.53	4.97	4.72	4.87	5.47	5.72	5.56
1B_3_4	4.75	5.35	5.75	5.22	4.16	3.76	4.29	4.46	4.26	4.52	5.05	5.25	4.99
1B_3_5	4.82	5.48	5.80	5.27	4.14	3.81	4.35	4.47	4.31	4.58	5.14	5.31	5.04
1B_3_6	5.18	5.93	6.17	5.75	4.43	4.18	4.61	4.80	4.68	4.89	5.56	5.68	5.47
1B_3_7	5.26	6.08	6.25	5.83	4.43	4.26	4.68	4.84	4.76	4.97	5.67	5.75	5.54
1B_3_8	**5.33**	**6.23**	**6.31**	5.91	4.43	4.35	**4.75**	4.88	4.84	**5.04**	**5.78**	**5.82**	5.62
1B_3_9	4.44	5.37	5.26	4.69	3.49	3.60	4.17	3.96	4.01	4.30	4.90	4.84	4.56
1B_3_10	3.84	4.83	4.66	3.83	2.83	3.00	3.83	3.33	3.415	3.83	4.33	4.245	3.83

To conclude, low-performance RPAS are sensitive to changes in the weights associated to the procedure of selecting the best performing case. Depending on the importance given to safety and efficiency, different candidates are selected to be the best performing case. However, this analysis has been done mathematically, and the resulting best case of 1B_1 does not appear to be feasible when other operational aspects are considered. This would lead to additional challenges such as sharing the lower part of the busiest airspace with manned aviation, the consequences of contingency issues, etc. The amentioned trade-off between the KPAs should be made beforehand in order to establish the best combination of operational and performance requirements for low-performance RPAS.

8

Application to a Mixed Scenario

This scenario, named "Scenario 2", is aimed at verifying the challenge of integrating RPAS in a safe and efficient manner in non-segregated airspace. The scenario is based on a hypothetical future scenario where both types of RPAS are operating together sharing the airspace with manned aviation. The following considerations are applied:

- The requirements obtained from Scenarios 1A and 1B are assumed to be in place.
- The percentage of RPAS is kept to 20%. The replacement is applied only to en-route flights.
- Air traffic growth is set to +15%. Prediction of long-term planned flights are known to be inaccurate. Normally the demand is obtained on short-term based on the intentions and flight plans. The latest forecast performed by EUROCONTROL (STATFOR) covers up to 2035 [80]. The most-likely scenario foresees 50% more flights in 2035 than in 2012. Gathering data for the same period of time (10:00-11:00) for the different Tuesdays that belong to the corresponding AIRAC cycle for 2012 (AIRAC 1206), the following values of the demand are obtained:
    - Minimum value : 53. Applying a 50% growth → 79.5.
    - Maximum value : 62. Applying a 50% growth → 93.
    - Computing the average between both values, the resulting demand is **86**, which turns out to be 15% more than the number of flights of 2016.
- The same percentage of cruise flights than in the base scenario is maintained: 64%. This means that 55 flights are cruising while the remaining 31 are either climbing or descending while crossing the airspace sector.
- Capacity value is modified. The initial value that has been assessed by the french ANSP (DSNA) is 48. It has been reduced along the project to simulate the current impact of having a mixed traffic and higher latency than for commercial aviation. Nevertheless, in a future scenario controllers are expected to be used to handle mixed environments and ATM systems would improve their characteristics and performance, which eventually would improve the capacity and the efficiency of the ATM Network. These points allow to restore the capacity value to, at least, the minimum that is initially declared: 48 AC/h. An increase in capacity could have been considered but regarding the amount of flights that have been already handled in previous dates (varying from 37 up to 93), this capacity is considered suitable for this scenario. Moreover, since 2010 this capacity has been maintained the same. It should be noted that only one sector is being considered, but there is a possibility of splitting this sector into the different subsectors in order to handle more traffic. The purpose of this sectorization is to decompose the provision of ATS into tasks that are manageable for ATCos, within the nominal workload threshold. However, this sectorization process falls into the appropriate ANSPs' responsibilities which is out of the scope of this thesis.

In view of the preceding considerations, the number of RPAS to be integrated is 11 (20% of the 55 cruising flights). The proportion in which both types are divided is chosen arbitrarily through an algorithm in Matlab to select a number within the interval [1,11] resulting in 6 RP01 and 5 RP02. The goal of this scenario is to have an overview of what would happen in the future when RPAS will be operating in non-segregated airspace. That is the reason why only one study-case is considered. This scenario can only be developed once the requirements for both types of RPAS have been established.

The process followed to obtain the values of the indicators is the same as for scenarios 1A and 1B (Chapter 6). Table 8.1 collects the information about the RPAS replacements:

Table 8.1: Set of flights replaced by RPAS for Scenario 2.

Call Sign	RPAS type	Origin	Destination	Original cruise level	AS FL
EZY56HP	RP01	LFMN	EGGW	380	420
IBK9479	RP01	LEPA	EGKK	400	400
AMC215B	RP01	EGTE	LMML	390	410
TCX21PM	RP01	LEPA	EGSH	360	400
MINER	RP01	EGLF	LIRI	410	410
JTI111	RP01	EGGW	LIRS	310	290
GAF120	RP02	LIED	EDDK	220	220
AOV7770	RP02	LFPB	LFLS	270	270
RYR35JD	RP02	LFLM	LFQQ	340	300
N900BT	RP02	LFSB	LFPB	240	240
HOP8670	RP02	LFLC	LFPG	180	200

The results obtained for the indicators are presented in Table 8.2, including the results of the base scenario that has been used until now:

Table 8.2: Comparison between Base Scenario and Scenario 2.

Scenario	# of flights	Traffic demand	KPI01	KPI02	KPI03	KPI04	KPI05
BS	75	65	48	17	-131.21	-16.88	1
2	86	76	48	28	-218.41	-26.55	14

By analysing the results, it is found that efficiency in terms of flight time and flight path become worse: on average, cruise flights are spending 1’27" more in the sector and the route, 10 NM longer than the initial ones. The increase in the number of aircraft for the same volume of airspace has proved to have an impact on efficiency and safety. The increase in the safety indicator cannot be compared directly with the value of the base scenario, as there were ATCo decisions involved to resolve the conflicts, while there is no controller in the loop in Scenario 2. However, this value can be compared with the results of the best performing case of Scenario 1A ($KPI05_A$=11.96 AC/h) and Scenario 1B ($KPI05_B$=13.53 AC/h), which shows a slight worsening compared to both scenarios. Although same-performance RPAS are mainly operating above FL400 and low-performance RPAS below FL300, the increase in the number of airspace users has an impact on the number of potential conflicts detected: the same volume of airspace is shared among a greater amount of users.

These facts reflect one of the main trade-offs in aviation: safety and capacity (increase in capacity leads to higher volumes of traffic and higher number of potential conflicts detected). These values could be maintained for shorter period of times or under special circumstances, but not as nominal and sustained values.

The negative impact of future unmanned operations (both types operating simultaneously with manned aviation) is unavoidable. Even with the implementation of operational and performance requirements, four out of five indicators have worsen their values. Each ANSP should assess the outcome of this methodology in order to see if further restrictions are needed for their sectors to keep on reducing the impact: the number of RPAS (more or less than 20%), the type of RPAS (same-performance, low-performance or both types).

PART IV

CONCLUSIONS AND RECOMMENDATIONS

9

Conclusions and Recommendations

This chapter includes in Section 9.1 the main conclusions obtained after the research performed for this project. Recommendations for future work related to this topic are given in Section 9.2.

9.1. Conclusions

The significance of this project relies on the contribution to achieve a successful integration of RPAS operating in non-segregated airspace. From the three typical flight phases (en-route, terminal and approach), it covers the en-route phase but paves the way for the other two.

Regulations, operational procedures and requirements for RPAS lag behind the rapid grow of their technology and their expansion to a wide variety of applications and markets. Most of the key aspects (DAA systems, C2 link or contingency procedures) are still on a early stage without any certification or standardization. But the work done in this project aims to establish the methodology needed to assess minimum performance and operational requirements. Analysing the entire Network is not feasible as these requirements cannot be generalized. Therefore, the methodology is focused on a case study in Paris CTA.

