Impact of Integrated RPAS Operations in Terminal Control Area

P.A. Martín Fernández

Technische Universiteit Delft

Impact of Integrated RPAS Operations in Terminal Control Area

by

P.A. Martín Fernández

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Tueasday January 15th, 2019 at 11:00 AM.

Student number:	4621093	
Project duration:	January 1, 2018 – October 30, 2018	
Thesis committee:	Prof. dr. ir. J. M. Hoekstra,	TU Delft, supervisor
	Dr. ir. J. Ellerbroak,	TU Delft, supervisor
	Mike Lissone,	EUROCONTROL supervisor

Preface

With this Master Thesis I conclude my Master studies at the Delft University of Technology. This last two years and a few months have been full of great experiences, excellent education and, the best of all, great people. Attending my master's courses has been a pleasure due to the undenying passion and great disposition for teaching every Control & Operations proffesors has showcased. In particular, I would like to thank my thesis supervisors: Prof. dr. ir. J. M. Hoekstra and dr. ir. J. Ellerbroek for the support and advice provided during my thesis project.

I was very fortunate to be able to do my Master's Thesis in collaboration with EURCONTROL's UAS-ATM Integration team. I would like to express my immense gratitude to Mike Lissone for giving me the opportunity of working with them and being a wonderful and supportive mentor during and after my traineeship.

But a high quality education is not the only outcome of this years, most importantly, I have been so lucky to meet many great colleagues and friends: the *"RPAS Team"* Julia and Anastasiia who always made me feel part of the team; the *ECTL trainees crew* who made my year at EUROCONTROL full of great experiences in and outside of work; and all of the students who two years ago were only colleagues from class and over time became some of my closest friends. You are too many to be named here but you all know who you are and thanks to your friendship the harder times were bearable and the happier times became even more joyful.

More importantly and on a more personal note, none of my achievements are only mine as they would have been impossible without the unconditional and unresting support of my parents and grandmother. Their love and trust in me always acting as a source of energy and protection blanket that makes me able to achieve higher goals and be a happier person.

P.A. Martín Fernández
Delft, November 2018

Acronyms and Abbreviations

ACC Area Control Center

ANSP Air Navigation Service Provider

ATC Air Traffic Control

ATCo Air Traffic Control officer

ATM Air Traffic Management

BADA Base of Aircraft Data

BRLOS Beyond Radio Line-Of-Sight

C2 Command & Control

CAA Civil Aviation Authority

BRLOS Beyond Radio Line-Of-Sight

CTR Controlled Traffic Region, Control zone

EASA European Aviation Safety Agency

EDDM Munich Airport

ERSG European RPAS Steering Group

EUROCAE EURopean Organization for Civil Aviation Equipment

FAA Federal Aviation Administration

FL Flight Level

ft feet

ICAO International Civil Aviation Organization

IFR Instrumental Flight Rules

RD Research & Development

RLOS Radio Line-Of-Sight

RPA Remote Piloted Aircraft

RPAS Remotely Piloted Aircraft System

RPS Remote Pilot Station

RTCA Radio Technical Commission for Aeronautics

TMA Terminal Maneuvering Area

VFR Visual Flight Rules

VHL Very High Level

VLL Very Low Level

UAS Unmanned Aircraft System

UAV Unmanned Aerial Vehicle

Contents

List of Figures

List of Tables

I

Scientific Paper

Impact of Integrated RPAS Operations in TMA

Patricia A. Martin Fernandez
Supervisors: Prof. dr. ir. J. M. Hoekstra, dr. ir. J. Ellerbroek,
Section Control & Simulation, Department Control and Operations, Faculty of Aerospace Engineering
Delft University of Technology, Delft, Netherlands
EUROCONTROL Supervisor: Mike Lissone
Unmanned Aircraft System (UAS) air traffic management (ATM) Integration Manager

***Abstract*—The fast growing Unmanned Aircraft scene accounts for an increasing number of new users who should have access to the airspace as any other full-fledged airspace user. Simultaneously, in order to maintain the currently achieved levels of performance in ATM, Unmanned Vehicles ought to be compliant with existing aviation regulations as well as with specially tailored requirements and standards. A subset of those requirements should address flight performance, which can be very diverse among Unmanned Aircraft. At the present time, there is a lack of research on this particular aspect of Unmanned Aircraft Systems integration in ATM, as solutions to other type of technological and regulatory issues are being pursued. By means of fast-time simulations of non-segregated RPAS operations in a given airspace, this project studies how Unmanned Operations impact ATM system performance in terms of Safety, Efficiency and Capacity and makes a suggestion on where the line could be drawn regarding admissible RPAS Flight Performance for TMA.**

***Index Terms*—RPAS, UAS, ATM, UTM, Integration, Flight Performance**

I. Introduction

Drones were once an obscure military exclusive technology with a dubious reputation, but nowadays Unmanned Aircraft Systems (UAS) are the drivers of a blooming new market that encompasses numerous and diverse civilian services. The defining feature of not having a pilot on board opens the door to new types of operations that, due to their dangerous nature or intrinsic difficulty, are best performed by unmanned aircraft. Operations such as: infrastructure preventative maintenance, precision agriculture, search and rescue missions, urgent delivery, civil protection and humanitarian missions. The use of UAS for these types of operations and many others is expected to grow in the following years. A forecast made by SESAR Joint Undertaking predicts that Unmanned Aircraft will represent the 20% of the fleet for mobility purposes by 2050, which would suppose approximately 10.000 aircraft more [1].

The promising growth prospect for the UAS market means that a huge number of new airspace users will have to be accommodated in the future Air Traffic Management system. Several international organizations such as ICAO, FAA, EUROCONTROL, EASA, RTCA, EUROCAE and many national ANSPs are currently developing regulations, certification standards, and concepts of operations, as well as researching new technologies that will allow the successful integration of UAS in ATM. They all concur on the same principle: UAS must be treated like any other ATM user, this meaning that they shall follow the same rules as well as benefit from the same rights [2]. The presence of Unmanned Vehicles (either autonomous or remotely piloted) should not negatively impact other ATM users. Ideally, safety and efficiency levels achieved currently should be maintained and the impact on Air Traffic Controllers' workload should be minimized.

Remotely Piloted Aircraft Systems (RPAS), the subset of UAS which is not autonomous but controlled from outside of the vehicle, are of special interest since they are expected to be integrated first into controlled traffic [3]. RPAS have three main components: Remotely Piloted Aircraft (RPA), Remote Pilot Station (RPS) and Command and Control Link (C2 Link) [3]. The C2 Link is probably the most critical and essential part of RPAS since it is the only means the Pilot In Command has to manage the flight and control the RPA. If the C2 Link fails or is disrupted in any way the safety of the operation is immediately compromised.

This research project has been made in collaboration with EUROCONTROL's UAS/ATM Team. The UAS/ATM Team works for the safe integration of UAS into ATM by providing guidance on every aspect of the topic, from regulation to technical expertise. This project in particular studies the impact of non-segregated RPAS operations in Terminal Control Area, with special focus on how Flight Performance affects the airspace performance measured in terms of Safety, Efficiency and Capacity.

Section II of this document provides background information regarding the present state of UAS Integration in ATM. Section III contains the methodology and experiment design. Section IV contains the results of the carried out experiment. Section V contains the discussion of the results and, finally, section VI gathers the conclusions of this study.

II. Background

Seamlessly integrating UAS into the current aviation system is a complex task for which several gaps have been identified in areas of activity such as standardization, regulation, certification, flight procedures, airspace assessment, flight rules, personnel training, and research and development [4]. In order to preserve the currently achieved levels of performance in ATM, UAS should be handled like any other airspace user. As the Remotely Piloted subset of UAS is expected to be integrated first, EUROCONTROL identified in their Concept of Operations for RPAS integration in ATM the following four integration principles [5]:

- The integration of RPAS shall not entail 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 risk: the way RPAS operations are conducted shall be equivalent to that of manned aircraft, to the best possible extent.
- RPAS must be transparent to ATC and other airspace users. [5]

ICAO, FAA and the European RPAS Steering Group (ERSG), in their respective roadmaps, have envisioned a gradual transition divided in three phases: **Initial Operations/Accomodation**, **Integration** and **Evolution**. Being nowadays at the first stage and moving towards the Integration phase [4]. Integration is achieved when UAS operations are conducted according to the developed regulations, meeting the established threshold performance requirements and restrictions to access non-segregated airspace are alleviated [6].

RPAS is a quite heterogenous group which can be categorized following diverse criteria such as: size, weight, endurance and range, engine type, wing loading, risks or type of operations. EUROCONTROL's "RPAS ATM CONOPS" categorizes RPAS according to their type of operations and altitude where they take place as follows [5]:

- **Very Low Level operations (VLL) - RPAS flying below 500ft** - These operations take place below the typical IFR and VFR altitudes for manned aviation, still some airspace users fly at these altitudes such as: balloons, paratroopers, some VFR traffic, gliders, etc. These operations can be either in Visual Line of Sight or Beyond Visual Line Of Sight.
- **IFR and VFR Operations - RPAS flying between 500ft and FL600** - The majority of manned aviation (both VFR and IFR) operate at these altitudes, thus, RPAS are expected to comply with either VFR or IFR. Technically speaking, being compliant with IFR is more feasible so IFR RPAS operations are expected to occur before VFR. Currently, the common practice for dealing with this type of RPAS operations is **segregation of the airspace**, assessing the situation case by case.
- **Very High Level operations (VHL) - RPAS flying above FL600** - Regular commercial aviation does not operate at these altitudes, but still UAS would have to share the airspace with military aircraft and cross controlled and busier airspace at the beginning and end of their mission. [5]

VLL Operations are expected to provide the greatest economic growth and utility for society, therefore, numeorus research activities are being carried out in this area. The main common goal is to develop an equivalent system as ATM but for UAS: **UTM**. In Europe, UTM is also known as **U-Space**. In 2017 the European Commission together with the SESAR Joint Undertaking published the U-Space blueprint, a very high level document describing how an hypothetical future where UAS are seamlessly integrated in urban airspace would look like [7]. On this line, EUROCONTROL is leading two key projects based on the U-Space/UTM concept: **CORUS** (Concept of Operations for European UTM System) [8] and **PODIUM** (Providing Operations of Drones with Initial UTM) [9]. Not only public insituions but also private companies are moving forward the UTM concept by partening with Air Navigation Service Providers (ANSP) regarding the development of drone traffic management solutions and demonstrations of UTM capabilities [10] [11].

In **controlled airspace**, the current procedure of segregating UAS operations from manned aviation is not sustainable in the long run given the expected growth of both manned and unmanned air traffic. For **non-segregated UAS operations** to take place safety is paramount. In ATM safety is assured by combining several layers which together minimize the probability of airborne collision: Strategic Conflict Management, Separation Provision, Collision Avoidance and finally there is the pilot's See and Avoid capability. For UAS operations to be safe, the lack of pilot's see and avoid function should be compensated by imposing higher requirements to the other layers [12]. A failure in more than one layer is needed for an event of Loss of Separation to occur. It is in controlled airspace where these layers fully contribute to separation assurance, which allows to reach the conclusion that IFR Operations in controlled airspace are the safer option when it comes to BVLOS UAS Operations [13]. In UAS, the lack of Pilot's See and Avoid needs to be compensated by **Detect and Avoid** systems and algorithms. Interoperability between UAS Detect and Avoid systems and manned aircraft ACAS must be assured by means of compatible and unambiguous resolution advisories given to any aircraft, irrespective of manned or unmanned, involved in a potential conflict [14].

A reliable **Command and Control Link** is essential for the safety and success of any type of RPAS operation. C2 Link does not only function as a mean of controlling the UAV, but also as a source of information about the state of the system and thus, should compensate for the lack of situation awareness on both the aircraft surroundings and the on-board systems [15]. Even though C2 Link can be provided by means of different technologies, a set of requirements ought to be met in terms of communication transaction time, continuity, availability and integrity [16]. Contingency procedures ought to be defined for those situations when RPAS lose the C2 Link connection, or experience other types of malfunctioning.

Flight Performance is another key aspect of RPAS integration in ATM that is usually mentioned but rarely thoroughly addressed. Generally speaking, existing RPAS have worse flight performance characteristics (range, endurance, ceiling, vertical and horizontal speeds...) than civil commercial aircraft [17]. At the same time, the abcense of human occupants could erase some performance limitations for newly manufactured RPAS whose flight performance could surpass manned aviation's. Greater thrust-to-weight ratios, less acceleration constraints, tighter turns, steeper climb and descent segments are expected in a general faster and more responsive vehicles [18]. It is only logical to think that managing any airspace with aircraft of such diverse flight performances is a complex task that can increase the workload of Air Traffic Controllers, which in turn directly impacts the airspace's capacity and performance. Hence, it is necessary that the Air Navigation authorities and flight planning systems take into account the different RPAS flight performances as both airliners and RPAS will have to comply with the same rules and procedures [19]. Some strategies for mitigating the effect of this diversity of performances are: establishing new route structures, strategic segregation for groups with similar profiles, tactical management of diverse profiles, automation enhancements to handle complex and diverse trajectories and improved surveillance capabilities for UAS [20].

According to ICAO, UAS flight performances should not greatly differ from those of manned aviation so as not to impose a higher workload on the ATCo [2]. The reality is that manned aircraft cover a wide range of flight performances and little to none research has focused on quantitatively establishing flight performance requirements for these new airspace users. This is the gap this project aims to fill. Last year, in collaboration with EUROCONTROL's UAS/ATM Team, another Master Thesis Project on this same topic was produced. In this MSc Thesis a methodology to determine the minimum performance requirements for UAS in the en-route phase was developed [21]. Continuing on that work, this project will focus on the Terminal Control Area (TMA) and the climbing and descending phases of the flight. It is expected that Flight Performance will have a greater impact on aircraft with changing flight profiles.

III. Experiment Design and Procedure

The research **objective is to study the impact of RPAS integration in ATM by analyzing their effect on a given airspace in terms of Safety, Efficiency and Capacity, by means of fast-time simulations**. In order to accomplish that goal, the different simulation scenarios are built (first the baseline without RPAS and then several scenarios where RPAS are introduced), the simulations are run and a predefined set of metrics is measured in for every combination of Independent Variables.

The scope of this research project is limited to **IFR RPAS operations in TMA** and conceptually located during the **Integration phase** during which a substantial portion of IFR operations will be performed by RPAS.

A. Simulation software

Thanks to EUROCONTROL it was possible to use AirTOp, a state-of-the-art fast-time simulator that combines airspace and airport modeling. Among its many characteristics what stood out as particularly useful for this study was the possibility of simulating Air Traffic Controllers, conflict resolution and workload calculation. The Conflict Resolution and Detection algorithms, as well as the Controller workload calculation schema, were developed with the guidance of real life ATCo's [22].

1) Conflict Detection and Resolution: This AirTOp functionality is able to detect a future violation of minimum separation between two aircraft; simulate the necessary actions taken by the controller, such as vectoring, altitude changes, speed changes, synchronized descent towards a common way-point etc, in order to separate both aircraft once this future violation of separation is detected; and a reporting of an actual violation of minimum separation between two aircraft. The detection of future violation of minimum separation (either vertical or lateral) between two aircraft is performed automatically by creating, for every aircraft, an "Aircraft Ghost" that represents the same aircraft flying a predefined number of minutes ahead in time (the default value of 10 minutes was used).

Once a potential conflict is detected, AirTOp tries to solve it if there is a "Radar Controlled" assigned to the airspace and this Radar Controller has a defined "Decision Tree" for solving the conflicts. This what-if tree models the reasoning a controller performs to choose the most appropriate procedure to separate two aircraft. The default tree is defined in a way that the simulated controller will prefer procedures that will give them less workload and will also penalize the aircraft the less. The Decision Tree (see Appendix A) was designed in collaboration with real ATCo's and is customizable. It has Conflict Conditions as its parent nodes and Resolution Actions as its leaf nodes. It filters the potential conflict until an applicable Resolution Action at a leaf node is found, if any.

All the information, statistics and actions taken during a conflict are registered and reported automatically.

2) Controller Workload Schema: AirTOp computes two types of workload:

- **Task-based:** An average work duration is assigned to each of a list of tasks, such as ATC Sector entry/exit, altitude change clearance, etc. The total workload is calculated by multiplying this average by the number of times the task is performed. Each tasks can be subdivided into activities, such as communication, strip update etc; then, the total workload for each activity across all tasks is also calculated.

- **Monitoring-based:** Monitoring tasks are those which have a start and an end event that delimit the time during which an aircraft is monitored. These could be, for example, sector entry and exit, or conflict beginning and end. Each monitoring task is assigned a period duration representing the interval at which the task is performed, and an average work duration which is assigned to the controller each time the task is performed.

Those two workloads are added together to calculate the total workload for each Radar Controller. The workload is a rolling average over a specified time interval, and is updated dynamically during the simulation.

AirTOp includes a predefined Controlled Workload Schema which was developed in close collaboration with real life ATCo's. It includes numerous parameters which can be modified by the user such as: activities and sub-activities which generate workload, duration of those activities, weights for pondering how much the activities influence the workload of the Radar Controller, frequency for workload calculation, etc.

B. Baseline scenario

In order to a build a faithful representation of reality, real airspace structure and historical traffic data obtained from EUROCONTROL's Data Demand Repository were employed for the construction of the baseline simulation scenario. Due to time constraints a single TMA was chosen, **Munich TMA**, and traffic data from one day, **25th of October 2017** (AIRAC cycle 1711). Munich's airport, being the 9th busiest airport in Europe [23], has been considered to be representative of the busy European skies, while still not being an extremely crowded airspace. Besides, its parallel runways configuration make the resulting departing and arriving traffic not excessively complex. Munich TMA is a class C airspace (as defined by ICAO) which means that ATC clearance is required, separation is provided to all IFR traffic, there is no speed limitation and continuous two-way radio communication is required [24].