For the same reason, the outcome (specific cruise speed and/or rate of climb) is not expected to be directly applied: each ANSP should apply this methodology to their own sectors and determine the optimum values although they can be used as a reference. As is done for manned aviation, these values should be contained in the appropriate AIP in order to be publicly available for all the users. To some extent, this process is comparable to the establishment of minimum altitudes defined for some waypoints or routes, or minimum cruise speed for certain routes or part of them. It is responsibility of each ANSP to set these requirements based on the specific characteristics of the airspace at issue.

Nevertheless, not only minimum performance requirements need to be assessed by the ANSPs but also the limits of the altitude segregation rules. It has been established that the busiest part of the airspace is kept between FL300 and FL400, though these limits could differ from one sector to another. Taking advantage of the recent development of the Collaborative Decision Making (CDM) concept in aviation, the operator or the remote pilot and the controllers could agree on the most convenient FL for their intended operation considering the time, date and sectors of the operation.

RPAS are very wide by varying in terms of performance. However, limited data regarding RPAS performance is available. From the four available models in BADA, two of them have been selected: one with the same performance than manned aviation (same-performance RPAS), which corresponds to an RQ4A, and a second profile, low-performance RPAS, which corresponds to an MQ-9.

The most critical areas within the predefined Key Performance Areas are capacity, safety and efficiency. Different indicators have been used in order to assess the impact on the ATM Network: capacity and sector overload (from the capacity area), flight time extension and flight path extension (from efficiency) and number of potential conflicts, as the main indicator of safety. The first two, capacity and sector overload, have been maintained constant along the project while the later three have resulted in variations while imposing different constraints.

Nowadays a mixed traffic is something completely new to the airspace users (especially to ATCos), while in a few years time they will be more used to handle this combination of unmanned and manned aviation. The impact of mixed traffic has been considered as one of the main factors in reducing capacity. Latency has been also taken into consideration when assessing the capacity. Latency is found to be the most critical aspect that affects capacity since the increase in the total latency lead to a decreased in capacity. The value of latency is completely independent on the performance characteristics of the RPAS. It only depends on the type of communication between ATC and the RP (voice/data and the communication architecture), the number of RPAS, and the maximum values of latency accepted.

If RPAS would be integrated in the ATM Network as it is now, the first impact would be on capacity and, by extension, sector overload. However, when analysing the substitution of both types of RPAS, RP01 in Scenario 1A and in Scenario 1B, both efficiency and safety have suffered. Safety is the area most penalized when introducing same-performance RPAS while both areas, safety and efficiency, are dramatically impacted when introducing low-performance RPAS. This fact proves that RPAS will need to comply with certain performance and operational requirements to achieve the same levels of safety, efficiency and capacity as they are now for manned aviation.

Monte Carlo simulations of air traffic have been performed in order to vary randomly the main input parameter of the project, that is the set of flights selected for substitution. For same-performance RPAS, the requirements that have been obtained from the best performing case are a combination of altitude segregation rules and a minimum cruise speed of 390 kts. On the other hand, for low-performance RPAS the best combination is altitude segregation rules, a minimum cruise speed of 280 kts and a minimum ROC of 1,000 fpm.

The outcome of the stochastic model has proved that even with these requirements in place, the impact on the Network is unavoidable. Even though integration seems to be the only feasible solution for a large amount of RPAS sharing the airspace with manned aviation, an impact on the Network will be always present. The establishment of operational and performance requirements contributes to reduce this impact, but as it has been proved, the initial values of the KPIs for the base scenario are very difficult to reach when RPAS operations are integrated in non-segregated airspace.

The case study, where both types of RPAS are sharing the airspace with manned aviation and a traffic growth has been applied, shows that the establishment of these performance and operational requirements is not enough to avoid an impact on the ATM Network. Four out of the five KPIs are negatively affected, which makes this situation infeasible for long periods of times.

New polices should be developed to improve the efficiency and safety. Current research is coming up with solutions such as changing airspace-user charges to trajectory-use charges (i.e. aircraft operators would be offered a range of routes with different costs based on the characteristics of each route and the services required) or the recently initiative denoted as Flight Efficiency Initiative, aimed at offering the most efficient routes on the same day of operation to aircraft operators.

The development of this methodology and its application to each airspace sector or traffic volume, has brought us one step closer to a full integration of unmanned aircraft into non-segregated airspace. Nonetheless, when integrating their operations, RPAS must be compliant with the rules of the air and the integration principles. Based on the results of this project, it can be established that minimum operational and performance requirements for unmanned operations will reduce the negative impact on the ATM Network. However, the integration of their operations is not fully compliant with the integration requirements: they are not as safe as manned aviation nor transparent to ATC and to other airspace users. Therefore, procedures, rules and polices have to be developed in order to further reduce this negative impact.

9.2. Recommendations for future work

There are several aspects regarding integration of RPAS in non-segregated airspace that have not been addressed in this project. Most of them have been identified, which keeps the door open to future research projects. Firstly, this project has covered only the en-route flight phase. A similar research could be performed for the other flight phases, terminal and approach. However, at this stage it might be too early to analyse in depth the approach part to conventional airports. So far, it is not foreseen to take-off or land at medium to big size airports with high levels of traffic. Most of these big airports (such as Amsterdam Schiphol, Paris Charles de Gaulle or London Heathrow) present congested levels and problems to balance demand and capacity. If apart from adding extra demand, dedicated infrastructure and training for controllers is needed, the impact on the daily operation of these airports will be huge. However, the climbing and descending part before reaching the cruise level could be investigated as a separate project.

Regarding wake turbulence, RPAS are known for being more sensitive to wake turbulence than manned aviation (especially the ones that have a low MTOW). The situation is worsened if the meteorological conditions are bad or in presence of wind. Following ICAO guidance [81], many countries have already adopted a time separation of 4 minutes and a wake turbulence radar separation minimum of 8 NM for those cases of a light aircraft following a super heavy aircraft (A380). A similar case-study should be performed for RPAS in order to include a new wake turbulence category (as it has been done for the A380) and to redefine the separation criteria to account for this new type of airspace user. This study would be the base for ANSPs and ATCos to provide enough separation when flying in front of, behind, or next to an RPAS.

Since the beginning of the thesis, it has been claimed that there are no requirements for latency in place yet, and nonetheless RPAS are already operating. Maximum acceptable values for latency, accounting for the different types of communication architectures, should be established to avoid increasing controllers' workload. This fact is linked to separation minima. Within this project, standard separation minima have been used. Further research about the influence of latency on separation minima and the possibility of establishing different values for separation depending on the maximum acceptable latency should be carried out.

Furthermore, separation minima can be also be investigated for different contingency issues. Depending on the type of contingency (C2 link loss, ATC communication failure, etc.) different thresholds of separation minima could be established. If for example an RPAS is operating in nominal conditions, the separation minima could be kept as it is for manned aviation (as has been done in this project). But when a C2 link loss occurs, one of the solutions to keep the operation safe and to avoid affecting the surrounding traffic could be to momentously increase the separation minima until the problem is solved. If the problem is not solved, the increased separation minima will be maintained but the RPA will follow the pre-established contingency procedure (and ATC will be aware of it). This also leads to another possible line of investigation, the establishment and standardization of contingency procedures.

On a more technical level and apart from the previously mentioned operational issues, the standardization of DAA systems to overcome the traditional "see and avoid" limitation and the C2 link service development (among many other technical gaps) needs to be researched. Development of new and none generically applicable performance models would be very useful in order to account for the variability of RPAS in future simulations.

In view of this discussion, it is clear that research and development projects are needed in order to achieve a safe integration of RPAS in non-segregated airspace.

PART V

ANNEXES

A

BADA Limitations

BADA, Base of Aircraft Data is one of the main aircraft performance model that has been used in most of the ATM research projects that require modelling and simulating aircraft performance. It has been developed by EUROCONTROL in cooperation with manufacturers and airlines. Even though there are already two set of families, BADA 3 and BADA 4, regarding RPAS only one package has been released until now. This package has modelled only four RPAS as they are presented in Chapter 2. This scarce number of unmanned models available is one of the main limitations of the problems, although from the four of them, two have been found to meet the requirements for the different scenarios. In fact, RPAS are very wide in terms of performance and it is not represented in the variety of RPAS models defined. For example, it could be the case of an RPAS cruising at 20-50 kts but at an altitude where commercial aviation operates, or on the contrary, a very fast RPAS whose ceiling is very low and thus, it will share the airspace with commercial aviation, gliders and so on.

Apart from the limitation in the number of RPAS available, there are other aspects that need to be considered:

- There are only three types of engines defined in BADA: Jet, turboprop and piston which cover the main and most used types. However, especially for RPAS, different types of engines might be required to be defined: rocket, diesel or electric. By default, if the type of engine that the aircraft has is not within the predefined types, the model is substituted by the engine corresponding to the B737-800 (jet type).
- Inconsistencies between the maximum operating airspeed (V_{MO}) contained in the OPF file and the cruise speeds in the release note [18]:

	RP01	**RP02**	**RP03**	**RP04**
V_{MO} (.OPF file)	320 kts	260 kts	145 kts	110 kts
Cruise speed (release note)	335 kts	200 kts	90 kts	85 kts
Cruise speed (.APF file)	200 kts	150 kts	70 kts	70 kts

  Table A.1: Differences in cruise speed

  Further details about how they have been obtained are needed (altitude, weight, etc.), especially for RP01. By taking a look at the RP01 column, the cruise speed published in the release note is bigger than the one in the OPF file, while for the rest of RPAS this is not the case.
- RP02 has a declared ceiling of 50,000 ft (this data coincides in the release note and in the OPF file). However, the cruise/clim/descent performance data included in the PTF file is not consistent. The cruise performance is defined up to FL500 for the three types of MTOWs (low, nominal and high) and the descent profile is defined for the nominal mass model up to FL500. Nevertheless, the climb profile is defined up to FL310 for nominal MTOW, FL390 for low MTOW and FL280 for high MTOW. Then, how is it possible to cruise or descent at FL500 if the climbing limit is set to FL310? That is the reason why the ceiling of this RPAS during the development of the project has been limited to FL310: since there is no climbing performance data defined for altitudes higher than FL310, the ceiling is limited.

- Although RP04 has not been used in this project, it presents a similar issue with the data gathered in the PTF file and the declared ceiling. The ceiling is set to FL150 but the climbing is limited to FL100 (for nominal MTOW).

Flight Phase	**RP02**				**RP04**			
	Low (OPF)	**Nominal (OPF)**	**High (OPF)**	**Ceiling (APF)**	**Low (OPF)**	**Nominal (OPF)**	**High (OPF)**	**Ceiling (APF)**
Cruise	FL500	FL500	FL500		FL150	FL150	FL150	
Climb	FL390	FL310	FL280	FL500	FL140	FL100	FL100	FL150
Descent	-	FL500	-		-	FL150	-	

Table A.2: Inconsistencies found in BADA for RP02 and RP04

When modelling aircraft performance, the main source of information is the AOM (aircraft operating manual) provided by the manufacturers. However, three of the four RPAS modelled in BADA are for military uses, which makes difficult to access their information. Their AOM is not publicly available. To solve this problem, there is a modified identification approach that is based on a flight simulator and the creation of an accurate aerodynamic model based on the blade element theory [82]. If data obtained from the simulator that has been developed to tackle the lack of data regarding their performance could be verified with real data, the accuracy of the models would improve and these limitations could be resolved.

B

CAPAN Methodology

B.1. LFFLMHJ

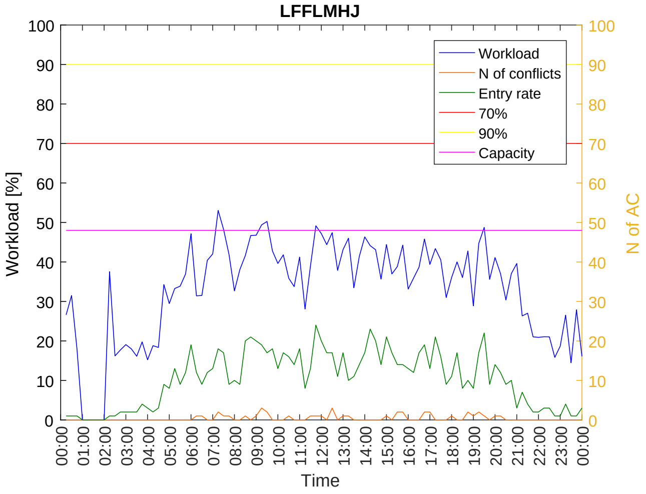


Figure B.1: Workload distribution for the sector LFFLMHJ.

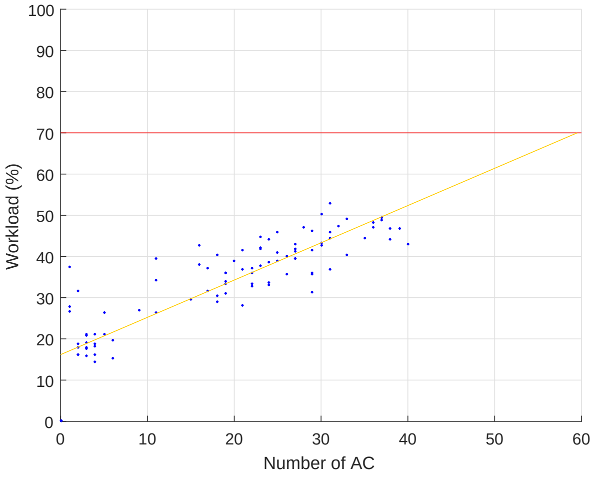
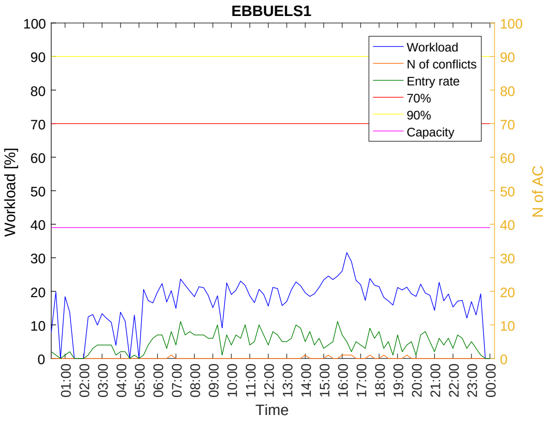
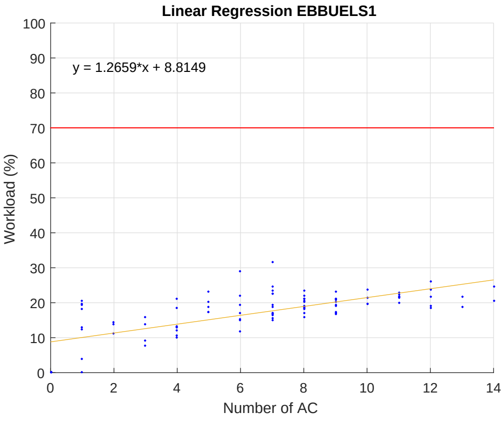


Figure B.2: CAPAN method for LFFLMHJ traffic volume.