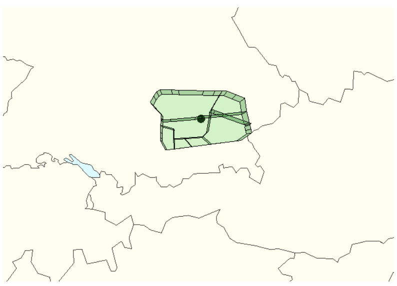


Fig. 1. Munich TMA plan view

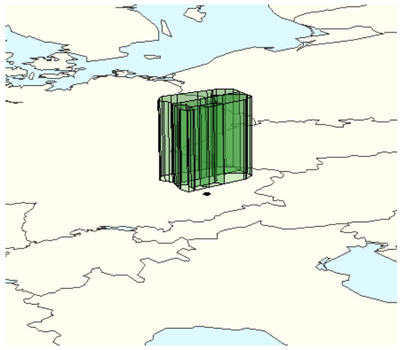


Fig. 2. Munich TMA 3D view

The coordinates defining the lateral limits of the airspace will be as defined on the DDR GASEL files. The vertical limits are set to GND-FL195 in the GASEL file, but the GND value is modified to 3500 ft, as defined on the German AIP [25] and consistent with Munich's Controlled Traffic Region's (CTR) upper limit. The CTR and related flight phases (Approach, take-off and landing) fall out of the scope of this project, while arrivals and departures do not. The FL195 value for the upper limit of the TMA defined in the GASEL files is higher than the one defined in the AIP (FL100) but it will not be modified as it is useful for gathering more data and cover a more diverse set of flight profiles. Figure 1 and 2 show a 3-D visualization of the airspace produced with EUROCONTROL's Network Strategic Tool (NEST).

For the traffic data an average weekday of an off-peak season was selected. During the 24 hours of the 25th of October, 1273 IFR flights crossed Munich TMA. The distribution of the flights over the day can be seen in Figure 3 . Most of those flights (94%) either arrived or departed from Munich airport. Two other airports (ICAO codes EDMA and EDMO) had a few IFR operations that day. 47% of the IFR flights were operated by an Airbus A320 aircraft family, this is partially due to Munich Airport being one of Lufthansa's hubs and a big part of Lufthansa's fleet being composed of these type of aircraft [34].

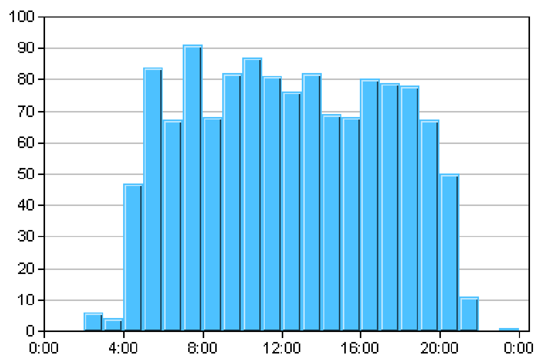


Fig. 3. Occupancy Counts. Obtained from NEST

C. RPAS Modeling

Once the baseline scenario is built the next step is to model and introduce RPAS in the simulation. For this experiment, the complex difference between RPAS and manned aircraft will be modeled in terms of: **Flight Performance** and **Separation Minima**.

The introduction of RPAS in the simulation scenario consist in having a percentage of the flights operated by RPAS instead of the initially designated aircraft. The percentage of RPAS (**Traffic Mix**) present in the traffic data-set will take the values: 5% 10% 15% or 20% depending on the scenario. The different percentages aim to reflect different stages of RPAS integration in ATM, up to the predictions made by the SESAR Joint Undertaking of 20% of the aircraft used for mobility purposes by 20150 being unmanned [1].

Substituting manned aircraft for RPAS means that the simulator employs the BADA file corresponding to the RPAS instead of the one of the aircraft designated on the flight plan. Currently there is not much data on RPAS Flight Performance. BADA contains four RPAS models, from which only two of them could realistically fly in controlled airspace such as a TMA: Global Hawk and MQ-9 Reaper. Table I shows a comparison between the flight performance parameters the RPAS models in BADA and other manned aircraft.

As it can be seen on the table, RP03 and RP04's flight performances are specially limited: their ceiling is quite low and their speeds are very far from those of the other aircraft. On the other hand, RP01 and RP02, while still not being on the level of manned aviation, have a more similar flight performance. Hence, RP01 and RP02 are the ones which can represent more realistically an RPAS that could fly in non-segregated airspace with commercial civil aviation. It is interesting to note that the Rate of Climb of RP01 is even better than those of manned aircraft. Eventhough, RQ-4A Global Hawk and MQ-9 Reaper are military drones commonly used as support for military missions, and it is unlikely that these military RPAS will share the airspace with civil commercial aviation on a daily basis, they are the best fit in terms of flight performance among the available RPAS models in BADA.

Global Hawk and MQ9 Reaper will not be the only Remotely Piloted Aircraft simulated. In order to reflect a possible mid-term future scenario where common aircraft become RPAS by not being controlled from the cockpit but from any other location outside of it. The following aircraft: **Airbus A320, ATR 72, Piper Cheyenne and Cirrus 22SR** are chosen as they represent diverse levels of flight performance. In a portion of the simulation scenarios, regular manned aircraft will be modeled as unmanned.

From table I the six aircraft employed in the simulation scenarios could be ranked in terms of Flight Performance as follows:

- **TAS:** $A320 > PAY3 > AT72 > RP01 > RP02 > S22T$
- **ROC:** $RP01 > A320 > PAY3 > RP02 > S22T > AT72$
- **ROD:** $PAY3 > A320 > AT72 > RP02 > RP01 > S22T$
- **Overall Flight Performance:** $A320 > PAY3 > RP01 > AT72 > RP02 > S22T$

The defining difference between RPAS and manned aircraft is the absence of a pilot on board of the aircraft and the use of the Command & Control Link (C2 Link) that allows the Pilot in Command to control the vehicle and manage the flight. ATC clearance and a two-way radio communication are required for aircraft to fly through controlled airspace and this requirements will naturally also apply to RPAS. For RPAS, due to the Pilot in Command not being on board, the communication signal is relayed through the RPA and one or more satellites (see Figure 4 which describes the most likely scenario).

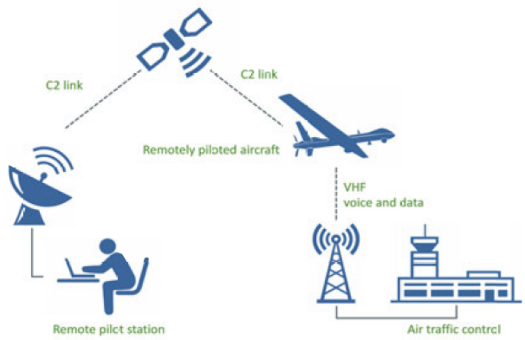


Fig. 4. Beyond Radio Line Of Sight via satellite [3]

As can be seen in this figure, the communication signal travels a much longer path than if the pilot was on board of the aircraft. This results in a substantial delay in the RPA reaction to ATC clearances as the PIC is not able to immediately act upon the RPA state. This latency in communications leads to increased ATCo workload and a reduction of airspace capacity [20]. On top of that, as a consequence of the time spent waiting for PIC response the ATCo might lose focus on the general situation of the airspace.

For a one-way communication path there is one standard VHF transmission, and a transmissions via satellite (two path or a round-trip). We can assume that the VFH transmission will comply with the standards and contribute with 236 ms latency [26]. For the satellited induced latency, it could be assumed that the satellite is in geostationary orbit at 35 786 km above Earth's equator, so the signal will take about a quarter of a second the round trip [27]. But this doesn't take into account

TABLE I
FLIGHT PERFORMANCE COMPARISON. THE THREE LAST COLUMNS REPRESENT THE TRUE AIRSPEED, RATE OF CLIMB AND RATE OF DESCEND FOR THE FLIGHT LEVELS BETWEEN FL30 AND FL195, THE TMA VERTICAL LIMITS

BADA Code	Aircraft	Type	Range (km)	Ceiling (ft)	MTOW (kg)	TAS (kt)	ROC (ft/min)	ROD (ft/min)
RP01	RQ4A Global Hawk	High Altitude Long Endurance	14000	60000	14628	209-271	2512-3671	824-1379
RP02	MQ9 Reaper	Medium Altitude Long Endurance	1852	50000	4760	157-204	886-2072	1690-1907
RP03	Generic Tactical RPAS	Low Altitude Long Endurance	200	16400	490	73-90	64-643	636-911
RP04	RQ2A Pioneer	Low Altitude Long Endurance	185	12000	205	73-87	101-428	391-551
A320	Airbus A320	Airliner Medium-Haul	6100	41000	78000	230-413	1750-3078	935-2363
PAY3	Piper Cheyenne III	Light Business	2500	33000	5000	188-285	1390-2514	2354-3112
AT72	ATR-72-200	Airliner Short-Haul	1600	25000	22000	188-279	529-1595	1426-1956
S22T	Cirrus SR22	General Aviation	2000	18000	1500	151-184	1019-1351	406-573

internal system latency so a safe value of 400ms will be picked (this value is also based on real data obtained by Eurocontrol experts). Each bit of the communication between Pilot and ATCo will have a (one-way) delay of:

$$Communications\ Delay = VHF + C2\ Link(satellite) \times 2 =$$
$$= 236 + 400 \times 2 = 1036\ ms$$

So, for every clearance or conversation bit the ATCo emits, they would have to wait for at least 2 seconds to get a response from the Pilot In Command. That is only if the pilot responds immediately, human factors have not been taken into account for the previous calculation.

Currently, in AirTOp it is not possible to model communication delays so a different approach is taken:

One possible strategy that could compensate for the above-mentioned shortcomings of RPAS and its associated communication latency is the reassessment of separation standards. On top of communication related issues, RPAS can be more vulnerable to wake turbulence due to their smaller size. This necessity has been already identified by the pertinent authorities but currently there is no published standard, as RPAS operations are being segregated from manned traffic. For the simulation scenarios RPAS **horizontal separation minima will be increased**. The broadly used value for horizontal separation in TMA is 3NM. For simplicity and practical reasons integer values were chosen (i.e.: it would not make sense to make the ATCo remember and work with a value of 3.6 NM). The proposed values are: **3NM** (0% increase), **4NM** (33% increase), **5NM** (67% increase) and **6NM** (100% increase). The value of 6NM is an extreme value for experiment purposes only as doubling the separation requirement might be too conservative and it does not seem reasonable when taking into account the UAS/ATM Integration principles. The vertical separation requirement for every scenario will remain at 1000ft.

D. Independent Variables

The operational differences explained in the previous section are the base upon which the experiment matrix is built. The different simulation scenarios are the product of all the possible combinations between the following three Independent Variables (IVs) with the following levels:

- **Flight Performance (FP)** - The selected aircraft are ranked from best to worse overall Flight Performance in terms of True Airspeed, Rate of Climb and Rate of Descend (see Table I) as follows:
  - A320
  - PAY3
  - RP01
  - AT72
  - RP02
  - S22T
- **Traffic Mix (TM)** - The percentage of aircraft that is substituted by RPAS:
  - 5%
  - 10%
  - 15%
  - 20%
- **Separation Minima (SM)** - Lateral separation requirement between RPAS and any other aircraft:
  - 3NM
  - 4NM
  - 5NM
  - 6NM

Having three Independent Variables translates into a three-dimensional experiment matrix formed by the 96 combinations of the IV levels. If the baseline (the scenario with no RPAS in it, just the historical traffic data) is taken into account, a total of 97 different scenarios are simulated. Each scenario is run 5 times. The reason for running each simulation scenario more than once is to bestow more statistical significance on the results. The single set of results obtained from simulating each scenario only once could be the product of an anomaly, an outlier or extreme case. The reason for running only 5 repeats is time constraints: each simulation run takes between 15 and 20 minutes, therefore, running the 485 simulations takes a full week.

Since the experiment is a computer simulation, simply running the same simulation scenario over and over yields the exact same results unless some randomization is implemented. Randomization consists in introducing small differences into the conditions of the simulation in order to make each simulation run unique and independent so as to get meaningful results. The randomization in this experiment consist of randomly selecting which flight plans, out of the total of 1273 that take place during the selected day, are flown by RPAS. The percentage of RPAS present in the simulation is fixed and defined by the experiment matrix, but which particular aircraft are substituted by RPAS is decided randomly. Regarding the Baseline, as there are no RPAS involved, the randomization consist on slightly altering the actual departing times of some flights so that some of them would depart a few minutes ($\simeq 5$) earlier or later. This arrangement is actually more realistic than what the nominal simulation would do, where each flight starts exactly at the time specified in their flight plan. In real life delays and unexpected events occur and aircraft do not depart exactly when they are meant to.

E. Dependent Variables

A set of metrics is defined for the purpose of analyzing the airspace performance of the different scenarios in terms of **Safety, Efficiency and Capacity**. For each one of the 485 runs AirTOp creates several report files (both by default and user-defined) containing a large volume of data. From that data the following 13 metrics or Dependent Variables (DV) are selected and defined as follows:

- **Safety:**
  - **Conflicts (#)** - Number of conflicts that occur in the given airspace during the given 24 hour time-frame. A conflict, in this context, is defined as a situation where, if no action is taken, the vertical and horizontal distance between two aircraft will be less than the required separation distance. If more than two aircraft are involved in a conflict, each pair of aircraft is counted separately.
  - **Events of Loss of Separation (#)** - Number of times an actual loss of separation occurs in the given airspace during the given time-frame. An Event of Loss of Separation takes place when two aircraft are flying at a distance shorter than the required separation distance, both vertically and horizontally. If more than two aircraft are involved in a loss of separation event, each pair of aircraft will be counted separately.
  - **Horizontal Separation (ratio)** - This metric measures the lateral distance between the pair of aircraft involved in a event of loss of separation at the closest point of approach. It is computed as a ratio since the Lateral Separation Requirement varies between the scenarios. Therefore, values closer to one indicate a safer situation.

$$H.\ Separation = \frac{Actual\ Separation\ Distance}{Required\ Separation\ Distance}$$

  - **Vertical separation (ft)** - This metric measures the vertical distance between the pair of aircraft involved in a event of loss of separation at the closest point of approach. Since there is no extra requirement for vertical separation, this metric directly quantifies the closest distance in feet between the pair of aircraft.
- **Efficiency:**
  - **Trajectory efficiency (%)** - Ratio, in percentage form, between the followed trajectory and the optimal shortest distance between the airspace entry and exit points.

$$Trajectory\ Eff.\ (\%) = \frac{Distance\ Flown}{Great\ Circle\ Distance}$$

  - **Distance (NM)** - Average distance traveled inside the airspace measured in Nautical Miles.
  - **Fuel (Kg)** - Average quantity of fuel burned while flying in the airspace measured in Kilograms.
  - **Time (min)** - Time spent, in average, inside the airspace measured in minutes.
  - **Delay (min)** - Avereage time difference, in minutes, between the estimated and the actual arrival times. The estimated arrival time is calculated by AirTOp before the simulation starts by taking into account the performance of the aircraft.
- **Capacity:**
  - **Workload (%)** - In this context, workload is a measurement of the mental load the Air Traffic Controller undergoes while controlling the airspace, whether it is giving clearances, solving conflicts or coordinating with other ATCo's. It does not measure the time it takes to physically perform the action, just the mental load. Workload is measured as a percentage and calculated as the ratio between the sum of the duration of each activity and a period of one hour. Hence, a workload of 50 would mean that the ATCo has spent 30 minutes out of 60 thinking about how to perform the tasks. As the TMA under

study is divided in North and South to reflect reality, this metric is given for each sub-sector.

$$Workload\ (\%) = \frac{Work\ Duration\ (min)}{Time\ Period\ (min)} \times 100$$

- **Occupancy (%)** - Occupancy measures what percentage of declared airspace capacity that is being used. As the TMA under study is divided in North and South to reflect reality, this metric is given for each sub-sector. The total declared capacity for the selected TMA is 90 aircraft per hour, divided equally between the two partitions.

$$Occupancy\ (\%) = \frac{Number\ Aircraft}{Declared\ Capacity} \times 100$$

F. Assumptions

The following assumptions and simplifications were made:

- The simulations take place in the mid-term future, when RPAS operations are not segregated from manned aviation.
- C2 link service is provided
- No C2 Link loss occurs during the simulation, so no contingency procedure is triggered.
- Detect and Avoid systems are in place.
- RPAS comply with every airspace requirement in terms of equipment.
- No rogue aircraft, every airspace user collaborates with ATC.
- An airspace assessment has been executed and there are no-drone zones in the volume of the airspace selected for the project. Currently, this is not true as most European regulations on UAS declare CTR as no-drone zones. It is assumed that in the Mid-term future, UAS will be allowed to operate using manned aviation airports and operate in CTRs without endangering other users.
- Meteorological conditions are not taken into account.

G. Hypothesis

It is almost certain that the integration of RPAS operations with manned aviation will disrupt the normal performance of the airspace. The presence of RPAS in the airspace is expected to negatively affect the performance of the airspace, in terms of the following Key Performance Areas, as follows:

- **Safety (H1):** A higher number of conflicts are expected in the scenarios with RPAS compared to the baseline scenario. In addition, those conflicts will be more severe as a consequence of the limited RPAS flight performance and the imposed increased separation requirement for RPAS. Safety is expected to be the most negatively affected Key Performance Area.
- **Efficiency (H2):** More time will be spent on the airspace, on average, due to the lower speeds of RPAS. The average distance flown inside the sector could increase too as a consequence of the resolution of the conflicts. In terms of fuel consumption, nothing can be hypothesized as two opposing effects are expected: increased times and distances flown against the lower consumption of the RPAS models used in the simulation.
- **Capacity (H3):** The workload of the Air Traffic Controller will increase as more conflicts are expected to occur. The airspace will be become more crowded as flights will spend more time in it.

It is also expected that Flight Performance will be a significant factor for every metric by itselft and in combination with Traffic Mix. Separation minima is expected to be a significant factor mainly for the Safety metrics and Workload.