B.2. EBBUELS1

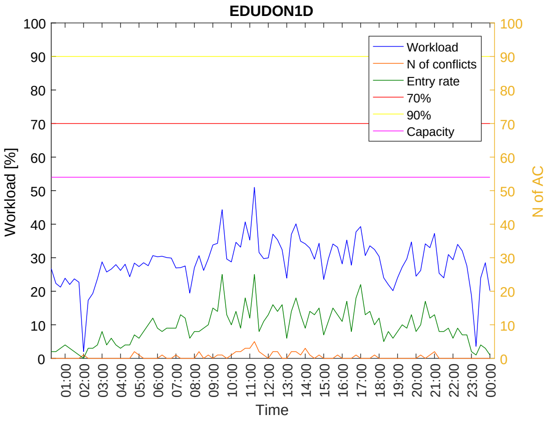


(a) Workload diagram

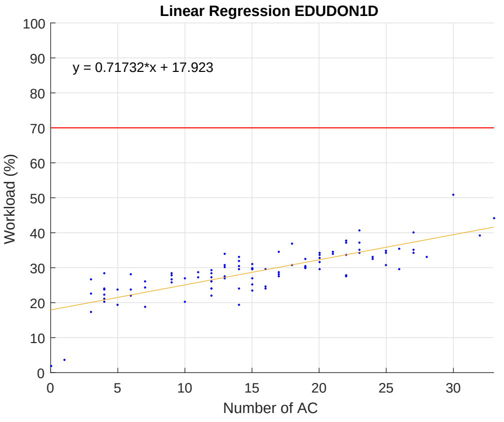


(b) Linear regression

B.3. EDUDON1D

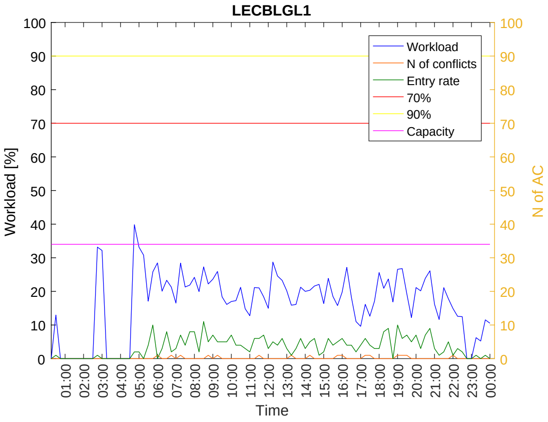


(a) Workload diagram

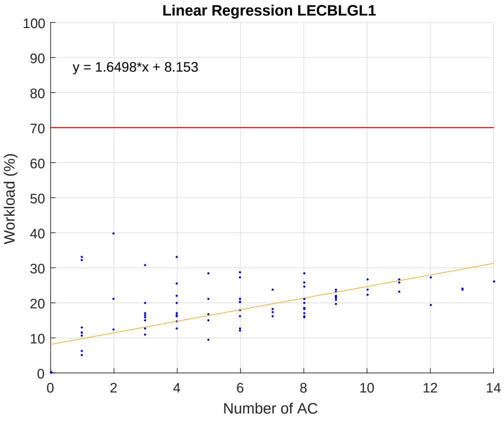


(b) Linear regression

B.4. LECBLGL1

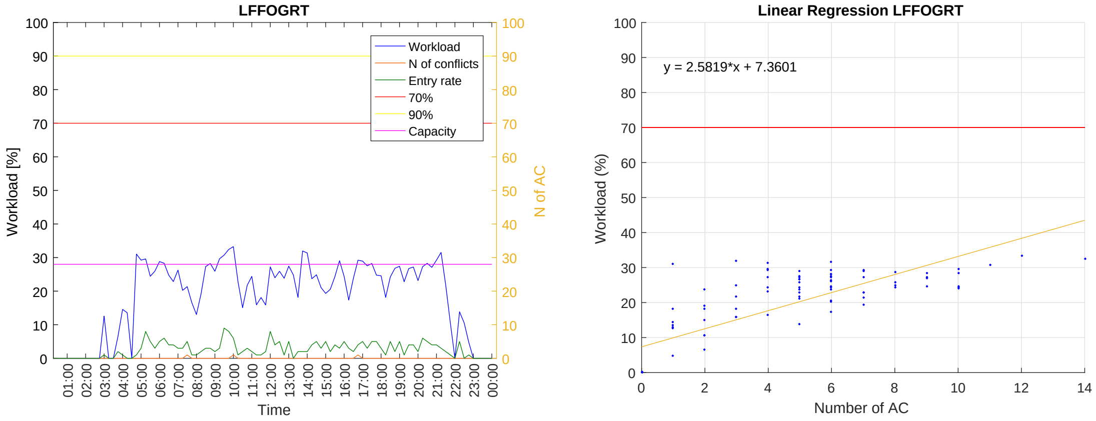


(a) Workload diagram



(b) Linear regression

B.5. LFFOGRT



(a) Workload diagram (b) Linear regression

B.6. Correlation

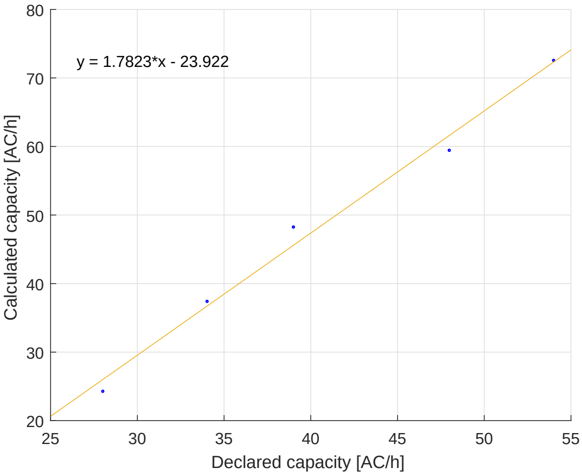


Figure B.7: Correlation between the declared capacity and the calculated capacity

C

Monte Carlo Simulations

C.1. Monte Carlo Applied to SIM Designer

NEST includes a tool called SIM Designer which allows to design and to automate the tasks needed for the simulations. They are based on two main features: processes (represented as square boxes) and data blocks (blocks with rounded corners). The latter are used as input/output for the processes. For this project, Figure C.1 shows all the blocks that are needed for the simulations and the flow between them

The main processes are the following:

- **Environment**, which gathers information regarding airport, waypoints, sectors, routes, etc. from the desired Network file.
- **2D traffic**, which finds and assigns the routes to the traffic. This process includes the functionality necessary to avoid traffic to cross different sectors than the original one.
- **4D trajectory**: from the 2D file generated after the previous process, 4D trajectories are calculated. Constraint files can be attached to this process which has been used to limit the FL (Flight level constraints) in order to force the climbing or to verify that altitude segregation rules are applied.
- **Recombine Missing Flights**: there might be some flights that cannot comply with some network constraints that are called missing flights. A small percentage of flights fall within this category. This module recombines the assigned traffic with the missing flights, providing the *.so6* traffic file necessary to compute the number of conflicts.
- **Airspace/Traffic information**: provides information about the intersection of traffic and the desired airspace volumes. This process provides as an output the *.t5* file that is used to calculate KPI03 and KPI04.