IV. RESULTS

Since the experiment design has three Independent Variables and the interactions between them regarding the Dependent Variables could be significant, Three-way Independent measures ANOVA test will be employed for every metric. The assumptions for applying Three-way independent ANOVA are considered to be sufficiently met: the Dependent variables are measures as interval or ratio data; measurements are independent due to the randomization of each simulation run; the obtained data does not pass the Shaphiro-Wilk test for normality for every metric but the number of data points is constant withing groups of the Independent Variables and the number of data points is higher than 30; lastly, the homogeneity of variance is not always guaranteed for every Dependent Variable, but ANOVA is robust against the violation of this assumption when the number of data points is the same over all levels of the IV.

No significant interaction was found between the three IVs regarding any of the DVs. Significant two-way interactions were found between the IVs for the majority of the metrics, specially between Traffic Mix and Flight Performance. This interaction was expected since the effect of the Flight Performance of RPAS on the metrics will logically be enhanced as the percentage of RPAS in the simulation scenario is increased. As a means of post-hoc test, when there is a significant two-way interaction, the simple effects for each level of the other IV are tested. If every simple effect is significant, it can be said that the IV has a significant effect on the DV.

The consecutive performance of hypothesis tests on the same data testing for the same family of hypothesis was corrected by means of the Holm-Bonferroni correction. Initially significance was set to $\alpha = 0.05$, which was decreased successively according to the Holm-Bonferroni correction algorithm. Due to the fact that for many of the IV-DV relationship combinations a significant interaction effect was found between pairs of IVs (FP*TM, FP*SM and TM*SM) and the significance was tested for one IV at each level of the other IV (simple effects); in the end, around 100 extra ANOVA tests were performed for each family of hypothesis (H1, H2, H3). The new α after the Holm-Bonferroni correction ranged from 0.05 to 0.0005. Hereafter, when a difference or effect among variables is deemed as significant or not significant it is with respect to its corresponding value after having applied the Holm-Bonferroni correction ($p < [0.05 - 0.0005]$).

A. Safety

1) Conflicts: Fewer conflicts are computed in those scenarios where the RPAS **Flight Performance** is better (closer to the Flight Performance of the A320). As it can be seen in Figure 5 the three best performing aircraft remain very close to the values of the baseline, while the three worse performing aircraft register substantially more conflicts. S22T and RP02 present a specially high number of Conflicts, around 50% more than the baseline. In order to analyze the results with respect to Flight Performance at a higher level of detail its is necessary to have in mind table I and how the six different aircraft were ranked according to their flight performance in terms of TAS, ROC and ROD separately (subsection III-C). For instance, the fact that the slower aircraft (RP02 and S22T) score a much higher number of conflicts than the others indicate that True Airspeed is a relevant factor. RP01 and A320, whose rate of climb is the best out of the six aircraft, scoring fewer conflicts than PAY3 and AT72 indicates that ROC also has a relevant effect on the Number of Conflicts. ROD does not seem to be an important factor since PAY3 and AT72 scenarios had more conflicts than A320 and RP01 scenarios.

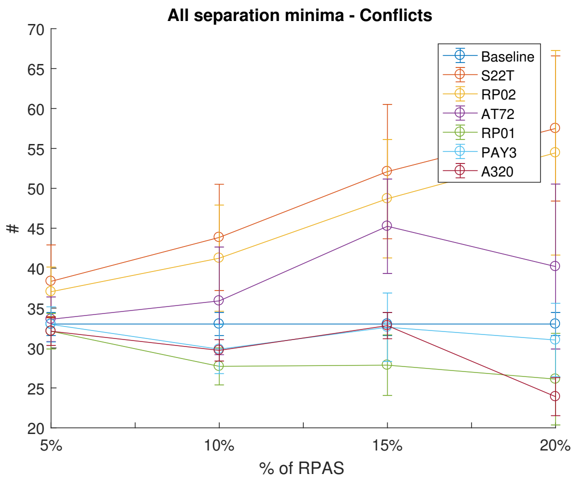


Fig. 5. Number of conflicts against Traffic Mix

In Figure 5 it can aso be seen that increasing the **percentage of RPAS** in the airspace increases the number of Conflicts for the three worse performing aircraft (AT72, RP02 and S22T) while for the three best performing aircraft (A320, PAY3, RP01) it is the opposite, the number of Conflicts decreases.

By means of the three-way ANOVA test it has been found that there is a significant interaction between Flight Performance and Traffic Mix regarding the number of Conflicts. The simple effects of Flight Performance are always significant, at every level of Traffic Mix. The simple effects of Traffic Mix are almost always significant but for the AT72 scenarios. From looking at the graphs it can be concluded that there is an additive effect between those two IVs in a way that Traffic Mix amplifies the effect of Flight Performance, as could be expected.

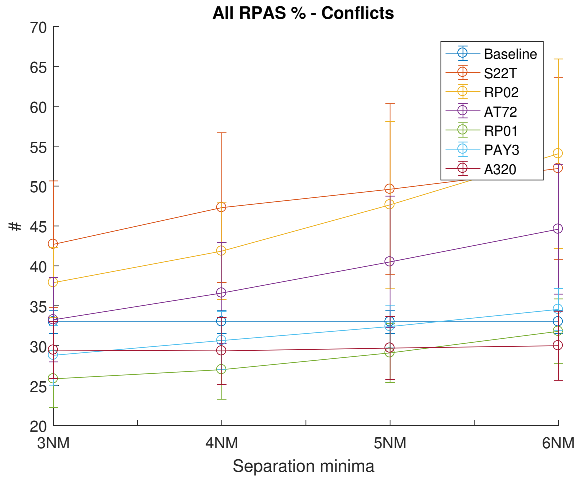


Fig. 6. Number of conflicts against Separation Minima

As can be seen in Figure 6 an increase in Separation Minima translates in an slightly increase in number of Conflicts for every aircraft except for the case of the A320, which remains constant. This observed effect is significant for the PAY3, AT72, RP02 and S22T scenarios.

2) Events of Loss of Separation: Counterintuitively, for some of the RPAS scenarios (AT72, RP02 and S22T) the number of Events of Loss of Separation is higher than the number of Conflicts. A possible explanation for this anomaly is that when a Conflict is solved by the simulated ATCo, another Conflict or Event of Loss of Separation involving a different pair of aircraft is generated. The way the simulator detects Conflicts does not allow it to detect this second Conflict and that is why it is not computed as such but directly as an Event of Loss of Separation. It is also likely that this effect cascades generating several Events of Loss of Separation steming from a single Conflict. It is also important to notice that the simulator is not able to solve every conflict , as it can be seen from the 20 Events of Loss of Separation already present in the baseline.

As it can be seen on Figure 7 the three worse performing aircraft produce a substantially more Events of Loss of Separation than the three best performing aircraft. While in the scenarios with A320 and RP01 RPAS register values similar to the baseline of around 20 Events, on the S22T scenarios between 80 and 140 Events of Loss of Separation took place, which is several times the Baseline value. Again, TAS and ROC seem to be the main factors within **Flight Performance**.

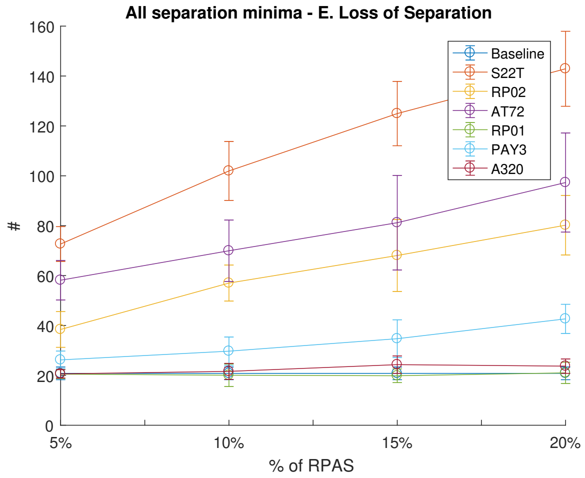


Fig. 7. Events of Loss of Separation against Traffic Mix

The larger the percentage of RPAS present in the airspace the more Events of Loss of Separation occur, with the exception of A320 and RP01 which remain constant. This effect is significant. The largest gradient corresponds to the S22T scenarios which register around 75 Events with 5% RPAS and around 140 with 20% RPAS.

As the Separation Minima increases, the number Events of Loss of Separation registered in the airspace increases significantly only for some of the aircraft, as it can be seen in figure 8.

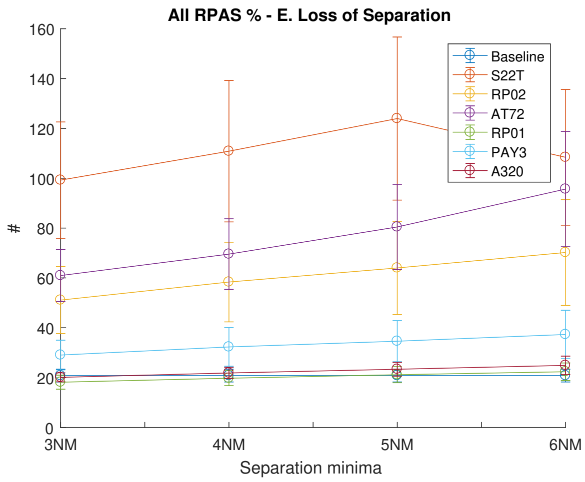


Fig. 8. Events of Loss of Separation against Separation Minima

3) Lateral Separation: Regarding **Flight Performance**, PAY3 and AT72 in general scored slightly higher (safer) values than the baseline, A320 and RP01 did slightly worse and RP02 and S22T substantially worse. Thus, considering the differences in flight performance parameters between the 6 aircraft, it can be concluded that TAS had a bigger effect than ROC and ROD. The largest difference, between AT72 and RP02, accounts for 1NM when the Separation Minima is 6NM and 0.5NM when it is 3NM.The differences found are statistically significant.

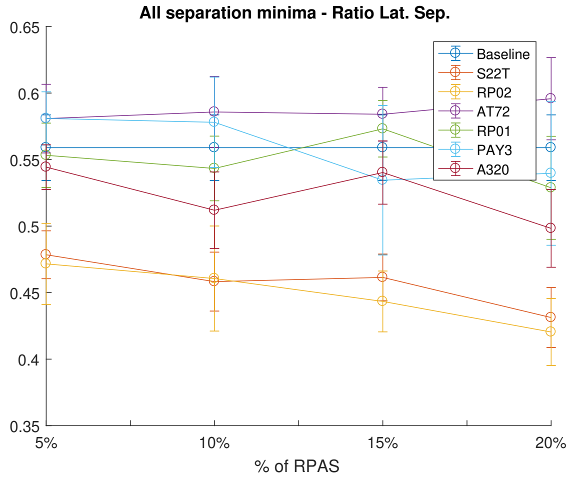


Fig. 9. Lateral separation at Closest Point in ELOS (ratio) against Traffic Mix

The effect of the **Traffic Mix** on Lateral separation is not always significant as there is is a significant interaction between Flight Performance and Traffic Mix: as the FP is worsen, the decrease in Lateral Separation, as percentage of RPAS increases, is accentuated.

The effect of **Separation Minima** is not significant.

4) Vertical Separation: Unexpectedly, the Vertical Separation score for every RPAS **Flight Performance** is better than the baseline, being PAY3 the best and A320 (and the Baseline) the worst. The fact that PAY3 scores the highest and A320 and RP01 so poorly could be an indication that ROD is a more relevant factor for this metric than TAS and ROC. The difference between PAY3 scenarios and the Baseline is of almost 250ft. Flight Performance is a significant factor of the variation of Vertical Separation.

Traffic Mix is has no significant main effect on Vertical Separation, only when in interaction with Flight Performance.

It has been found that **Separation Minima** is a significant source of variation regarding Vertical Separation. As showed in Figure 11 as Separation minima increases the Vertical Separation at the Closest Point of Approach increases slightly.

B. Efficiency

Regarding the Efficiency metrics, the Independent Variable **Separation Minima** has no significant effect on any of the

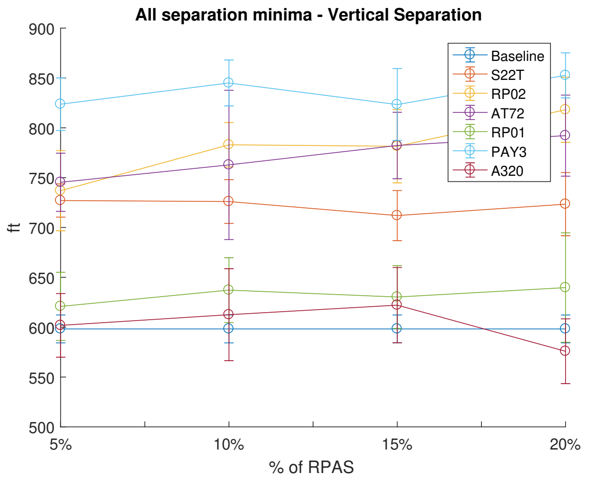


Fig. 10. Vertical Separation at Closest Point in ELOS against Traffic Mix

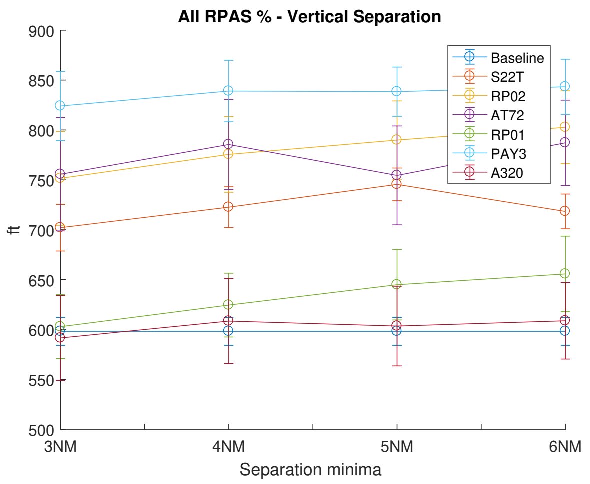


Fig. 11. Vertical Separation at Closest Point in ELOS against Separation Minima

Dependent Variables. **Flight Performance** is a significant factor regarding all of the Efficiency Dependent Variables. Even though there is a significant interaction between Traffic Mix and Flight Performance, **Traffic Mix** has also a significant effect on the Efficiency metrics as almost all the simple effects are significant. It has been found that there is an additive interaction between Traffic Mix and Flight Performance in a way that TM accentuates the effect of FP.

1) Trajectory efficiency: In figure 12 it can be noted that the maximum difference between the scores is of only 2% which accounts for 1NM which effectively is not much when considering that flights cover distances several orders of magnitude higher, but with respect to the distance traveled in the TMA (20NM) 1NM is somewhat meaningful.

For the A320, RP01 and AT72 scenarios the values obtained for Trajectory Efficiency are very similar to the Baseline. PAY3 and RP02 perform slightly worse, and S22T slightly better. Hence, no clear relationship with overall **performance** is observed, nor with either TAS, ROC or ROD.

The **Traffic Mix** effect on Trajectory Efficiency is not consistent. There is a significant interaction with Flight Performance that amplifies its effect, so that as the percentage of RPAS increases the differences between RP02 and PAY3 with S22T increase.

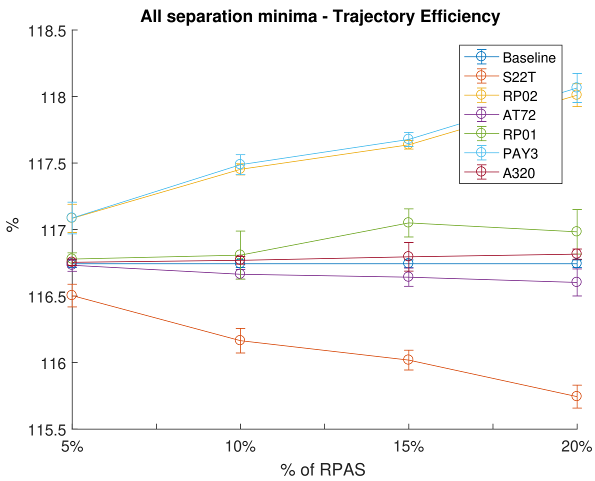


Fig. 12. Distance Efficiency against Traffic Mix

2) Distance: Logically, this metric shows a similar behavior than the previous one. As it is shown in Figure 13 the maximum difference is again of 1NM. It is remarkable that in PAY3 scenarios a shorter distance is traveled consistently, which can be due to PAY3 having the best Flight Performance in terms of Rate of Descend and being the second est in terms of True Airspeed. Those features could be resulting in PAY3 aircraft being more efficient and traveling shorter distances when avoiding conflicts. Another explanation is that the good ROD makes PAY3 reach the lower limit of the the TMA, effectively exiting the simulation and stopping the measurement of their distance traveled in the TMA, sooner than other aircraft.

The virtually identical to the baseline results for the A320 and AT72 are to be expected due to the similarity between the Flight Performance of this aircraft and those of the Baseline (where half of the flights were flown by an A320).

Strangely, in a middle ground between the Baseline and PAY3 values, aircraft with quite different Flight Performances are found: S22T, RP02 and RP01. S22T and RP02 share being the worst performing aircraft, but RP01 was expected to register values closer to the Baseline, as its Flight Performance is more similar to the A320. In any case, the difference in Distance covered is quite small and can be due to the types of Conflicts that arose during the simulations and how they where solved.

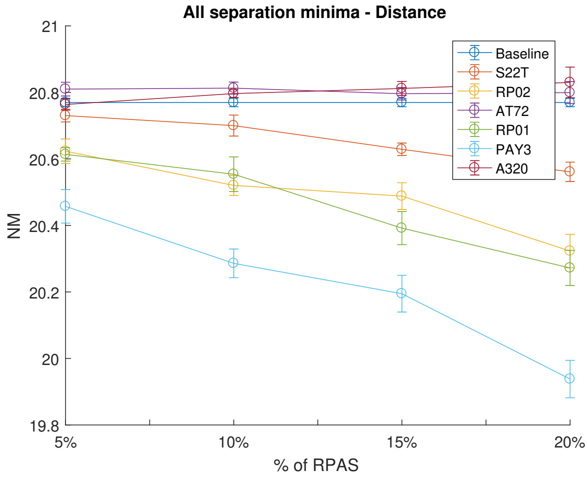


Fig. 13. Distance against Traffic Mix

3) Fuel: As expected, less fuel is burned in every scenario with RPAS in it since the selected aircraft models are lighter aircraft, which naturally burn less fuel. The values of A320 scenarios are very similar to those of the baseline. Not only the weight but TAS could also be a significant factor. Logically, as the percentage of those lighter aircraft in the airspace is increased, the fuel consumption decreases as is shown in Figure 14. Traffic Mix and Flight Performance have a significant interaction regarding Fuel consumption.

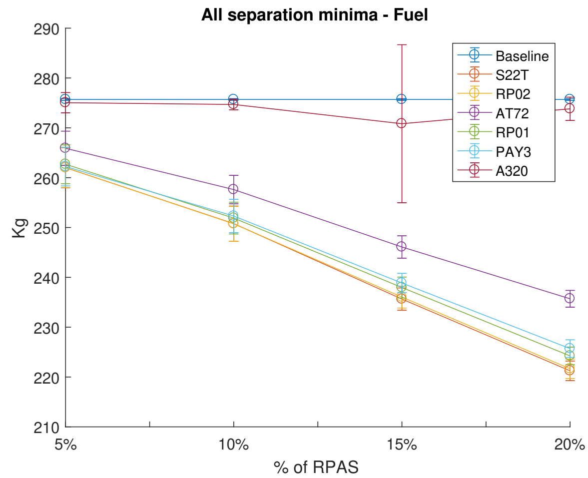


Fig. 14. Fuel against Traffic Mix

4) Time: As it can be seen in Figure 15, the maximum difference is of less than a minute.

The worse the Flight Performance, the more Time is spent in the TMA. TAS is noticeably the main factor, but ROC is also relevant as the RP01 scenarios perform better that the AT72 and PAY3 scenarios.

As the percentage of RPAS is increased, Time increases. There is an interaction between Traffic Mix and Flight Performance.

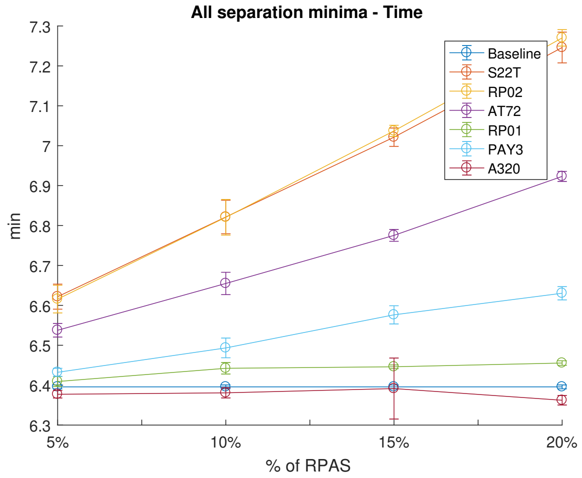


Fig. 15. Time against Traffic Mix

5) Delay: It can be seen in Figure 16 that as the **Flight Performance** worsens the Delay increases. S22T and RP02 register average delays of around 11 minutes, PAY and AT72 6 inutes, RP01 3 minutes (same as the Baseline, where randomly distributed delays of a few minutes were introduced) and A320 has virtually no Delay. TAS seems to be the main contributor within Flight Performance, but ROC is also an important factor as RP01 scenarios score better that PAY3 and AT72 ones.

Traffic Mix and Flight Performance have a significant interaction and the more RPAS are introduced into the airspace the more Delay is registered.

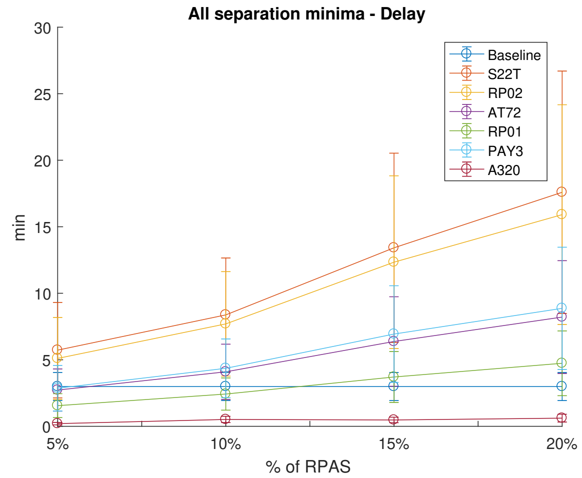


Fig. 16. Delay against Traffic Mix

C. Capacity

1) Workload: The largest difference within the Workload scores is around 6-7%, which equates to 4 minutes in an hour.

The worst performing aircraft (RP02 and S22T) produce the higher Workload. PAY3 and AT72 are not very far behind. And in A320 and RP01 scenarios the Workload remains at Baseline levels. TAS and ROC seem to be the main factors within flight performance since RP01 scenarios have better scores than PAY3 and AT72 scenarios. The effect of **Flight Performance** is significant.

As seen in Figures 17 and 18 Workload increases significantly as the **percentage of RPAS** increases.

Workload also increases significantly as the **Separation Minima** increases (Figures 19 and 20) as expected since an important part of the Workload comes from solving Conflicts (for which Separation Minima was a significant factor combined with Flight Performance).

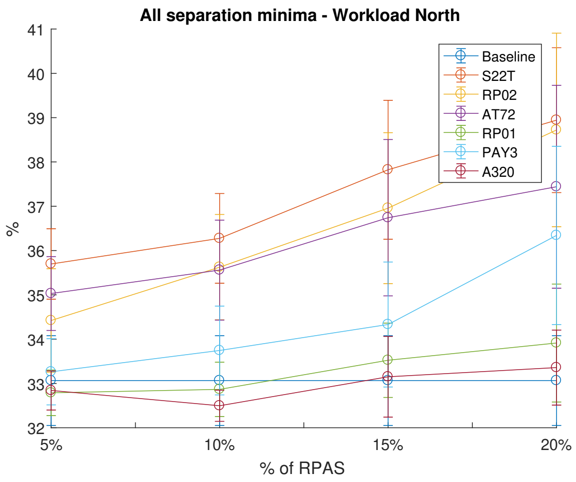


Fig. 17. Workload N against Traffic Mix

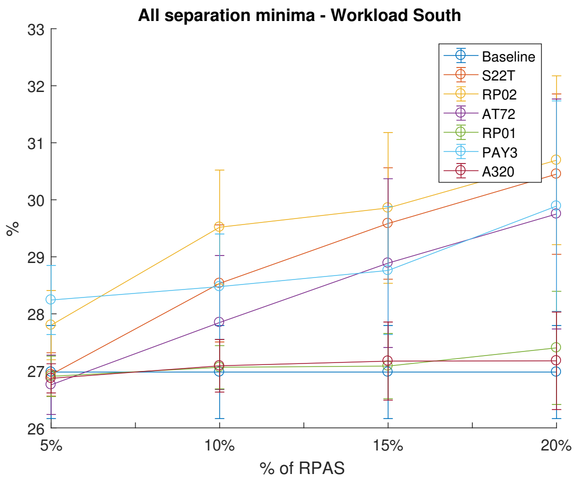


Fig. 18. Workload S against Traffic Mix

2) Occupancy: The mean Occupancy of the TMA allong the different scenarios remains almost constant with a maximum variation of around 2% of the declared capacity

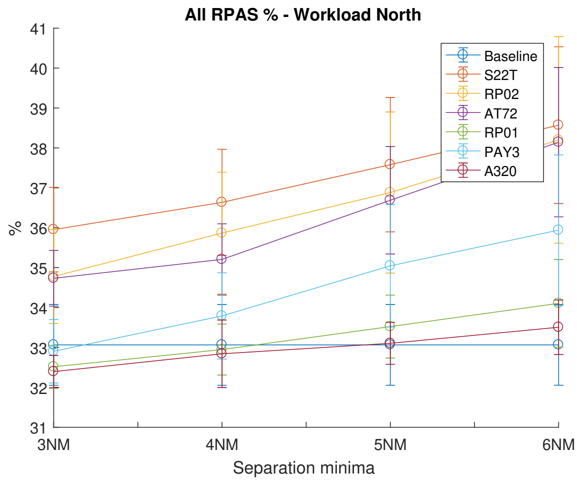


Fig. 19. Workload N against Separation Minima

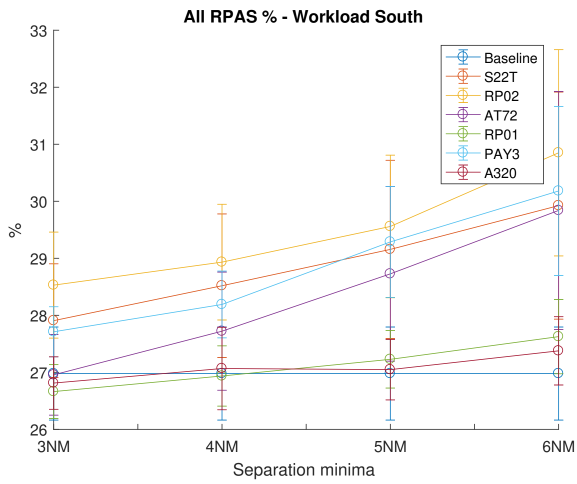


Fig. 20. Workload S against Separation Minima

of the TMA (90 aircraft per hour) that equals to one or two aircraft more per hour, which in practice is not a meaningful difference.

V. Discussion

From the analysis of the results it can be concluded that **Safety** is the most affected Key Performance Area. As RPAS Flight Performance worsens, in terms of True Airspeed, Rate of Climb and Rate of Descend, the number of **Conflicts** and **Events of Loss of Separation** increases considerably. Although, it is true that the obtained values for Conflicts and Events of Loss of Separation cannot be taken at face value since the ATCo model in AirTOp has its limitations and a real life ATCo would have performed more effectively, it is also true that the difference between the scores of S22T and RP02 and the other aircraft are severe. It can be deduced that RPAS with such poor Flight Performance would have to be handled in a special way so as not to disrupt the normal operation of the TMA (i.e.: designing special procedures for them or severely alter the arrival/departing sequence in order to account for their lower speed). That special treatment can be accommodated when there is only a few aircraft in the airspace with special characteristics, the same way it is currently being done with slower aircraft. Nowadays, few aircraft with such poor flight performance fly in controlled airspace, where airliners are the main user. More than 95% of IFR traffic in the data-set was operated by some aircraft whose flight performance is equivalent or comparable to an airliner. So it is logical to think that when there is a substantial proportion of the aircraft whose flight performance greatly differs from the common aircraft, the task of controlling the airspace becomes increasingly complex. Letting any RPAS with any Flight Performance operate in controlled airspace, particularly TMA, would contravene the RPAS/ATM Integration Principles since it has been proven that, their different Flight Performance has a negative impact on the current users of the airspace and on ATC. Therefore, an option to avoid that disruption could be to impose a Flight Performance threshold in terms of Flight Performance for RPAS that intend to fly IFR in a TMA. That threshold could initially be set at **MQ-9 Reaper's Flight Performance** and from there study what happens on real life simulations. Since True Airspeed and Rate of Climb have been the most relevant component of Flight Performance throughout the analysis of results, the proposal would be to set the threshold at **True Airspeed higher than [157 - 204] knots** and **Rate of Climb of at least [886 - 202] ft/min** (Flight Levels between FL030 and FL200). Rate Of Descend was almost never a significant factor, so no limit can be inferred. It is important to emphasize that the proposed threshold is no more than a initial point from which the ANSP's or pertinent authorities could start working on solving the problem. The results of a fast-time simulation cannot be taken at face value and real data ought to be obtained in order to make an educated decision.

Efficiency and Capacity have resulted notably less influenced by the introduction of RPAS in the airspace, still there has been a significant and substantial increase in **Delay** and **Workload** values.

Specially interesting are the results obtained for **Fuel** consumption. The introduction of RPAS in the airspace substantially reduces how much fuel is burned. This finding, while obvious due to the big differences between A320 and the other aircraft models in terms of weight, can make the case for the idea that the integration of RPAS in aviation could be a step forward towards a more environmentally friendly ATM system. Other types of aircraft are possible when the considerations and design requirements related with having humans on-board are disregarded (I.e.: turn rates, angles, g-forces). Besides, different types of missions are now possible with RPAS which could trigger the development of increasingly fuel efficient vehicles.

Regarding the imposed increased Separation Minima for RPAS, it could be seen as an extra operational requirement for RPAS that could increase Safety at the expense of ATCo's workload as more Conflicts and Events of Loss of Separation would occur but theoretically the closest point of approach would be farther from the aircraft. This effect was not supported by the simulations as the effect of Separation Minima was not significant of Horizontal Separation and vague on Vertical Separation at the closest point of approach.

As a follow up **future work** it could be interesting to study the effect of other Flight Performance parameters such as turn rates. Another interesting improvement would be to, instead of assigning relatively arbitrary values to the Separation Minima in order to compensate and model the communications delay inherent to RPAS, to actually simulate it with real values. This functionality is currently being developed and will be available in a future AirTOp version.

As in any experiment it is always useful to get a higher number of data points that confers more statistical significance to the results, in this case, that would mean performing a higher number of simulation runs, using a larger time-frame or modeling and simulating more TMAs.

Following similar methodologies the En-route phase and the TMA environment have been studied, hereafter, it could be of interest to study the entirety of the flight, from take-off to landing.

Lastly, fast-time simulation has its domain which is serving as an initial approach to a problem. Fast-time simulation is a reasonably inexpensive tool that is useful to gain insight that will be used for the design of better tuned, more costly, real life simulations. A variation of the scenarios studied in this project could be tested in real life simulations with real RPAS and Traffic Controllers in order to obtain a better insight on the interaction between manned and unmanned aviation.

VI. Conclusions

An experiment based on fast-time simulations was conducted in order to analyze the effect or RPAS integration in a TMA environment. A comparison was made between the baseline without RPAS and different scenarios where the Flight Performance, Traffic Mix and Separation Minima of RPAS were varied. Results showed that there is a significant effect of RPAS Flight performance of the airpace performance measured in terms of Safety, Efficiency and Capacity. Being safety the most affected area. Worsening RPAS Flight Performances translated into higher number of conflicts and events of loss of separation and reduced separation distances. As the RPAS presence in the airspace was increased the airspace performance indicators worsened. A reasonable initial lower bound regarding Flight Performance for RPAS operating in TMA was proposed.

References

[1] *European Drone Outlook Study. Unlocking the value for Europe*, SESAR Joint Undertaking, Nov. 2016.

[2] ICAO, *Remotely Piloted Aircraft System (RPAS) Concept Of Operations (CONOPS) For International IFR Operations.*, International Civil Aviation Organization, 2011. [Online]. Available: https://www.icao.int/safety/UA/Documents/RPAS%20CONOPS.pdf

[3] ——, *Doc 10019, Manual on Remotely Piloted Aircraft Systems (RPAS)*, first edition ed., International Civil Aviation Organization, Montreal, 2015.

[4] FAA, *Integration of Civil Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) Roadmap*, first edition ed., Federal Aviation Administration, U.S. Department of Transportation, Nov. 2013.

[5] M. Lissone and D. Colin, *RPAS ATM CONOPS*, EUROCONTROL, 2017.

[6] ERSG, *Roadmap for the integration of civil Remotely-Piloted Aircraft Systems into the European Aviation System*, European RPAS Steering Group, European Commission, Jun. 2013.

[7] *U-Space Blueprint*, SESAR Joint Undertaking, European Commission, Belgium, 2017. [Online]. Available: https://www.sesarju.eu/sites/default/files/documents/reports/U-space%20Blueprint%20brochure%20final.PDF

[8] Sesar joint undertaking website - corus project. SESAR Joint Undertaking. [Online]. Available: https://www.sesarju.eu/projects/corus

[9] Eurocontrol website - podium project. EUROCONTROL,. [Online]. Available: http://www.eurocontrol.int/news/u-space-steps-podium

[10] (2018, Mar.) Altitude angel website, press release. Altitude Angel, NATS. [Online]. Available: https://www.altitudeangel.com/blog/nats-enters-strategic-partnership-with-altitude-angel

[11] (2018, Mar.) Airmap website, press release. [Online]. Available: https://www.airmap.com/switzerland-u-space-skyguide-demo/

[12] B. Korn, S. Tittel, and C. Edinger, "Stepwise integration of uas in non-segregated airspace - the potential of tailored uas atm procedures," in *2012 Integrated Communications, Navigation and Surveillance Conference*, April 2012, pp. P1–1–P1–8.

[13] T. L. Martin and D. A. Campbell, "Rpas integration within an australian atm system: What equipment and which airspace," in *2014 International Conference on Unmanned Aircraft Systems (ICUAS)*, May 2014, pp. 656–668.

[14] E. Londner, "Interoperability of horizontal and vertical resolution advisories," in *Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)*, P. of the USA/FAA Air Traffic Management R&D Seminar, Ed., 2015.

[15] S. F. Ali and L. Nguyen, "Uas c2 data link performance for safe automatic flight guidance and control operation," in *2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC)*, Sept 2016, pp. 1–6.

[16] *RPAS C2 link Required Communication Performance (C2 link RCP) concept*, Joint Authorities for Rulemaking of Unmanned Systems, Oct. 2014. [Online]. Available: http://jarus-rpas.org/sites/jarus-rpas.org/files/storage/Library-Documents/jar_02_doc_jarus_rpas_c2_link_rcp_-_10_oct_2014_1.pdf

[17] *Approach To The Introduction Of RPAS In BADA 3 Aircraft Performance Model*, Eec technical note no. 15/11/06-50 ed., EUROCONTROL EXPERIMENTAL CENTRE, Dec. 2015, eEC Technical Note No. 15/11/06-50.