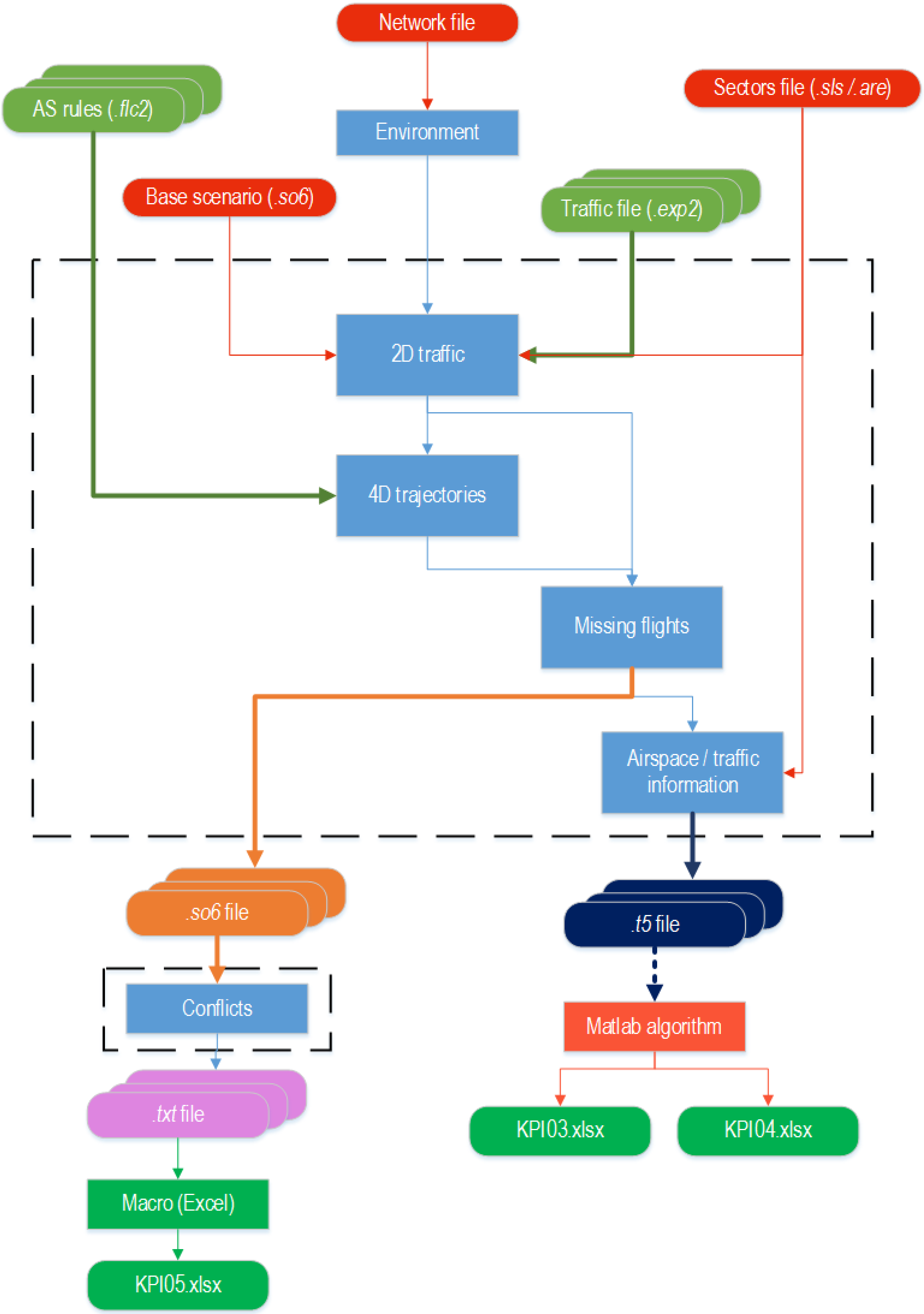


Figure C.1: Block diagram Monte Carlo simulations in SIM Designer

C.2. Pseudo-Code for the Selection of the Set of Flights

Algorithm 1 Replacement of unmanned flights

```
Input: flight_list.xlsx
Get (for ENR flights): origin, destination, cruise_level, ENR_ID
Get (for all flights): flight_ID

Procedure: Correlation between ENR_ID & flight_ID
% ENR flights go from 1 to 48; Total flight list goes from 1 to 75.
for i=1:48 do
    pos=find (ENR _ID == flight_ID) ← pos=Flight _number
    write [i origin destination cruise_level ENR_ID Flight_number]
end for

Procedure: Random selection of flight numbers to be replaced by RPAS
for n=1:300 do
    Generate randomly 10 numbers ∈ [1,48] ← ENR_f_number
    Check no numbers are repeated
    while ∃ Repeated numbers do
        Generate again the sequence
    end while
    for all ENR_f_number do
        Find: origin (origin_replacement); destination (destination_replacement); ID (flight_ID); RFL (FL_replacements)
        Write Replacement_Matrix=[ENR_f_number origin_replacement destination_replacement flight_ID FL_replacements]
    end for

    Procedure: Assignation of FL (for same performance RPAS)
    for  k=1:1:10 do
        if (FL_replacements(k)>300)&&(FL_replacements(k)<400) then
            if FL_replacements(k)>350 then
                if FL_replacements(k)==360 then
                    FL_replacements(k)=400;
                else if FL_replacements(k)==380 then
                    FL_replacements(k)=420;
                else
                    optiono=[410 430];
                    pos_optiono = randi(length(optiono));
                    FL_replacements(k) = optiono(pos_optiono);
                end if
            else if FL_replacements(k)<350 then
                if (FL_replacements(k) == 310) || (FL_replacements(k) == 330) then
                    optione2=[290 290];
                    pos_optione2 = randi(length(optione2));
                    FL_replacements(k) = optione2(pos_optione2);
                else
                    optiono2=[280 280];
                    pos_optiono2 = randi(length(optiono2));
                    FL_replacements(k) = optiono2(pos_optiono2);
                end if
```

```
44:             else if FL_replacements(k)==350 then
45:                 FL_replacements(k)=290;
46:             end if
47:         end if
48:     end for

49:     Procedure: Write Flight Level Constraints
50:     Open txt file for writing
51:     for index=1:10 do
52:         var=ENR_f_number(index);
53:         fprintf "if(DEP / origin_replacement(index)/ &&ARR / destination_replacement(index)/ &&$3==0)FL_CONT=
54: FL_replacements(index)";
55:     end for
56:     Close file and save it as .flc2

57:     Procedure: Modification of the traffic file
58:     Input: traffic_demand.exp2
59:     %Replacement of AC_type based on Flight ID
60:     for r1=1:1:10 do
61:         [row]=find(flight_ID(r1));
62:         Modify AC type(row)==('RP01');
63:     end for

64:     %Replacement of the RFL based on Flight ID and the FLC (FL_replacements)
65:     for r2=1:1:10 do
66:         [row2]=find(flight_ID(r1));
67:         Modify RFL(row2)==FL_replacements(r2);
68:     end for
69:     Close file and save it as .exp2
70: end for
```

In order to use this code for the replacement of the lower performance RPAS, the following changes are needed:

- Altitude segregation (replace lines 22-48 with the following code):

Algorithm 2 Altitude segregation for RP02

```
 1: for k do=1:1:10
 2:     if (FL_replacements(k)>300) then
 3:         FL_2ci=FL_replacements(k)/10;
 4:         if mod( FL_2ci,2) == 0 then
 5:             optiono=[300 280];
 6:             pos_optiono = randi(length(optiono));
 7:             FL_replacements(k) = optiono(pos_optiono);
 8:         else
 9:             FL_replacements(k)=290;
10:         end if
11:     end if
12: end for
```

- RPAS type (replace line 62 with the following code): Modify AC type(row)==('RP02');

C.3. Pseudo-Code for the Calculation of KPI03 and KPI04

Algorithm 3 KPI03 and KPI04

```
Input: initial_traffic_demand.t5
Get initial data: flight_ID; entry_FL_i; exit_FL_i; crossing_dist_i; crossing_time_i.

Procedure: Filter ENR traffic
if (entry_FL_i-exitFL_i) $\in$ [-20,20] then
    Store info: ENR_info=[flight_ID crossing_dist_i crossing_time_i]
end if

Procedure: Gather data per collapsed sector
% Information is provided per elementary sector. It is necessary to convert the data to get the information per collapsed sector.
Create auxiliary matrix (copy of ENR_info = aux)
for i do=1:size(aux,1)
    find(aux(i,1))==ENR_info
    % To see if there are repeated elements which means that there are flights crossing more than one elementary sector.
    if $\nexists$ repeated then
        Store information
    else
        for each repeated element (per flight) do
            Add crossing_time_i & crossing_distance_i
        end for
    end if
end for
Return: flight_ID_Initial
Return: crossing_time_Initial
Return: crossing_distance_Initial

Procedure: Calculation of KPIs
for for n=1:300 do
    Input: actual_traffic_demand_n.t5
    Repeat same procedure as for the initial traffic file
    Return: flight_ID_Actual_n
    Return: crossing_time_Actual_n
    Return: crossing_distance_Actual_n
    Check which flights are in both lists
    for l=1:max(size(flight_ID_Initial,1),size(flight_ID_Actual_n,1) do
        if If flights are in both lists (initial and actual) then
            duration_1A(l)=crossing_time_Initial - crossing_time_Actual_n
            length_1A(l)=crossing_distance_Initial - crossing_distance_Actual_n
            Store result
        end if
    end forKPI03_1A(n,1)=mean(duration_1A); KPI04_1A(n,2)=mean(length_1A);
end for
```

C.4. Scenarios Matrix

Scenario	RPAS TYPE	AS	Cruise Speed [kts]																	ROC [fpm]				Requirements	
			Nom	210	220	230	240	250	260	270	280	290	300	350	360	370	380	390	400	250	500	750	1000	OPER	PERF
1A_1	RP01		✓																						
1A_2	RP01	✓	✓																					✓	
1A_3_1	RP01	✓												✓										✓	✓
1A_3_2	RP01	✓													✓									✓	✓
1A_3_3	RP01	✓														✓								✓	✓
1A_3_4	RP01	✓															✓							✓	✓
1A_3_5	RP01	✓																✓						✓	✓
1A_3_6	RP01	✓																	✓					✓	✓
1A_3_7	RP01																		✓						✓
1A_3_8	RP01																	✓							✓
1B_1	RP02		✓																						
1B_2	RP02	✓	✓																					✓	
1B_2_A	RP02	✓	✓																	✓				✓	✓
1B_2_B	RP02	✓	✓																		✓			✓	✓
1B_2_C	RP02	✓	✓																			✓		✓	✓
1B_2_D	RP02	✓	✓																				✓	✓	✓
1B_3_1	RP02	✓		✓																				✓	✓
1B_3_2	RP02	✓			✓																			✓	✓
1B_3_3	RP02	✓				✓																		✓	✓
1B_3_4	RP02	✓					✓																	✓	✓
1B_3_5	RP02	✓						✓																✓	✓
1B_3_6	RP02	✓							✓															✓	✓
1B_3_7	RP02	✓								✓														✓	✓
1B_3_7_A	RP02	✓								✓										✓				✓	✓
1B_3_7_B	RP02	✓								✓											✓			✓	✓
1B_3_7_C	RP02	✓								✓												✓		✓	✓
1B_3_7_C	RP02	✓								✓													✓	✓	✓
1B_3_8	RP02	✓									✓													✓	✓
1B_3_8_A	RP02	✓									✓									✓				✓	✓
1B_3_8_B	RP02	✓									✓										✓			✓	✓
1B_3_8_C	RP02	✓									✓											✓		✓	✓
1B_3_8_D	RP02	✓									✓												✓	✓	✓
1B_3_9	RP02	✓										✓												✓	✓
1B_3_10	RP02	✓											✓											✓	✓

D

Results of the Stochastic Model

D.1. Scenario 1A

D.1.1. Parameter estimation - Scenario 1A

Table D.1: Results of the stochastic model for Scenario 1A.

Scenario	Change	KPI	Mean	σ_x	MOE	LB_CI	UB_CI
1	Replacement	03	-124.30	8.51	0.96	-125.27	-123.34
		04	-10.14	-	-	-	-
		05	14.82	2.26	0.256	14.56	15.07
2	AS	03	-233.5	24.73	2.81	-236.66	-230.71
		04	-22.73	2.83	0.32	-22.45	-22.40
		05	12.21	2.06	0.23	11.97	12.44
3_1	350 kts + AS	03	-226.17	23.14	2.62	-228.79	-223.55
		04	-22.75	2.74	0.31	-23.06	-22.44
		05	12.29	2.09	0.24	12.06	12.53
3_2	360 kts + AS	03	-222.49	22.88	2.59	-225.08	-219.90
		04	-22.75	2.74	0.31	-23.06	-22.44
		05	12.20	2.20	0.25	11.95	12.45
3_3	370 kts + AS	03	-218.25	22.60	2.56	-220.81	-215.69
		04	-22.75	2.74	0.31	-23.06	-22.44
		05	12.04	2.20	0.25	11.79	12.29
3_4	380 kts + AS	03	-214.23	22.37	2.54	-216.76	-211.69
		04	-22.75	2.74	0.31	-23.06	-22.44
		05	12.18	2..11	0.24	11.94	12.42
3_5	390 kts + AS	03	-210.35	22.20	2.51	-212.86	-207.84
		04	-22.75	2.74	0.31	-23.06	-22.44
		05	11.96	1.95	0.22	11.74	12.09
3_6	400 kts + AS	03	-206.39	22.05	2.50	-208.89	-203.89
		04	-22.75	2.74	0.31	-23.06	-22.44
		05	12.33	2.11	0.24	12.09	12.58
3_7	400 kts	03	-99.62	6.06	0.69	-100.31	-98.93
		04	10.14	-	-	-	-
		05	13.87	2.18	0.25	13.61	14.11
3_8	390 kts	03	-103.14	6.24	0.71	-103.85	-102.43
		04	10.14	-	-	-	-
		05	14.55	2.09	0.25	14.30	14.80

D.2. Scenario 1B

D.2.1. Parameter estimation - Scenario 1B

Table D.2: Results of the stochastic model for Scenario 1B (Cruise speed).

Scenario	Change	KPI	Mean	σ_x	MOE	LB_CI	UB_CI
1	Replacement	03	-275.91	34.66	3.95	-279.86	-271.96
		04	-23.75	3.81	0.43	-24.18	-23.32
		05	13.06	1.93	0.22	12.83	13.27
2	AS	03	-344.92	35.28	4.03	-348.94	-340.89
		04	-24.01	3.75	0.42	-24.43	-23.58
		05	13.68	2.39	0.27	13.40	13.95
3_1	210 kts + AS	03	-315.21	31.35	3.59	-318.80	-311.62
		04	-22.02	3.33	0.38	-22.40	-21.64
		05	13.63	2.25	0.26	13.37	13.88
3_2	220 kts + AS	03	-302.65	30.02	3.44	-306.08	-299.21
		04	-22.02	3.33	0.38	-22.40	-21.64
		05	13.34	2.22	0.25	13.08	13.58
3_3	230 kts + AS	03	-292.12	29.05	3.33	-295.44	-288.79
		04	-22.01	3.33	0.38	-22.38	-21.63
		05	13.41	2.11	0.2	13.18	13.66
3_4	240 kts + AS	03	-282.29	28.21	3.23	-285.52	-279.06
		04	-22.02	3.33	0.38	-22.40	-21.64
		05	13.66	2.17	0.25	13.41	13.90
3_5	250 kts + AS	03	-274.30	29.96	3.39	-277.69	-270.91
		04	-22.02	3.33	0.38	-22.40	-21.64
		05	13.67	2.22	0.25	13.41	13.92
3_6	260 kts + AS	03	-265.45	27.8	3.18	-268.64	-262.28
		04	-22.02	3.33	0.38	-22.40	-21.64
		05	13.54	2.23	0.25	13.29	13.79
3_7	270 kts + AS	03	-257.68	27.38	3.12	-260.80	-254.56
		04	-22.02	3.33	0.38	-22.40	-21.64
		05	13.54	2.23	0.25	13.29	13.79
3_8	280 kts + AS	03	-250.22	26.96	3.07	-253.29	-247.15
		04	-22.02	3.33	0.38	-22.40	-21.64
		05	13.53	2.25	0.25	13.27	13.78
3_9	290 kts + AS	03	-245.80	27.15	3.08	-248.89	-242.72
		04	-22.35	2.98	0.34	-22.69	-22.01
		05	13.89	2.43	0.27	13.62	14.14
3_10	300 kts + AS	03	-239.31	25.50	2.89	-242.21	-236.42
		04	-22.35	2.98	0.34	-22.69	-22.01
		05	14.29	2.38	0.27	14.02	14.56

Table D.3: Results of the stochastic model for Scenario 1B (ROC).

Scenario	**Change**	**KPI**	**Mean**	σ_x	**MOE**	**LB_CI**	**UB_CI**
2_A	AS + 250 fpm	03	-293.63	40.57	4.61	-298.25	-289.02
		04	-23.74	4.22	0.48	-24.21	-23.26
		05	13.54	2.52	0.29	13.25	13.83
2_B	AS + 500 fpm	03	-293.65	40.57	4.61	-298.27	-289.04
		04	-23.74	4.22	0.48	-24.22	-23.26
		05	13.57	2.22	0.25	13.32	13.82
2_C	AS + 750 fpm	03	-293.17	40.67	4.63	-297.80	-288.55
		04	-23.74	4.22	0.48	-24.22	-23.26
		05	12.72	2.14	0.24	12.47	12.96
2_D	AS + 1000 fpm	03	-293.63	40.16	4.58	-298.21	-289.21
		04	-23.73	4.21	0.48	-24.22	-23.26
		05	12.73	2.14	0.24	12.49	12.98
3_7_A	AS + 270 kts + 250 fpm	03	-247.30	35.83	4.07	-251.37	-243.22
		04	-23.74	4.22	0.48	-24.22	-23.26
		05	13.90	2.70	0.31	13.59	14.20
3_7_B	AS + 270 kts + 500 fpm	03	-247.21	35.84	4.08	-251.28	-243.13
		04	-23.74	4.22	0.48	-24.22	-23.26
		05	14.12	2.53	0.29	13.83	14.41
3_7_C	AS + 270 kts + 750 fpm	03	-246.82	35.81	4.07	-250.89	-242.75
		04	-23.74	4.22	0.48	-24.22	-23.26
		05	13.95	2.40	0.27	13.68	14.22
3_7_D	AS + 270 kts + 1000 fpm	03	-246.85	35.84	4.08	-250.92	-242.77
		04	-23.74	4.22	0.48	-24.22	-23.26
		05	13.26	2.24	0.25	13.01	13.52
3_8_A	AS + 280 kts + 250 fpm	03	-242.42	35.48	4.04	-246.45	-238.38
		04	-23.74	4.22	0.48	-24.21	-23.26
		05	13.81	2.66	0.30	13.51	14.11
3_8_B	AS + 280 kts + 500 fpm	03	-242.34	35.49	4.04	-246.38	-238.30
		04	-23.74	4.22	0.48	-24.21	-23.26
		05	14.27	2.56	0.29	13.98	14.56
3_8_C	AS + 280 kts + 750 fpm	03	-241.93	35.57	4.04	-245.97	-237.88
		04	-23.74	4.22	0.48	-24.21	-23.26
		05	13.08	1.97	0.23	12.85	13.30
3_8_D	AS + 280 kts + 1000 fpm	03	-241.97	35.49	4.04	-246.00	-237.93
		04	-23.74	4.21	0.48	-24.22	-23.26
		05	13.03	2.21	0.25	12.78	13.28