[18] C. Wargo, G. Hunter, K. Leiden, J. Glaneuski, B. V. Acker, and K. Hatton, "New entrants (rpa/space vehicles) operational impacts upon nas atm and atc," in *2015 IEEE/AIAA 34th Digital Avionics Systems Conference (DASC)*, Sept 2015, pp. 1–37.

[19] R. R. Cordón, F. J. S. Nieto, and C. C. Rejado, "Rpas integration in non segregated airspace: the sesar approach," in *Proceedings of the SESAR Innovation Days*. EUROCONTROL, November 2014, pp. 19–20. [Online]. Available: http://oa.upm.es/48602/

[20] L. Ribeiro, S. Giles, R. Katkin, T. Topiwala, and M. Minnix, "Challenges and opportunities to integrate uas in the national airspace system," in *2017 Integrated Communications, Navigation and Surveillance Conference (ICNS)*, April 2017, pp. 1–18.

[21] A. H. Chisvert, "Impact of rpas operations on the atm network minimum performance and operational requirements for the en-route phase," Master's thesis, Delft University of Technology, Jul. 2017.

[22] Airtopsoft, *AirTOp User Guide*, 2015, internal Document.

[23] (2018, Jan.) Aci europe airport traffic report. Airports Council International. Accessed in February. [Online]. Available: https://www.aci-europe.org/

[24] *Annex 11 - Air Traffic Services*, Thirteenth edition ed., International Civil Aviation Organization (ICAO), 2001.

[25] European aeronautical database - ead. EUROCONTROL. [Online]. Available: https://www.ead.eurocontrol.int/fwf-eadbasic/restricted/user/aip/aip_overview.faces

[26] *Manual on Required Communication Performance*, International Civil Aviation Organization (ICAO), 2006.

[27] B. Elbert, *The Satellite Communication Applications Handbook*, ser. Artech House space technology and applications library. Artech House, 2004. [Online]. Available: https://books.google.nl/books?id=D9k5s2-mMKgC

II

Preliminary Report [Already graded]

1 Introduction

Unmanned Aircraft have evolved from being considered, no so long ago, an obscure military technology with a dubious reputation, to driving a blooming market that enables numerous civilian services. The defining feature of not having a pilot on board opens the door to new types of operations that, due to their dangerous nature or intrinsic difficulty for manned aviation, are best performed by unmanned aircraft. Some of these operations are: infrastructure preventative maintenance, precision agriculture, search and rescue missions, urgent delivery, civil protection and humanitarian missions. The use of UAS for these types of operations and many others is expected to grow in the following years. A forecast made by SESAR Joint Undertaking predicts that Unmanned Aircraft will represent the 20% of the fleet for mobility purposes by 2050, which would suppose approximately 10.000 aircraft more [1].

The promising growth prospects for the UAS market imply that a huge number of new airspace users will have to be accommodated in the future Air Traffic Management system. Several international organizations such as ICAO, FAA, EUROCONTROL, EASA, RTCA, EUROCAE and many national ANSPs are currently developing regulations, certification standards, and concepts of operations, as well as researching new technologies that will allow the successful integration of UAS in ATM. They all concur on the same principle: UAS must be treated like any other ATM user, this meaning that they shall follow the same rules as well as benefit from the same rights. [2]. The presence of Unmanned Vehicles (either autonomous or remotely piloted) should not negatively impact other ATM users. Ideally, safety and efficiency levels achieved currently should be maintained. The impact on Air Traffic Controllers' workload should be minimized as well.

This project is made in collaboration with the UAS/ATM Team of EUROCONTROL. EUROCONTROL, the Pan-European organization for the safety of air traffic, works for the safety and efficiency of ATM and plays a key role in the Single European Sky [3]. The UAS/ATM Team works for the safe integration of UAS into ATM by providing guidance on every aspect of the topic, from regulation to technical expertise. This project in particular studies the effect of having manned and unmanned aviation operating non-segregatedly in a Terminal Control Area.

The following section of this document presents the Literature Review on the State of the Art of UAS and their integration into ATM. After that, the research objective and questions are stated. Then, the methodology and experimental set-up are described. This document ends with a brief project planning chapter.

2
State Of the Art

This section is divided into two parts: first, a system description of UAS will be made; secondly, the state-of-the-art of UAS integration into ATM will be presented.

2.1. Introduction to UAS

Before getting to the heart of the matter, some terminology ought to be clarified as there is the tendency to use indistinctively different terms that have slightly different meanings. The following definitions, by the Civil International Aviation Organization, must be clear while reading this document:

- **Aircraft:** *An aircraft is defined 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*[4].
- **UAS (Unmanned Aircraft System):** *An aircraft which is intended to be operated with no pilot on board is classified as unmanned*[4].
- **RPAS (Remotely Piloted Aircraft System):** *RPA are piloted from RPS (Remote Pilot Station) utilizing a command and control (C2) link. Together with other components such as launch and recovery equipment, if utilized, the RPA, RPS and C2 link comprise an RPAS. Thus, RPAS is a subset of UAS*[4].
- **UAV (Unmanned Aerial Vehicle):** UAV is the airborne part of an UAS, but it is an obsolete term according to ICAO.
- **Drone:** Drone is the widely used colloquial generic term that is used to name any type of UAS.

In this document, in line with ICAO's recommendations, the term UAS will be used when referring to the general concept of Unmanned Aircraft, regardless of whether they are Remotely Piloted or Autonomous [4]. The term RPAS will be used only when referring to the Remotely Piloted subset of UAS. The distinction is important since ICAO concludes in "Manual for Remotely Piloted Aircraft Systems" that *"... only unmanned aircraft that are remotely piloted could be integrated alongside manned aircraft in non-segregated airspace and at aerodromes"* [4]. Although this affirmation may be disproved in the future, it does describe the current situation. Furthermore, it is aligned with the scope of this project, which focuses only on Remotely Piloted UAS.

RPAS are composed of several parts and subsystems that should be acknowledged, as they pose different problematics regarding UAS integration in ATM. Thus, the components of RPAS are defined as follows [4]:

- ***RPA - Remotely Piloted Aircraft*** *An unmanned aircraft which is piloted from a remote pilot station.*

- ***RPS - Remote Pilot Station*** *The RPS is the component of the RPAS containing the equipment used to pilot the RPA. The RPS can range from a hand-held device up to a multi-console station. It may be located inside or outside; it may be stationary or mobile (installed in a vehicle/ship/aircraft).*
- ***C2 Link - Command and Control*** *The C2 link connects the RPS and the RPA for the purpose 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). The distinction between RLOS and BRLOS mainly concerns whether any part of the communications link introduces appreciable or variable delay into the communications than the architecture of the link.*
  - *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 time-frame.*
  - *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 transmissions in a time-frame comparable to that of an RLOS system. [4]*

2.2. UAS integration in ATM

The challenge of seamlessly integrating UAS into the current aviation system is a complex task with many ramifications. Several gaps have been identified in areas of activity such as standardization, regulation, certification, flight procedures, airspace assessment, flight rules, personnel training, and research and development [5]. If UAS are to be integrated into the ATM system without deteriorating the existing levels of safety efficiency and capacity, they should be just like any other airspace user. The EUROCONTROL Concept of Operations for UAS integration in ATM identifies the following four principles [6]:

- The integration of RPAS shall not entail 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 risk: the way RPAS operations are conducted shall be equivalent to that of manned aircraft, to the best possible extent.
- RPAS must be transparent (alike) to ATC and other airspace users.

ICAO, FAA and the European RPAS Steering Group (ERSG), in their respective roadmaps, have envisioned a gradual transition divided in three phases[5] [7]. Although the time-frames identified by these organizations slightly differ, their definition of the phases is consistent and can be summarized as follows:

- **Accommodation (FAA, ICAO)/Initial Operations (ERSG):** During this phase the access of UAS to the airspace is limited and is considered on a case by case scenario. Operations are conducted under restrictions defined by the Civil Aviation Authorities and take place mostly in segregated airspace. During this near-term time frame, national and international regulations are developed, research and development is carried out and requirements are defined.
- **Integration:** In this phase UAS conduct their operations according to the developed regulations and meeting the established threshold performance requirements. Restrictions to access non-segregated airspace are alleviated. During this mid-term time-frame harmonization on a worldwide scale that allows cross border operations will be sought.
- **Evolution:** All required policies, regulations, procedures, guidance material, technologies, and training are in place and routinely updated to support UAS operations. During this far-term time frame, appropriately certified and approved RPAS, flown by licensed remote pilots and under the legal responsibility of certified RPAS operators will be able to operate cross border, in non-segregated airspace and over any populated territory.

Different regulations and concept of operations categorize UAS following diverse criteria such as: size, weight, endurance and range, engine type, wing loading, risks (i.e.: EASA's Concept of operations for drones [8]) and type of operations. This last classification is the basis for EUROCONTROL's "RPAS ATM CONOPS" [6], which presents an interesting overview of different RPAS Operations by first dividing them by the altitude at which they occur. Understanding this classification can be useful for properly limiting the scope of this project, thus, a summarized version is provided:

- **Very Low Level operations (VLL) - UAS flying below 500ft** - Although these operations take place below the typical IFR and VFR altitudes for manned aviation, UAS still share the airspace with some users such as balloons, paratroopers, some VFR traffic and gliders. When the operations take place more than 500 meters away from the Pilot in command they are referred to as BVLOS (Beyond Visual Line Of Sight), otherwise being VLOS operations (Visual Line Of Sight) [2]. The next two categories are all BVLOS.
- **IFR and VFR Operations - UAS flying between 500ft and FL600** - Here UAS share the airspace with manned traffic (both VFR and IFR), and thus, they are expected to comply with either VFR or IFR rules. Technically speaking, being compliant with IFR is more feasible so that is what is expected to happen in the first place. VFR is technically more difficult to achieve due to the lack mature enough see and avoid technology and the fact that there is no valid business case for it, so it is expected to happen later in the future [6]. Currently, the common practice for dealing with this type of UAS operations is the segregation of the airspace, assessing the situation case by case. This means that portions of the national airspace are exclusively reserved for drones, either temporarily or permanently.
- **Very High Level operations (VHL) - UAS flying above FL600** - Regular commercial aviation does not operate at these altitudes, but still UAS would have to share the airspace with military aircraft. The types of missions UAS are expected to perform at this altitude are supposed to last for months [6]. Although this part of the airspace is almost empty, UAS would still have to cross controlled and busier airspace at the beginning and end of their mission.

Arguably, **VLL Operations** are at the center stage since they are expected to provide the greatest utility for society and economic growth, hence, VLL Operations gather the biggest efforts from regulators and researchers. The main common goal is to develop an equivalent system as ATM but for UAS: UTM. In Europe, UTM is also known as U-Space. In 2017 the European Commission together with the SESAR Joint Undertaking published the U-Space blueprint, a very high level document describing how an hypothetical future where UAS are seamlessly integrated in urban airspace would look like [9].

Currently, EUROCONTROL is leading two key projects based on the U-Space/UTM concept: CORUS (Concept of Operations for European UTM System) and PODIUM (Providing Operations of Drones with Initial UTM). **CORUS** is a project funded within SESAR Joint Undertaking and EU's Horizon 2020 program which aims to develop a concept of operations for drones based on the U-Space blueprint and the Helsinki Declaration [10] [11]. **PODIUM** is a large-scale demonstration project that will perform four complementary large-scale demonstrations with over 185 drone flights at four different locations in Denmark, France and The Netherlands. UTM solutions will be demonstrated for both VLOS and BVLOS drone flights. The scope covers very low level operations in rural and urban areas, in the vicinity of airports, in uncontrolled and controlled airspace, and in mixed environments with manned aviation [12].

Another project focused on urban airspace is **Metropolis**, by the Technical University of Delft together with ENAC, DLR and NLR, which investigated different airspace structure concepts for urban transport organization for the future (50+ years) [13].

The VLL operations scenario is moving fast and almost everyday something new is happening. For instance, as these lines are being written, UK's ANSP NATS and the UK-based drone traffic management solutions company **Altitude Angel** are joining forces [14]; while in Switzerland the Swiss ANPS Skyguide and **Airmap** (the biggest, US based, UTM service provider) have partnered for Europe's first live demonstration of sophisticated U-space capabilities [15].

Regarding the region of the airspace where manned aircraft fly, the current procedure of segregating UAS operations from manned aviation is not sustainable in the long run given the expected growth of both manned and unmanned air traffic. For **non-segregated UAS operations** to take place safety is paramount. In ATM safety is assured by combining several layers which together minimize the probability of airborne collision: Strategic Conflict Management (i.e.: airspace design and flow management), Separation Provision (ie.: right of way rules, ATC Separation services, Flight Information and Surveillance services), Collision Avoidance (i.e.: TCAS) and finally there is the pilot's See and Avoid capability [16]. A failure in more than one layer is needed for an event of Loss of Separation to occur. It is in controlled airspace where these layers fully contribute to separation assurance, which allows to reach the conclusion that IFR Operations in controlled airspace are the safer option when it comes to BVLOS UAS Operations [17]. For UAS operations to be safe, the lack of pilot's see and avoid function should be compensated by imposing higher requirements to the other layers [16].

Two very prolific areas of research for the safe integration of UAS in ATM are C2 Link and Detect and Avoid:

First of all, a reliable **Command and Control Link** is essential for the safety and success of any type of UAS operation. C2 Link does not only function as a mean of controlling the UAV, but also as a source of information on the state of the system and thus, should compensate for the lack of situation awareness on both the external environment of the aircraft and the on-board systems [18]. Even though C2 Link can be provided by means of different technologies, a set of requirement ought to be met in terms of communication transaction time, continuity, availability and integrity [19]. Contingency procedures are being defined for those situation when RPAS lose the C2 Link connection, or experience other types of malfunctioning. These contingency procedures are varied and depend on type of operation, location, type of airspace type of mission, altitude, etc. Although they are not yet standardized some contingency procedures include the following actions: change altitude to regain C2 Link connection, return to the departure point, fly towards a predefined emergency airport, fly straight to the next flight plan way point, fly a predefined holding pattern [16].

Secondly, for unmanned aviation to be as safe as manned aviation, the lack of See and Avoid needs to be compensated by **Detect and Avoid** systems and algorithms. Interoperability between UAS Detect and Avoid systems and manned aircraft ACAS must be assured by means of compatible and unambiguous resolution advisories given to any aircraft, irrespective of manned or unmanned, involved in a potential conflict [20]. On top of that, the already established parameters for separation assurance (i.e., volumes, times, distances) will have to be revised in order to contemplate the presence of RPAS in a shared airspace [21].

RTCA SC-228 is currently working to develop the Minimum Operational Performance Standards (MOPS) for DAA equipment and a Command and Control (C2) Data Link MOPS establishing L-Band and C-Band solutions [22].

UAS **flight performance** is another key aspect of UAS integration in ATM that is usually mentioned but rarely thoroughly addressed. Generally speaking, existing UAS have worse flight performance characteristics (range, endurance, ceiling, vertical and horizontal speeds...) than civil commercial aircraft [23]. But on the other hand, the lack of human occupants could erase some performance limitations for newly manufactured UAS whose flight performance could surpass manned aviation's. Greater thrust-to-weight ratios, less acceleration constraints, tighter turns, steeper climb and descent segments are expected in a general faster and more responsive vehicles [24]. It is only logical to think that managing any airspace with aircraft of such diverse flight performances is a complex task that can increase the workload of Air Traffic Controllers, which in turn directly impacts on the airspace's capacity and performance. Hence, it is necessary that the Air Navigation authorities and flight planning systems take into account the different RPAS flight performances [24] as both airliners and RPAS will have to comply with the same rules and procedures [25]. Some strategies for mitigating the effect of this diversity of performances are: establishing new route structures, strategic segregation for groups with similar profiles, tactical management of diverse profiles, automation enhancements to handle complex and diverse trajectories and improved surveillance capabilities for UAS [26].

According to ICAO, UAS flight performances should not greatly differ from those of manned aviation so as not to impose a higher workload on the ATCo [2]. The reality is that manned aircraft cover a wide range of flight performances and little to none research has focused on establishing quantitatively flight performance requirements for new airspace users. This is the gap this project aims to fill. Last year, in collaboration with EUROCONTROL's UAS/ATM Team, another Master Thesis Project on this same topic was produced. In this MSc Thesis a methodology to determine the minimum performance requirements for UAS in the en-route phase was developed [27]. Continuing on that work, this project will study the Terminal Control Area (TMA), which is the controlled airspace around one, or several, airports. This type of airspace is worthy of study since performance characteristics have a greater impact on aircraft with diverse flight profiles.

3

Research Objective and Questions

This project is framed into the ongoing international efforts to successfully integrate UAS into ATM. The main objective of the project is to **set the basis for developing flight performance requirements for Remotely Piloted Aircraft by studying the impact of integrating RPAS operations with controlled manned aviation in Terminal Control Area.**

The methodology developed for this purpose encompasses the definition of adequate Key Performance Indicators for the measurement of UAS impact on overall airspace performance, and fast-time simulations of a real TMA with real historic data of IFR traffic. In order to meet the objective of the project, the following question and sub-questions will have to be answered:

- **What are the minimum flight performance parameters UAS should comply with in order to be integrated with manned aviation without negatively impacting it?**
- **What other distinctive characteristics of RPAS are of relevance when integrating RPAS operations with manned aviation in a non-segregated airspace?**
  - How do the integrated operations of UAS with manned aviation impact the TMA's safety?
  - How do the integrated operations of UAS with manned aviation impact the TMA's efficiency?
  - How do the integrated operations of UAS with manned aviation impact the TMA's capacity?
  - Since a disruption is expected due to the intrinsic characteristics of RPAS, to what degree a loss of Safety, Efficiency and Capacity is acceptable?

3.1. Scope

Among the many and various research topics regarding Integration of UAS into ATM, this MSc Thesis' scope is limited to:

- **RPAS**
- **IFR Operations**
- **Controlled Airspace - TMA**
- **Mid-term future**

As explained in the previous chapter, RPAS is the particular subset of UAS that is expected to be integrated with manned aviation in the first place, due to safety and technological feasibility reasons. The selection of RPAS as the system of study involves a set of considerations to bear in mind when modeling these systems into the simulation. Those considerations are flight performance, communications delay and separations standards, which will be described in the following chapter.

Among RPAS operations, only IFR operations will be considered, since they are expected to occur before VFR operations and be more widespread in the studied time-frame [6]. The selected time-frame is Mid-term future. As it was mentioned previously, The SESAR Joint Undertaking outlook study for drones estimated that by the year 2050 20% of the fleet used for mobility purposes will be unmanned [1]. This information will be used to model a realistic ratio of unmanned to manned aircraft on the simulation scenarios.

Finally, and with the aim of following on previous MSc Thesis work which focused on the en-route phase [27], the Controlled Terminal Airspace on an Airport is selected as the scenario for the simulation. Thereby, aircraft performing different flight phases (climbing, descending and cruising) will be analyzed. Analyzing the integration of RPAS in Terminal Airspace is also relevant due to the increasing number of reports of drones flying too close to manned aviation and in forbidden areas made by pilots, incidents from which a large proportion happens in the airspace around airports [28].

4

Experimental set-up

The method chosen for studying the effect of integrated RPAS operations with manned aviation is **fast-time simulation**. Performing fast-time simulations on realistically modeled scenarios allows to obtain reliable results rapidly and cost-efficiently.

The whole process on how the experiment is set-up can be summarized as follows: First, a realistic base simulation scenario will be built using real data of airspace structure, traffic and aircraft performance. Secondly, a number of assumptions and simplifications will be made, which translate into modifications to the input data and the simulation settings. The crucial modification to the initial data is the substitution of a percentage of the aircraft for RPAS, which will fly the same flight plans. The introduced Remotely Piloted Aircraft will present different flight performances at different levels of similarity with respect to manned aircraft. The percentage of the RPAS present in the airspace as well as the separation criteria applied to them will be also variables of the experiment. The simulation scenarios are built by combining all the possibilities of the mentioned variables: **flight performance, percentage of RPAS and separation minima**. From the fast-time simulations airspace performance data will be obtained in terms of **Safety, Efficiency and Capacity**. Previously a proper set of metrics has been defined. Finally, the obtained data from the simulations will be analyzed. The simulator chosen for this project is AirTOp.

A detailed description of this methodology and its components can be found in the next subsections.

4.1. Input data

In order to build a faithful simulation scenario the following input data sets will be imported into the simulation platform:

- Airspace environment: GASEL files
- Real historical traffic data: ALT_FT+ files
- Aircraft performance data: BADA 3 files

4.1.1. Airspace Environment and traffic data

Both Airspace environment and traffic data are obtained from EUROCONTROL's Demand Data Repository. GASEL and ALT_FT+ are the file formats required by AirTOp.

The environment dataset is composed of many files with diverse information such as: free route area, 3D sector definition, airport coordinates, route segment definitions, weekend/night routes, ACCs, configurations, traffic volumes, regulations, airports, navigation points...

On the other hand, historical traffic data is composed of a list of flight trajectories for a given day. Airport of origin and destination, runway, aircraft identification, operator, type of aircraft, Off-Block Times, regulations, airspace intersection data, way-points, fuel data and route charges are some of the fields in the ALL_FT+ files. On top of that, these files contain 3 types of traffic information:

- **Initial Trajectory** is the last filed flight plan from the airline [29].
- **Regulated Trajectory** is the same as the last filed flight plan above except for ATFM delayed flights that contain a constant time-offset corresponding to the Computer-Assisted Slot Allocation (CASA, formerly known as CFMU) calculated ATFM delay for each flight. Equivalent to initial flight plan for non-delayed flights [29].
- **Actual Trajectory** starts as the last filed flight plan (initial trajectory) and then is updated with available radar information whenever the flight deviates from its last filed flight plan by more than any of the predetermined NMOC thresholds of 5 minutes, 7FL or 20NM. The frequency of the radar data feed used by NMOC to update filed flight plans to construct the actual trajectory is one minute. This trajectory represents the closest estimate available in official NEST data files of the flight trajectories actually handled by controllers on the day of operations [29].

The **Initial trajectory** is the most suitable dataset for this project as it conveys the intended flight path and is not affected by ATFM delays which could be due to issues that occurred only on the selected date or in a particular airspace, and other factors beyond the scope of this project. It has been checked that the dataset for the Initial Trajectory and the Regulated Trajectory contains roughly the same data. The Actual Trajectory dataset contains no relevant information for this project as the simulator will be the one to calculate the flown trajectory for the different scenarios.

4.1.2. BADA 3

BADA 3 is composed by a collection of ASCII files containing performance and operating procedure coefficients for 1091 different aircraft types. These coefficients are used to calculate thrust, drag and fuel flow, and to specify nominal cruise, climb and descent speeds [30]. This data will be used by the simulator to accurately calculate the aircraft trajectory. 220 of those aircraft types are considered as directly supported and the data is provided directly in specific files. The other 871 aircraft types are considered as equivalent to one of the directly supported aircraft types and the data is specified to be the same as one of them [30].

The version of BADA used for this project is BADA 3.14. There are six types of files in the dataset [30]:

- **Synonym File:** It is a single file containing a list of all the supported aircraft indicating if they are supported directly or supported by equivalence to one of the directly supported aircraft types.
- **Operations Performance File:** One file for each directly supported aircraft type. It contains parameter values for the mass, flight envelope, drag, engine thrust and fuel consumption of the aircraft.
- **Airline Procedures File:** One file for each directly supported aircraft type. It contains a summary table of speeds, climb/descent rates and fuel consumption at various flight levels.
- **Performance Table Data File:** One for each directly supported aircraft type. It contains a detailed table of computed performance values at various flight levels.
- **Global Parameter File:** This single file contains those parameters that are independent of the aircraft type and those that are of general use (such as maximum acceleration or thrust factors).

Figure 4.1 is an example of an Operations Performance File where the all the different blocks of information can be seen.

Figure 4.1: A306 Operations Performance File [30]