D.2.2. Hypothesis testing KPI03 - Scenario 1B

Table D.4: Games-Howell test result for Analysis C of KPI03 - Scenario B

Subscenario I	Subscenario J	Mean Difference (I-J)	Std. Error	p-value
2_A	2_B	0.02	3.33	1.00
	2_C	-0.46	3.33	1.00
	2_D	0.00	3.32	1.00
3_7_A	3_8_A	-4.88	2.93	0.88
	3_7_B	-0.09	2.94	1.00
	3_8_B	-4.96	2.93	0.87
	3_7_C	-0.48	2.94	1.00
	3_8_C	-5.37	2.93	0.80
	3_7_D	-0.45	2.94	1.00
	3_8_D	-5.33	2.93	0.81
3_8_A	3_7_A	4.88	2.93	0.88
	3_7_B	4.79	2.93	0.89
	3_8_B	-0.08	2.91	1.00
	3_7_C	4.41	2.93	0.94
	3_8_C	-0.49	2.92	1.00
	3_7_D	4.43	2.93	0.94
	3_8_D	-0.45	2.91	1.00
2_B	2_A	-0.02	3.33	1.00
	2_C	-0.48	3.33	1.00
	2_D	-0.02	3.32	1.00
3_7_B	3_7_A	0.09	2.94	1.00
	3_8_A	-4.79	2.93	0.89
	3_8_B	-4.87	2.93	0.88
	3_7_C	-0.38	2.94	1.00
	3_8_C	-5.28	2.93	0.82
	3_7_D	-0.36	2.94	1.00
	3_8_D	-5.24	2.93	0.82
3_8_B	3_7_A	4.96	2.93	0.87
	3_8_A	0.08	2.91	1.00
	3_7_B	4.87	2.93	0.88
	3_7_C	4.48	2.93	0.93
	3_8_C	-0.41	2.92	1.00
	3_7_D	4.51	2.93	0.93
	3_8_D	-0.37	2.91	1.00
2_C	2_A	0.46	3.33	1.00
	2_B	0.48	3.33	1.00
	2_D	0.46	3.32	1.00
3_7_C	3_7_A	0.48	2.94	1.00
	3_8_A	-4.41	2.93	0.94
	3_7_B	0.38	2.94	1.00
	3_8_B	-4.48	2.93	0.93
	3_8_C	-4.89	2.93	0.88
	3_7_D	0.02	2.94	1.00
	3_8_D	-4.85	2.93	0.89
3_8_C	3_7_A	5.37	2.93	0.80
	3_8_A	0.49	2.92	1.00
	3_7_B	5.28	2.93	0.82
	3_8_B	0.41	2.92	1.00
	3_7_C	4.89	2.93	0.88
	3_7_D	4.92	2.93	0.88
	3_8_D	0.04	2.92	1.00
2_D	2_A	0.00	3.32	1.00
	2_B	0.02	3.32	1.00
	2_C	-0.46	3.32	1.00
3_7_D	3_7_A	0.45	2.94	1.00
	3_8_A	-4.43	2.93	0.94
	3_7_B	0.36	2.94	1.00
	3_8_B	-4.51	2.93	0.93
	3_7_C	-0.02	2.94	1.00
	3_8_C	-4.92	2.93	0.88
	3_8_D	-4.88	2.93	0.88
3_8_D	3_7_A	5.33	2.93	0.81
	3_8_A	0.45	2.91	1.00
	3_7_B	5.24	2.93	0.82
	3_8_B	0.37	2.91	1.00
	3_7_C	4.85	2.93	0.89
	3_8_C	-0.04	2.92	1.00
	3_7_D	4.88	2.93	0.88

D.2.3. Hypothesis testing KPI04 - Scenario 1B

Table D.5: Games-Howell test result for Analysis C of KPI04 - Scenario B

Subscenario I	Subscenario J	Mean Difference (I-J)	Std. Error	p-value
2_A	2_B	0.02	3.33	1.00
	2_C	-0.46	3.33	1.00
	2_D	0.00	3.32	1.00
3_7_A	3_8_A	-4.88	2.93	0.88
	3_7_B	-0.09	2.94	1.00
	3_8_B	-4.96	2.93	0.87
	3_7_C	-0.48	2.94	1.00
	3_8_C	-5.37	2.93	0.80
	3_7_D	-0.45	2.94	1.00
	3_8_D	-5.33	2.93	0.81
3_8_A	3_7_A	4.88	2.93	0.88
	3_7_B	4.79	2.93	0.89
	3_8_B	-0.08	2.91	1.00
	3_7_C	4.41	2.93	0.94
	3_8_C	-0.49	2.92	1.00
	3_7_D	4.43	2.93	0.94
	3_8_D	-0.45	2.91	1.00
2_B	2_A	-0.02	3.33	1.00
	2_C	-0.48	3.33	1.00
	2_D	-0.02	3.32	1.00
3_7_B	3_7_A	0.09	2.94	1.00
	3_8_A	-4.79	2.93	0.89
	3_8_B	-4.87	2.93	0.88
	3_7_C	-0.38	2.94	1.00
	3_8_C	-5.28	2.93	0.82
	3_7_D	-0.36	2.94	1.00
	3_8_D	-5.24	2.93	0.82
3_8_B	3_7_A	4.96	2.93	0.87
	3_8_A	0.08	2.91	1.00
	3_7_B	4.87	2.93	0.88
	3_7_C	4.48	2.93	0.93
	3_8_C	-0.41	2.92	1.00
	3_7_D	4.51	2.93	0.93
	3_8_D	-0.37	2.91	1.00
2_C	2_A	0.46	3.33	1.00
	2_B	0.48	3.33	1.00
	2_D	0.46	3.32	1.00
3_7_C	3_7_A	0.48	2.94	1.00
	3_8_A	-4.41	2.93	0.94
	3_7_B	0.38	2.94	1.00
	3_8_B	-4.48	2.93	0.93
	3_8_C	-4.89	2.93	0.88
	3_7_D	0.02	2.94	1.00
	3_8_D	-4.85	2.93	0.89
3_8_C	3_7_A	5.37	2.93	0.80
	3_8_A	0.49	2.92	1.00
	3_7_B	5.28	2.93	0.82
	3_8_B	0.41	2.92	1.00
	3_7_C	4.89	2.93	0.88
	3_7_D	4.92	2.93	0.88
	3_8_D	0.04	2.92	1.00
2_D	2_A	0.00	3.32	1.00
	2_B	0.02	3.32	1.00
	2_C	-0.46	3.32	1.00
3_7_D	3_7_A	0.45	2.94	1.00
	3_8_A	-4.43	2.93	0.94
	3_7_B	0.36	2.94	1.00
	3_8_B	-4.51	2.93	0.93
	3_7_C	-0.02	2.94	1.00
	3_8_C	-4.92	2.93	0.88
	3_8_D	-4.88	2.93	0.88
3_8_D	3_7_A	5.33	2.93	0.81
	3_8_A	0.45	2.91	1.00
	3_7_B	5.24	2.93	0.82
	3_8_B	0.37	2.91	1.00
	3_7_C	4.85	2.93	0.89
	3_8_C	-0.04	2.92	1.00
	3_7_D	4.88	2.93	0.88