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCC A306__.OPF CCCCCCCCCCCCCCCCCCCCCCCCCCCCC/
CC                                                                    /
CC                AIRCRAFT PERFORMANCE OPERATIONAL FILE               /
CC                                                                    /
CC                                                                    /
CC      File_name: A306__.OPF                                         /
CC                                                                    /
CC      Creation_date: Apr 30 2002                                    /
CC                                                                    /
CC      Modification_date: Sep 05 2008                                /
CC                                                                    /
CC                                                                    /
CC====== Actype ======================================================/
CD   A306__         2 engines    Jet                         H        /
CC  A300B4-622    with PW4158 engines                       wake      /
CC                                                                    /
CC====== Mass (t) ====================================================/
CC    reference      minimum      maximum     max payload  mass grad  /
CD     .14000E+03   .87000E+02   .17170E+03   .39000E+02   .15103E+00 /
CC====== Flight envelope =============================================/
CC     VMO(KCAS)        MMO        Max.Alt       Hmax       temp grad  /
CD     .33500E+03   .82000E+00   .41000E+05   .32378E+05   -.2716E+02 /
CC====== Aerodynamics ================================================/
CC Wing Area and Buffet coefficients (SIM)                            /
CCndrst Surf(m2)     Clbo(M=0)       k           CM16                 /
CD 5   .26000E+03   .13150E+01   .84080E+00   .00000E+00              /
CC   Configuration characteristics                                    /
CC n Phase  Name    Vstall(KCAS)    CD0          CD2        unused    /
CD 1 CR   Clean     .15100E+03   .20591E-01   .51977E-01   .00000E+00 /
CD 2 IC   S15F00    .11700E+03   .33057E-01   .45362E-01   .00000E+00 /
CD 3 TO   S15F00    .11700E+03   .33057E-01   .45362E-01   .00000E+00 /
CD 4 AP   S15F15    .10900E+03   .38031E-01   .44932E-01   .00000E+00 /
CD 5 LD   S30F40    .97000E+02   .78935E-01   .44822E-01   .00000E+00 /
CC   Spoiler                                                          /
CD 1      RET                                                         /
CD 2      EXT                                  .00000E+00   .00000E+00 /
CC   Gear                                                             /
CD 1      UP                                                          /
CD 2      DOWN                    .22500E-01   .00000E+00   .00000E+00 /
CC   Brakes                                                           /
CD 1      OFF                                                         /
CD 2      ON                                   .00000E+00   .00000E+00 /
CC====== Engine Thrust ===============================================/
CC          Max climb thrust coefficients (SIM)                       /
CD     .29716E+06   .51306E+05   .56296E-10   .84814E+01   .44597E-02 /
CC     Desc(low)    Desc(high)   Desc level   Desc(app)     Desc(ld)  /
CD     .32012E-01   .40310E-01   .15161E+05   .13124E+00   .39136E+00 /
CC     Desc CAS     Desc Mach     unused       unused       unused    /
CD     .30000E+03   .78000E+00   .00000E+00   .00000E+00   .00000E+00 /
CC====== Fuel Consumption ============================================/
CC   Thrust Specific Fuel Consumption Coefficients                    /
CD     .63936E+00   .10047E+04                                        /
CC   Descent Fuel Flow Coefficients                                   /
CD     .21196E+02   .67071E+05                                        /
CC   Cruise Corr.    unused       unused       unused       unused    /
CD     .98852E+00   .00000E+00   .00000E+00   .00000E+00   .00000E+00 /
CC====== Ground ======================================================/
CC        TOL          LDL         span        length       unused    /
CD     .23620E+04   .15550E+04   .44840E+02   .54080E+02   .00000E+00 /
CC====================================================================/
FI                                                                    /
```

4.2. Location and Time

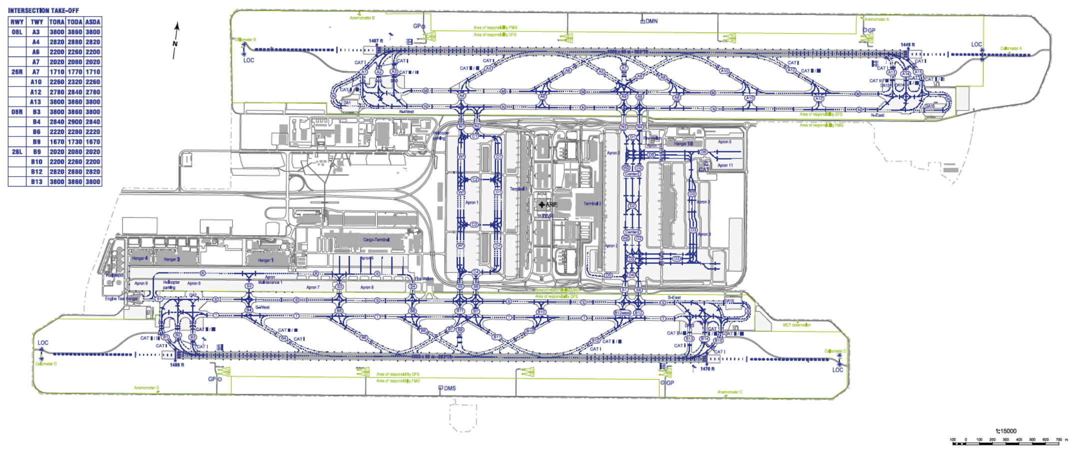
Due to time constrains, the study will be confined to one TMA and one day, particularly **Munich TMA** and the **25th of October, 2017**. The date belongs to AIRAC cycle 1711.

Munich Terminal Airspace has been considered suitable for this study due to two main reasons: first, the main airport of the selected TMA ought to be busy in order to be representative of the busy European airspace; secondly, for modeling and simulation reasons, the traffic in the selected TMA should not be too complex.

Munich airport (ICAO Code: EDDM) is a reasonably busy airport, according to the Airports Council International Airport Traffic Report of 2017, it is the 9th busiest airport in Europe with more than 44,5 million passengers in 2017, an increase of 5,5% over the previous year [31].

As it can be seen in 4.2, Munich airport has two parallel runways. Other European airports were discarded for having too many and/or crossing runways, which can make the departing and arriving traffic more complex. Munich TMA also encompasses other smaller regional airports, only two of which (ICAO codes: EDMA

Figure 4.2: Munich Aerodrome Chart [32]



and EDMO) had scarce IFR traffic in the dataset used for the simulations.

In Annex 11, ICAO describes the seven types of airspaces classes (from A to G) together with the services provided and requirements for each 4.3:

Figure 4.3: ATS airspace classes ICAO [33]

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.

TMAs are mostly labeled as C or D airspaces. Munich TMA is class C which means that ATC clearance is required, separation is provided to all IFR traffic, there is no speed limitation and continuous two-way radio communication is required.

Vertical limits of TMA are usually defined from a few thousand feet to around FL150, depending on the terrain and the surrounding airspace design. Horizontal limits present a much bigger range as they can cover

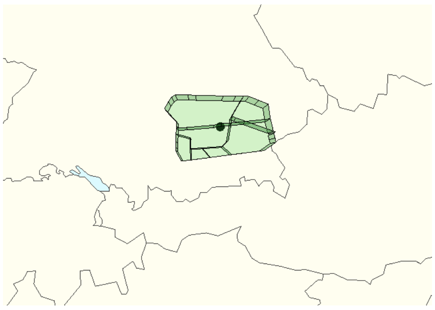


Figure 4.4: Munich TMA plan view

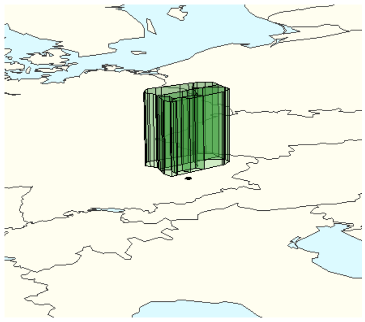


Figure 4.5: Munich TMA 3D view

from one to various airports and their surroundings.

The definition of TMA is sometimes source of ambiguity. On the German AIP, for instance, the term "TMA" is never used. On top of that, the AIP contains two different airspaces called "Airspace in the vicinity of airports" which are related to Munich, with slightly different horizontal and vertical limits. Nonetheless, only one of these airspaces is present in the GASEL files for airspace environment, therefore, for simplicity, this airspace is the one that will be used to build the base simulation scenario. This airspace vertical limits are set initially to GND-FL195, but the lower limits will be modified to 3500ft (which is Munich airport's CTR upper limit) in order to be more consistent with what a TMA should be. This project's scope is limited to the TMA, so what happens in the CTR (from 3500ft to GND in the case of Munich CTR) is out of the scope. In figures 4.4 and 4.5 Munich TMA and airport are displayed. The images are obtained from EURCONTROL's Network Strategic Monitoring Tool (NEST).

One of the main characteristics of IFR traffic in TMA is that it follows standardized procedures for departing and arriving to the airports called SID (Standard Instrumental Departure), STAR (Standard Terminal Arrival Route) and Instrument Approach procedures. It is unknown if RPAS will follow the same procedures as manned aviation or if special procedures will be designed for them. Particularly, Approach Procedures will be out of the scope of this project and they will not be flown: when the aircraft reaches the Initial Approach Fix, which is the also the last point of the STAR, they will fly directly to the airport and be out of the simulation so no data will be produced for them. This simplification is coherent with focusing on TMA and leaving CTR out of the scope, since the largest part of the approach procedure takes place in the CTR (for Munich, IAF are located at 5000ft and CTR starts at 3500ft). To sum up, this project's main area of focus is the effect of different flight performances of RPAS on the ascend and descend phases of the flight, those that take place just before or after the en-route phase , not on how RPAS will be integrated in airports. That area of study is still very immature and too many aspects of it are yet to be defined.

An example of each type of procedure in Munich TMA can be seen in Figures 4.6 , 4.7 and 4.8.

The chosen date is 25th October 2017, Wednesday. This day, a weekday far from the summer and winter holidays, is considered to be representative of a normal traffic situation. From NEST the occupancy counts for an specified sector can be obtained. In Figure 4.9 occupancy Max Daily Hourly Counts for Munich TMA for the whole AIRAC cycle number 1711 can be seen. The occupancy count for the 25th of October falls close to the average value of the whole cycle.

During the 24 hours of the 25h of October, 1272 IFR flights crossed Munich TMA. The distribution of the flights over the day can be seen in figure 4.10. A plan view of the flights is displayed in figure 4.11. figure 4.12 shows the 3D view of the flight profile followed by one of the aircraft that departed from Madrid Airport and landed in Munich. Most of the flight plans had Munich airport as either their arrival or departure airport, but not all of them. 594 of the 1272 IFR flights departed from Munich airport, and 596 arrived, which represents a 47% of the total, each. Only two other airports from Munich TMA had a few IFR operations that day: EDMA (19 operations) and EDMO (7 operations).

The 1272 IFR flights were mostly operated with aircraft from the A320 family, 603 precisely, which means a 47% of the flights. This is partially due to Munich Airport being one of Lufthansa's hub and a big part of Lufthansa's fleet being composed of those aircraft [34]. Other aircraft present on the flight list are CRJ9 (13%

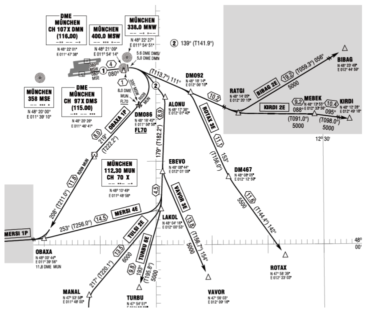


Figure 4.6: SID at EDDM [32]

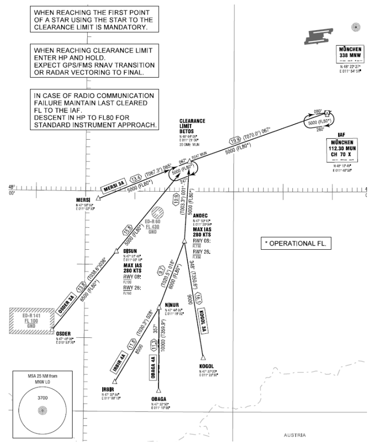


Figure 4.7: STAR at EDDM [32]

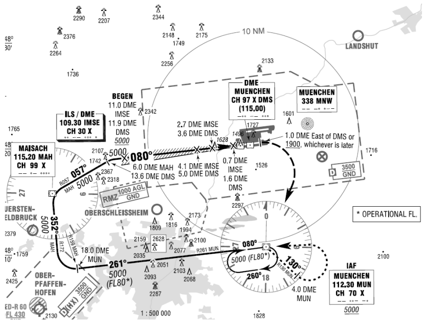
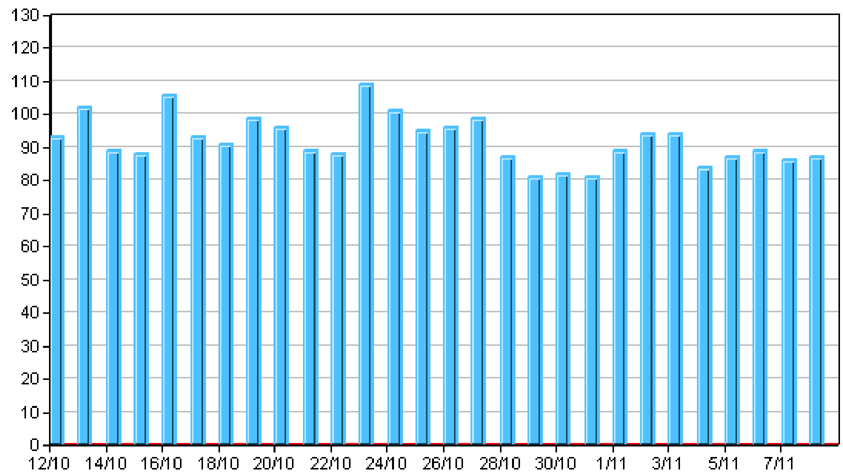


Figure 4.8: Approach procedure at EDDM [32]

Figure 4.9: Max Daily Hourly Counts. Obtained from NEST



of flights), E195 (10%) and B737 (7%).

Figure 4.10: Occupancy Counts. Obtained from NEST

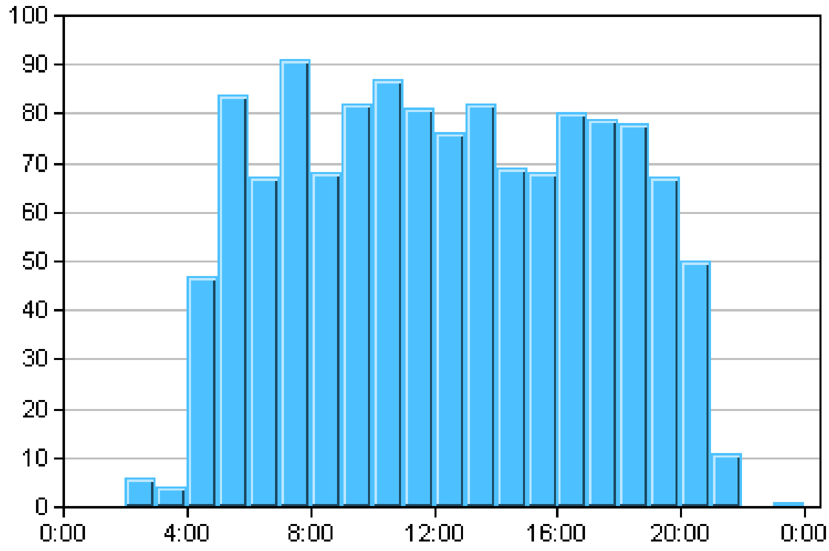


Figure 4.11: Plan view all IFR flights crossing Munich TMA on the 25th of October. Obtained from NEST

Figure 4.12: 3D view of a single trajectory. Obtained from NEST

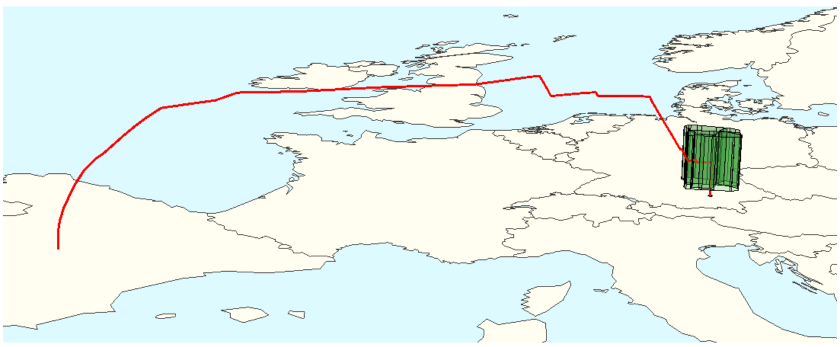


Figure 4.13: RQ4A Global Hawk [35]

Figure 4.14: MQ9 Reaper [36]

4.3. Modeling RPAS

Some modifications to the input data and some special simulator configurations will have to be applied so as to realistically model an airspace where RPAS and manned aviation are integrated and flying the same routes. A percentage of the flights recorded on the historical data will be operated by RPAS, depending on the scenario the percentage will be 5% 10% 15% or 20%. This different percentages aim to reflect different stages of RPAS integration in ATM, up to the predictions made by the SESAR Joint Undertaking of 20% of the aircraft used for mobility purposes by 20150 being unmanned [1]. On the simulation scenarios unmanned aircraft will be differentiated from manned aircraft mainly by their flight performance, but also by the separation standard that will be applied to them. These two particularities of the RPAS in the simulation scenarios will be explained in the following subsections.

4.3.1. Flight performance

For a large part of the scenarios, substituting manned aircraft for RPAS means that the BADA file of part of the aircraft flying through the airspace will be substituted by the BADA file corresponding to an RPAS model.

The 4 RPAS models present in BADA 3 are:

BADA code	**Aircraft name**	**Class**	**Range (km)**	**Endurance (h)**	**Ceiling (ft)**	**MTOW (kg)**	**Cruise speed (kt)**	**Engine type**
RP01	RQ4A Global Hawk	HALE	14000	28	60000	14,628	335	JET
RP02	MQ9 Reaper	MALE	1852	14	50000	4,760	200	TBP
RP03	Generic Tactical RPAS	LALE	2̃00	8-14	16400	490	90	PST
RP04	RQ2A Pioneer	LALE	185	5	12000	205	85	PST

Table 4.1: RPAS Models in BADA 3 [30]

The "Class" column comes from the Military RPAS classification based on altitude and endurance. Thus, the RPAS models present in BADA 3 correspond to the categories: Low Altitude Long Endurance (LALE), Medium Altitude Long Endurance (MALE) and High Altitude Long Endurance (HALE).

RPAS models in BADA 3 reflect how the flight performance of these military RPAS is worse when compared with civil commercial aircraft, in terms of vertical and horizontal speeds. Figures 4.15, 4.16 and 4.17 display a comparison of speeds (True Airspeed, Rate Of Climb and Rate Of Descend) between the two most common aircraft type present in the scenario (A320 and CRJ9), the four RPAS models in BADA 3, a short-haul regional airliner (ATR 72) and a small business aircraft (Piper Cheyenne 3).

As it can be noted from those figures , the performances of the RPAS are, in most of the cases, worse than those of the civil aircraft. RP03 and RP04's flight performances are specially limited: their ceiling is quite low and their speeds are very far from those of the other aircraft. On the other hand, RP01 and RP02, while still not being on the level of manned aviation, they have a more similar flight performance. Hence, RP01 and RP02 are the ones which can represent more realistically an RPAS that could fly in non-segregated airspace with commercial civil aviation. It is interesting to note that the Rate of Climb of RP01 is even better than those

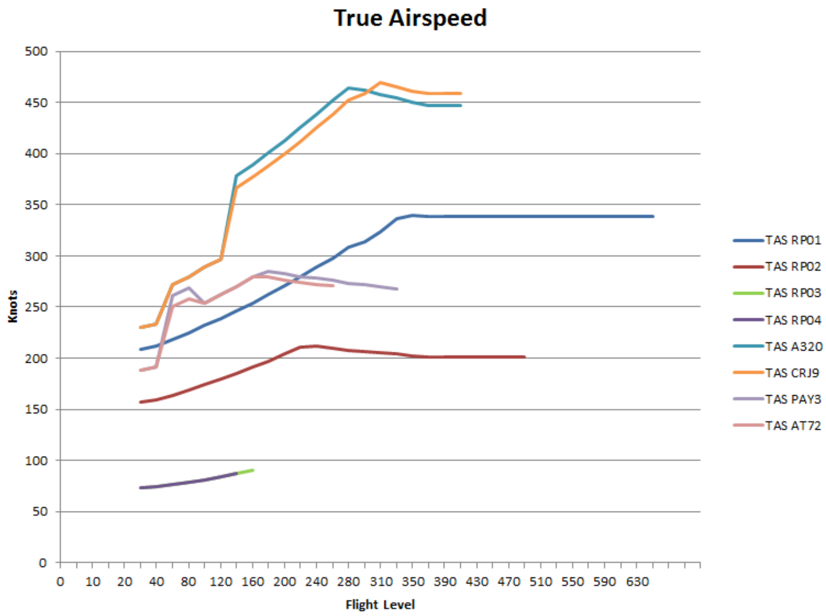


Figure 4.15: True Air Speed Comparison. Data from BADA 3 [30]

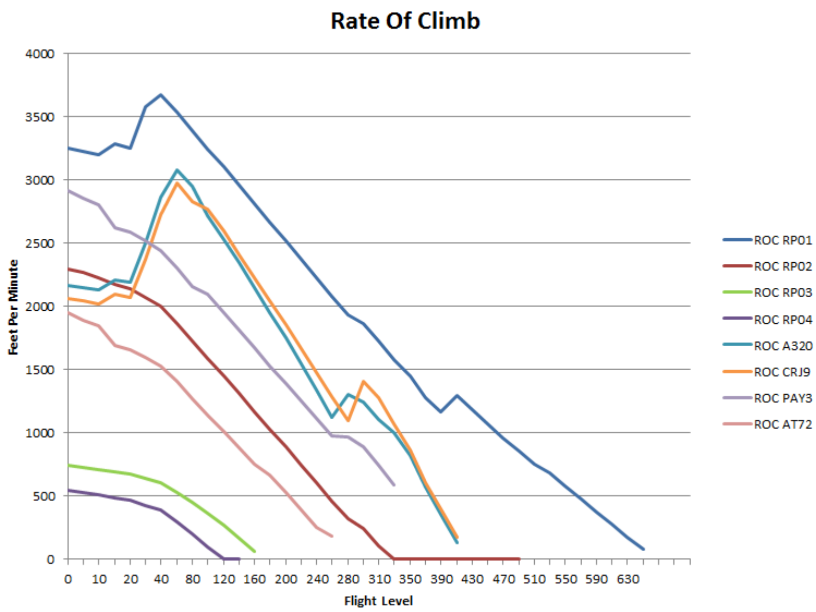


Figure 4.16: Rate Of Climb Comparison. Data from BADA 3 [30]

of manned aircraft. The RQ4A Global Hawk and MQ9 Reaper are military drones commonly used as support for military missions by providing persistent intelligence, surveillance, and reconnaissance information [35]. It is likely that these military RPAS will not share the airspace with civil commercial aviation on a daily basis, but, having such a limited data on RPAS flight performance and being this the criteria, they are the best fit available.

Global Hawk and **MQ9 Reaper** will not be the only Remotely Piloted Aircraft simulated. In part of the simulation scenarios, regular manned aircraft will be modeled as unmanned, this means that the same restrictions RPAS suffer will be applied to them (see next section). This is done to reflect a possible mid-term future scenario where RPAS are just regular aircraft that are not controlled from the cockpit but from any other location outside of it. **A320**, **ATR 72** and **Piper Cheyenne 3** are chosen as they represent diverse levels

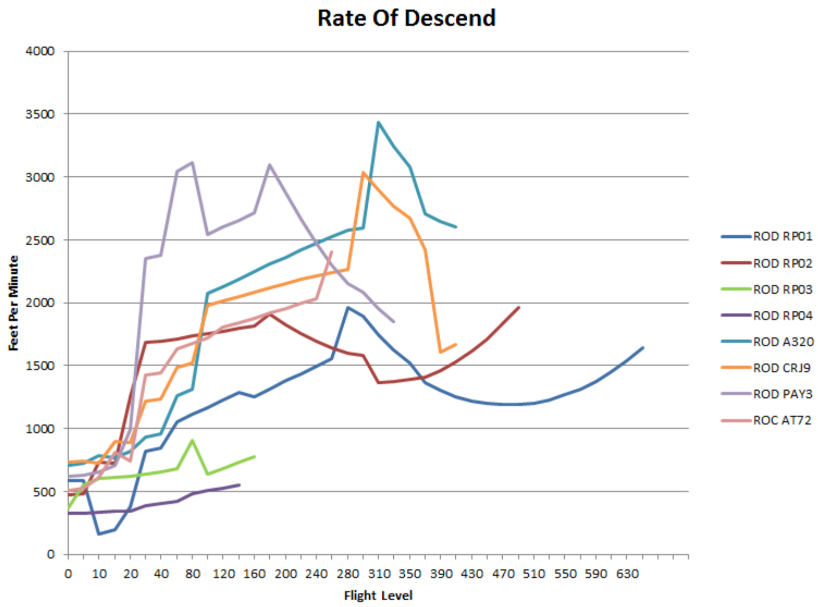


Figure 4.17: Rate Of Descend Comparison. Data from BADA 3 [30]

of flight performance.

4.3.2. Communications delay and Separation standard

The most obvious difference between RPAS and manned aviation is the absence of a pilot on board of the aircraft, this makes necessary the presence of the Command & Control Link (C2 Link). The C2 Link is essential for the successful operation of RPAS as it connects the Pilot in Command with the RPA for the purpose of managing the flight. The failure of the C2 Link during an RPAS operation is the main safety concern for ATM, hence, contingency procedures aim to be standardized are being developed. Contingency procedures for RPAS are out of the scope of this project and it will be assumed that there will be no C2 Link outage during the time-frame of the simulations.

The other aspect of the C2 Link that could negatively impact ATM is Pilot-ATCo communications latency. Having the signal relayed via the RPA and sometimes via satellite introduces delays that are not present in manned aviation. As it can be seen on Figure 4.3 both ATC clearance and a two-way radio communication are required for aircraft to fly through controlled airspace. This requirements will naturally also apply to RPAS. But logically, this communication will require longer periods of time due to the pilot of the RPA not being on board. Two different situations have been identified by ICAO: using the RPA as a relay point for ATC voice and data communications shown on Figures 4.18, 4.19 and 4.20 ; or ATC voice and data to/from the RPS without a relay via the RPA, as can be seen on Figures 4.21, 4.22 and 4.23.

The figures show how the Pilot In Command not being on board the RPA implies that the communication signal has to travel a much longer path. This results in a big latency in RPA reaction to ATC clearance as the PIC is not able to immediately act upon the RPA state. This latency in communications leads to increased ATCo workload and a reduction of airspace capacity [26]. On top of that, as a consequence of the time spent waiting for PIC response the ATCo might lose focus on the general situation of the airspace.