D.2.4. Hypothesis testing KPI05 - Scenario 1B

Table D.6: Games-Howell test result for Analysis C of KPI05 - Scenario B

Subscenario I	Subscenario J	Mean Difference (I-J)	Std. Error	p-value
2_A	3_7_A	-0.36	0.21	0.88
	3_8_A	-0.27	0.21	0.98
	2_B	-0.03	0.20	1.00
	3_7_B	-0.58	0.21	0.19
	3_7_C	-0.41	0.20	0.65
	3_8_C	0.46	0.19	0.37
	3_7_D	0.28	0.20	0.96
3_7_A	2_A	0.36	0.21	0.88
	3_8_A	0.08	0.22	1.00
	2_B	0.33	0.20	0.91
	3_7_B	-0.22	0.21	1.00
	3_8_B	-0.37	0.22	0.85
	3_7_C	-0.06	0.21	1.00
	3_7_D	0.63	0.20	0.08
	3_8_D	-0.37	0.22	0.85
3_8_A	2_A	0.27	0.21	0.98
	3_7_A	-0.08	0.22	1.00
	2_B	0.24	0.20	0.99
	3_7_B	-0.31	0.21	0.96
	3_8_B	-0.46	0.21	0.59
	3_7_C	-0.14	0.21	1.00
	3_7_D	0.55	0.20	0.21
	3_8_D	-0.46	0.21	0.59
2_B	2_A	0.03	0.20	1.00
	3_7_A	-0.33	0.20	0.91
	3_8_A	-0.24	0.20	0.99
	3_7_B	-0.55	0.20	0.19
	3_7_C	-0.38	0.19	0.68
	3_8_C	0.49	0.17	0.17
	3_7_D	0.31	0.18	0.87
3_7_B	2_A	0.58	0.21	0.19
	3_7_A	0.22	0.21	1.00
	3_8_A	0.31	0.21	0.96
	2_B	0.55	0.20	0.19
	3_8_B	-0.15	0.21	1.00
	3_7_C	0.16	0.20	1.00
	3_8_D	-0.15	0.21	1.00
3_8_B	3_7_A	0.37	0.22	0.85
	3_8_A	0.46	0.21	0.59
	3_7_B	0.15	0.21	1.00
	3_7_C	0.32	0.20	0.92
	3_8_D	0.00	0.21	1.00
2_C	3_8_C	-0.36	0.17	0.60
	2_D	-0.02	0.18	1.00
	3_7_D	-0.54	0.18	0.10
3_7_C	2_A	0.41	0.20	0.65
	3_7_A	0.06	0.21	1.00
	3_8_A	0.14	0.21	1.00
	2_B	0.38	0.19	0.68
	3_7_B	-0.16	0.20	1.00
	3_8_B	-0.32	0.20	0.92
	3_8_D	-0.32	0.20	0.92
3_8_C	2_A	-0.46	0.19	0.37
	2_B	-0.49	0.17	0.17
	2_C	0.36	0.17	0.60
	2_D	0.35	0.17	0.67
	3_7_D	-0.18	0.17	1.00
2_D	2_C	0.02	0.18	1.00
	3_8_C	-0.35	0.17	0.67
	3_7_D	-0.53	0.18	0.13
3_7_D	2_A	-0.28	0.20	0.96
	3_7_A	-0.63	0.20	0.08
	3_8_A	-0.55	0.20	0.21
	2_B	-0.31	0.18	0.87
	2_C	0.54	0.18	0.10
	3_8_C	0.18	0.17	1.00
	2_D	0.53	0.18	0.13
3_8_D	3_7_A	0.37	0.22	0.85
	3_8_A	0.46	0.21	0.59
	3_7_B	0.15	0.21	1.00
	3_8_B	0.00	0.21	1.00
	3_7_C	0.32	0.20	0.92

Table D.7: Games-Howell test result for Analysis D of KPI05 - Scenario B

Subscenario I	Subscenario J	Mean Difference (I-J)	Std. Error	p-value
1	3_2	-0.28	0.17	0.89
	3_3	-0.36	0.17	0.57
	3_6	-0.48	0.17	0.18
	3_7	-0.48	0.17	0.19
	3_8	-0.52	0.17	0.11
2	3_1	0.05	0.19	1.00
	3_2	0.34	0.19	0.82
	3_3	0.26	0.18	0.96
	3_4	0.02	0.19	1.00
	3_5	0.01	0.19	1.00
	3_6	0.14	0.19	1.00
	3_7	0.14	0.19	1.00
	3_8	0.10	0.19	1.00
	3_9	-0.22	0.20	0.99
	3_10	-0.61	0.20	0.08
3_1	2	-0.05	0.19	1.00
	3_2	0.29	0.18	0.92
	3_3	0.21	0.18	0.99
	3_4	-0.03	0.18	1.00
	3_5	-0.04	0.18	1.00
	3_6	0.09	0.18	1.00
	3_7	0.09	0.18	1.00
	3_8	0.05	0.18	1.00
	3_9	-0.27	0.19	0.96
3_2	1	0.28	0.17	0.89
	2	-0.34	0.19	0.82
	3_1	-0.29	0.18	0.92
	3_3	-0.08	0.18	1.00
	3_4	-0.32	0.18	0.83
	3_5	-0.33	0.18	0.81
	3_6	-0.20	0.18	0.99
	3_7	-0.20	0.18	1.00
	3_8	-0.24	0.18	0.98
	3_9	-0.56	0.19	0.14
3_3	1	0.36	0.17	0.57
	2	-0.26	0.18	0.96
	3_1	-0.21	0.18	0.99
	3_2	0.08	0.18	1.00
	3_4	-0.24	0.18	0.97
	3_5	-0.25	0.18	0.96
	3_6	-0.12	0.18	1.00
	3_7	-0.12	0.18	1.00
	3_8	-0.15	0.18	1.00
	3_9	-0.48	0.19	0.31
3_4	2	-0.02	0.19	1.00
	3_1	0.03	0.18	1.00
	3_2	0.32	0.18	0.83
	3_3	0.24	0.18	0.97
	3_5	-0.01	0.18	1.00
	3_6	0.12	0.18	1.00
	3_7	0.12	0.18	1.00
	3_8	0.08	0.18	1.00
	3_9	-0.24	0.19	0.98
3_5	2	-0.01	0.19	1.00
	3_1	0.04	0.18	1.00
	3_2	0.33	0.18	0.81
	3_3	0.25	0.18	0.96
	3_4	0.01	0.18	1.00
	3_6	0.13	0.18	1.00
	3_7	0.13	0.18	1.00
	3_8	0.10	0.18	1.00
	3_9	-0.23	0.19	0.99
	3_10	-0.62	0.19	0.05
3_6	1	0.48	0.17	0.18
	2	-0.14	0.19	1.00
	3_1	-0.09	0.18	1.00
	3_2	0.20	0.18	0.99
	3_3	0.12	0.18	1.00
	3_4	-0.12	0.18	1.00
	3_5	-0.13	0.18	1.00
	3_7	0.00	0.18	1.00
	3_8	-0.03	0.18	1.00
	3_9	-0.35	0.19	0.78
3_7	1	0.48	0.17	0.19
	2	-0.14	0.19	1.00
	3_1	-0.09	0.18	1.00
	3_2	0.20	0.18	1.00
	3_3	0.12	0.18	1.00
	3_4	-0.12	0.18	1.00
	3_5	-0.13	0.18	1.00
	3_6	0.00	0.18	1.00
	3_8	-0.04	0.18	1.00
	3_9	-0.36	0.19	0.78
3_8	1	0.52	0.17	0.11
	2	-0.10	0.19	1.00
	3_1	-0.05	0.18	1.00
	3_2	0.24	0.18	0.98
	3_3	0.15	0.18	1.00
	3_4	-0.08	0.18	1.00
	3_5	-0.10	0.18	1.00
	3_6	0.03	0.18	1.00
	3_7	0.04	0.18	1.00
	3_9	-0.32	0.19	0.88
3_9	2	0.22	0.20	0.99
	3_1	0.27	0.19	0.96
	3_2	0.56	0.19	0.14
	3_3	0.48	0.19	0.31
	3_4	0.24	0.19	0.98
	3_5	0.23	0.19	0.99
	3_6	0.35	0.19	0.78
	3_7	0.36	0.19	0.78
	3_8	0.32	0.19	0.88
	3_10	-0.39	0.20	0.69
3_10	2	0.61	0.20	0.08
	3_5	0.62	0.19	0.05
	3_9	0.39	0.20	0.69

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