If the worst case scenario is assumed, meaning the scenario with the longest delay in communication, but also keeping in mind that TMA are small airspaces (i.e, assuming transoceanic operations would not make sense). This scenario corresponds to the one in Figure 4.19: communications relayed via the RPA in a BRLOS operation. For a one-way communication path there is one standard VHF transmission, and a transmissions via satellite (two path or a round-trip). We can assume that the VFH transmission will comply with the standards and contribute with 236 ms latency [37]. For the satellited induced latency, it could be assumed that

Figure 4.18: Radio Line Of Sight [4]

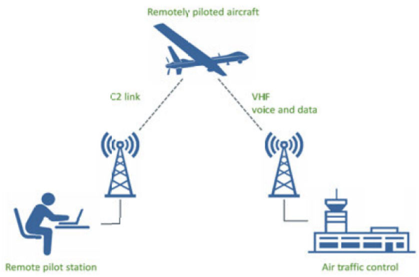


Figure 4.19: Beyond Radio Line Of Sight via satellite [4]

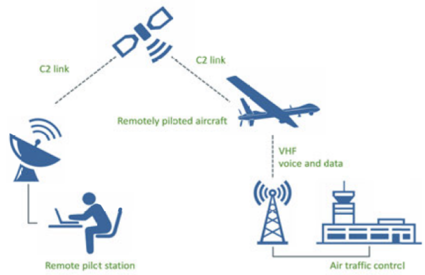


Figure 4.20: Beyond Radio Line Of Sight oceanic operations [4]

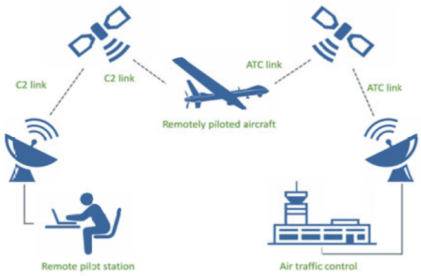


Figure 4.21: VHF ground to ground radio link [4]

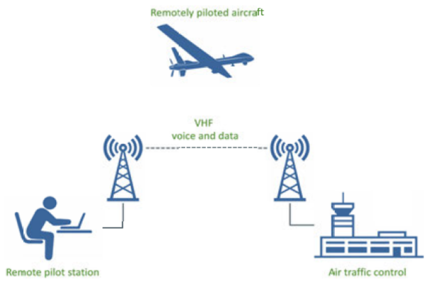


Figure 4.22: Ground only network [4]

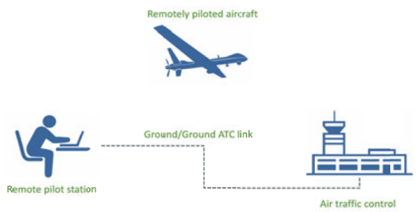
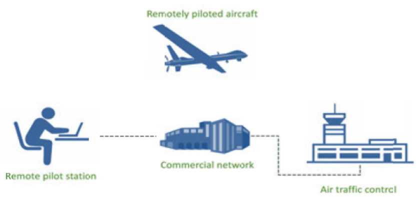


Figure 4.23: Ground via communications service provider [4]



the satellite is in geostationary orbit at 35 786 km above Earth's equator, so the signal will take about a quarter of a second the round trip [38]. But this doesn't take into account internal system latencies so a safe value of 400ms will be picked (this value is also based on real data obtained from experimentation from Eurocontrol experts). Each bit of the communication between Pilot and ATCo will have a (one-way) delay of:

$$Communications\ delay = VHF + C2\ Link(via\ satellite) \times 2 = 236 + 400 \times 2 = 1036ms.$$

So, for every clearance or conversation bit the ATCo gives, they would have to wait for at least 2 seconds to get a response from the Pilot In Command. That is only if the pilot responds immediately since human factors have not been taken into account for the previous calculation.

One possible strategy that could compensate for the above-mentioned shortcomings of RPAS and their C2 Link is the reassessment of separation standards. On top of communication issues, RPAS can be more vulnerable to wake turbulence due to their smaller size. This necessity has been already identified by the pertinent authorities but currently there is no published standard, as RPAS operations are being segregated from manned traffic. For the simulation scenarios RPAS **horizontal separation minima will be increased**. The broadly used value for lateral separation in TMA is 3NM. For simplicity and practical reasons integer values will be used (i.e.: it would not make sense to make the ATCo remember and work with a value of 3.6 NM). The proposed values are: **3NM** (0% increase), **4NM** (33% increase), **5NM** (67% increase) and **6NM** (100% increase). The value of 6NM is an extreme value for experiment purposes only as doubling the separation requirement might be too much and it does not seem reasonable when taking into account the UAS/ATM Integration principles. The vertical separation requirement for every scenario will be 1000ft.

4.4. Simulation platform

Through collaboration with EUROCONTROL for this MSc thesis, access to a state-of-the-art simulator, such as AirTOp, was granted. AirTOp is a fast-time simulator that combines airspace and airport modeling. Its main characteristics are: rule-based gate-to-gate fast-time simulation, multi-agent based modeling, integrated table and map-based application, integrated reporting, open, modular and extensible [39]. AirTOp is able to simulate an ATCo who can solve conflicts and for whom the workload is calculated automatically during the simulation, these two features in particular are of great value for this project and will be described in detail in the following sections. During the implementation of the Conflict Resolution and Detection algorithms, as well as for the Controller workload calculation schema AirTOp development team counted with the guidance of real life ATCos. Definitions and algorithm descriptions of the following sections are based on Airtop's User Guide [39] and personal experience with the simulator.

Figure 4.24 is a screenshot of the simulator window displaying all IFR traffic that crossed Munich TMA during the selected date.

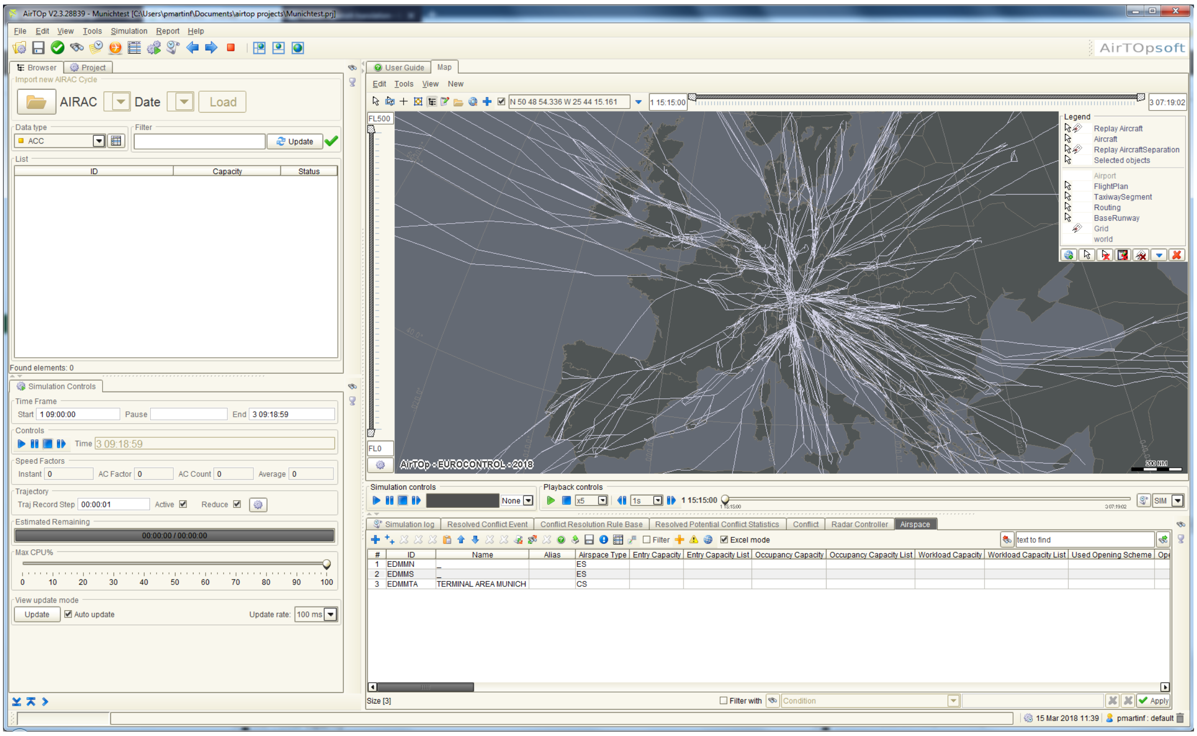


Figure 4.24: AirTOp Simulator. Screenshot obtained from AirTOp

4.4.1. Conflict Detection and Resolution

One of the main features of AirTOp is that it can detect and solve conflicts present in the simulated airspace by means of simulating a "Radar Controller". This functionality includes: detection of a future violation of minimum separation between two aircraft (**conflict detection**); the necessary actions taken by the controller, such as vectoring, altitude changes, speed changes, synchronized descent towards a common way-point etc, in order to separate both aircraft once this future violation of separation is detected (**conflict resolution**); and a **reporting** of an actual violation of minimum separation between two aircraft. The detection of future violation of minimum separation (either vertical or lateral) between two aircraft, which in AirTOp terms is called a **potential conflict** (an actual loss of separation would be a **real conflict**), is performed automatically by creating, for every aircraft, an "Aircraft Ghost" that represents the same aircraft flying several minutes ahead in time (10 minutes by default, user editable).

Once a potential conflict is detected, AirTOp will try to solve it if there is a "Radar Controlled" assigned to the airspace and this Radar Controller has a defined "Decision Tree" for solving the conflicts. This what-if tree models the reasoning a controller performs to choose the most appropriate procedure to separate two aircraft. The default tree is defined in a way that the simulated controller will prefer procedures that will give them less workload and will also penalize the aircraft the less. The Decision Tree, which is customizable, has Conflict Conditions as its parent nodes and Resolution Actions as its leaf nodes. It filters the potential conflict until an applicable Resolution Action at a leaf node is found, if any. The full default Decision Tree can be seen in Appendix A.

In Figure 4.25 an example of a particular conflict is given. First, the root node ROOT accepts any solvable detected potential Conflict. In the second level, the nodes check the vertical state of the real aircraft the moment the potential conflict is detected. In the third level, for every node of the second level, the vertical state of the aircraft at the start of the potential conflict are checked (the vertical state at the potential conflict detection location). In the fourth level, for every node of the third level, the Track Type of the potential Conflict is checked. As the nodes are read in order, the first three nodes of this level are specific situations that might require special resolution actions, and the next nodes are general situations. Finally, at the fifth level, the set of possible applicable resolution actions that can solve the potential Conflict are added. The resolution actions are placed in an approximate order of increasing workload to the controller and aircraft penalization (more changes to its initial Flight Plan, and, consequently, longer distances, more delay, more fuel burn etc).

All the information, statistics and actions taken during a conflict are registered and reported automatically.

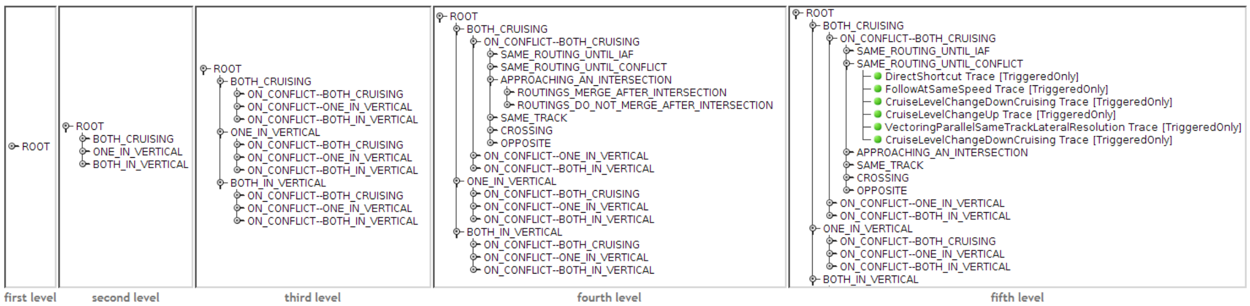


Figure 4.25: Conflict Resolution Tree, particular case [39]

The list of all the resolution actions defined in AirTOp is:

- Direct Shortcut
- Follow At Same Speed
- Follow Separated Until
- Stop Climb

- Stop Descent
- Accelerate Climb
- Accelerate Descent
- Cruise Level Change Up
- Cruise Level Change Down Cruising
- Cruise Level Change Down Climbing
- Vectoring Behind
- Vectoring Parallel At Intersection And Routings Do Not Merge
- Vectoring Parallel Same Track Lateral Resolution
- Vectoring Parallel Same Track Vertical Resolution
- Vectoring Parallel Opposite
- Change Speed

AirTOp also counts with a functionality called Manual Conflict Resolution Command, which is a user-specified conflict resolution command that overrides the Conflict Resolution Tree for an specific type of Conflict.

4.4.2. Controller Workload Schema

AirTOp provides two ways of calculating workload:

- **Task-based:** An average work duration is assigned to each of a list of tasks, such as ATC Sector entry / exit, altitude change clearance, etc. The total workload is calculated by multiplying this average by the number of times the task is performed. Each tasks can be subdivided into activities, such as communication, strip update etc; then, the total workload for each activity across all tasks is also calculated.
- **Monitoring-based:** A monitoring task is defined by giving a start event and an end event that delimit the time during which an Aircraft or other object will be monitored. These could be, for example, sector entry and exit, or Conflict begin and end. Each monitoring task is assigned a period duration representing the interval at which the task is performed, and an average work duration which is assigned to the controller each time the task is performed.

These two workloads are added together to calculate the total workload for each Radar Controller. The workload is a rolling average over a specified time interval, and is updated dynamically during the simulation.

AirTOp includes a predefined Controlled Workload Schema which was developed in close collaboration with real life ATCos. It includes numerous parameters which can be modified by the user such as: activities and sub-activities which generate workload, duration of those activities, weights for pondering how much the activites influence the workload of the Radar Controller, frequency for workload calculation, etc.

4.5. Metrics

RPAS' diverse flight performances and communications delay are expected to impact on the TMA's performance, which will be measured in terms of Safety, Efficiency and Capacity. These three Key Performance Areas have been chosen as being the most suitable for assessing airspace performance from the various KPAs that ICAO has identified [40]. The associated Key Performance Indicators for each KPA will be:

- **Safety**

  - N. of conflicts
  - N. of events of loss of separation
  - Conflict severity (scale 1-6)
- **Efficiency**
  - Route efficiency (%)
  - Fuel consumption (kg/flight)
- **Capacity**
  - Workload (% of time)
  - Sector occupancy (aircraft)
  - Sector overload (aircraft)

Those KPIs will serve to compare a reference baseline with the scenarios where manned aviation and RPAS are sharing the airspace. The baseline consist of the normal traffic with no RPAS and no Modification to the data so as to get the KPI's reference values.

All the Safety metrics are directly obtained from the simulator output data. AirTOp provides a reporting functionality that allows the user to define custom reports based on any property of any object in a simulation. There are also several default reports which can be added to any scenario which can be used as a basis for creating new types of reports. **Number of conflicts** and **losses of separation** are easily obtained from those reports. Furthermore, information regarding the type of conflict, resolution action taken, type of aircraft involved, etc. can also be obtained and analyzed.

AirTOp computes **Conflict severity** as the ratio between the actual and the required separation distances and then defines the following scale with values between 0 and 6, where 6 is a crash:

$$Ratio = \frac{Separation\,distance}{Required\,separation\,distance}$$

$Severity6 : ratio = 0$
$Severity5 : 0 < ratio < 0.20$
$Severity4 : 0.20 \leq ratio < 0.50$
$Severity3 : 0.50 \leq ratio < 1.00$
$Severity2 : 1.00 \leq ratio < 1.20$
$Severity1 : 1.20 \leq ratio < 1.50$
$Severity0 : 1.50 \leq ratio$

Severity 6 to 3 correspond to conflicts where a loss of separation occurs, and severity 2 to 0 are those conflicts which are successfully resolved.

Regarding efficiency, AirTOp is able to compute **Route Efficiency** Distance as percentage:

$$RouteEfficiencyDistance(\%) = \frac{Distance\,flown\,distance}{Great\,circle\,distance}$$

Since the duration of the flights and the velocities are also known from the output of the simulation, Route Efficiency in terms of Time could be calculated as well.
Both Distance and Time Efficiencies are calculated with respect to the optimal great circle route, but in the end all KPI will be compared with respect to the baselines defined. On top of that, given the fact that TMA are small airspaces, great circle distances will not greatly differ from the flight plan distance.

For **fuel consumption** calculations, AirTOp retrieves the fuel consumption from the BADA 3 file of each aircraft present in the simulation, which defines fuel consumption depending on the Aircraft altitude and its state (cruising, descending climbing).

For **workload** calculation AirTOp applies the following algorithm every time interval (10 minutes by default, can be modified):

1. Find the duration of the work involved in handling events (**task-based workload**): For each object which has a property that generates task-based workload count the number of change events for which the Radar Controller was responsible, and which occurred during the last time interval. Multiply this number by the corresponding defined duration, in seconds, of the work involved in handling these change events.

2. Find the duration of the work involved in monitoring objects (**monitoring-based workload**): For each monitoring task, which have a defined start and end events, determine the total monitoring duration for all monitored objects during the time interval.

3. Work duration during the last time interval is obtained by adding the durations from step 1 and 2.

4. The workload is the ratio between the duration of the work and the time interval, expressed as a percentage.

$$Workload(\%) = \frac{Work\,Duration\,(min)}{Time\,interval\,(min)} \times 100$$

The **sector occupancy** is the number of flights present in the sector and during a given time interval. It is easily obtained from AirTOp's output data.

Sector overload is the difference between the predefined sector capacity and the demand, which is the number of aircraft that want to enter the sector. The nominal capacity of Munich TMA is 121 every hour according to the data obtained from DDR. It is highly likely that this capacity cannot be maintained when RPAS are introduced due to the increased workload. Hence, a capacity re-assessment might need to be performed.

4.6. Assumptions

Simulating an hypothetical situation many years in the future is a complex task, thus, some assumptions and simplifications are made:

- The simulations take place in the mid-term future, when RPAS operate non-segregatedly with manned aviation and follow the same procedures.
- C2 link service is provided
- No C2 Link loss occurs during the simulation, so no contingency procedure is triggered.
- Detect and Avoid systems are in place.
- RPAS comply with every airspace requirement in terms of equipment.
- No rogue aircraft, every airspace user collaborates with ATC.
- An airspace assessment has been executed and there are no-drone zones in the volume of the airspace selected for the project. Currently, this is not true as most European regulations on UAS declare CTR as no-drone zones. It is assumed that in the Mid-term future, UAS will be allowed to operate using manned aviation airports and operate in CTRs without endangering other users.
- Meteorological conditions are not taken into account.

4.7. Experiment outline

To summarize, the project consists of comparing current airspace performance with an hypothetical future situation in which RPAS are integrated with manned aviation, focusing specially on the effect of diverse flight performances. The inherent characteristics of RPAS will introduce several sources of disruption into the scenarios, so a compromise solution will need to be found. The experiment outline is as follows:

- **Dependent variables:**
  - Safety
  - Efficiency
  - Capacity
- **Independent variables:**
  - Flight performance
  - Percentage of RPAS in the TMA
  - Separation standard
- **Fixed Parameters:**
  - Airspace configuration, size, shape, structure...
  - Traffic density
  - routes and Flight Plans

The experiment matrix is three-dimensional based on the following variables:

Table 4.2: Experiment Matrix

Flight Performance	% of RPAS	Separation
RP02	5%	3NM
RP01	10%	4NM
PAY3	15%	5NM
AT72	20%	6NM
A320		

The five aircraft models are selected due to their different levels of flight performance in terms of horizontal and vertical speeds. They are ordered from worse to best performance, being True Airspeed the variable which is more clearly distinct in the five aircraft, see Figure 4.15. Incidentally, those aircraft models are also a representation of different types of aviation: from civil (scheduled airline, regional and private) to military aviation. The RPAS models (**Global Hawk and MQ-9 Reaper**) are chosen from the four RPAS models present in BADA as they are the only two aircraft whose flight performance is comparable to manned aircraft (despite being military aircraft which are unlikely going to operate in a civil TMA such as Munich). The performance of the discarded RPAS is just nowhere near manned aviation's. 47% of the flights that crossed Munich TMA during the selected date were operated with a **Airbus A320**, which, additionally, is a good embodiment of the typical airliner. The intermediate levels between the A320 and the RPAS, in terms of flight performance, are filled with the regional aircraft **ATR-72** and the small business aircraft **Piper Cheyenne**, which is an aircraft that is currently being flown in the airspace even though its flight performance is not that good when compared to the airliners.

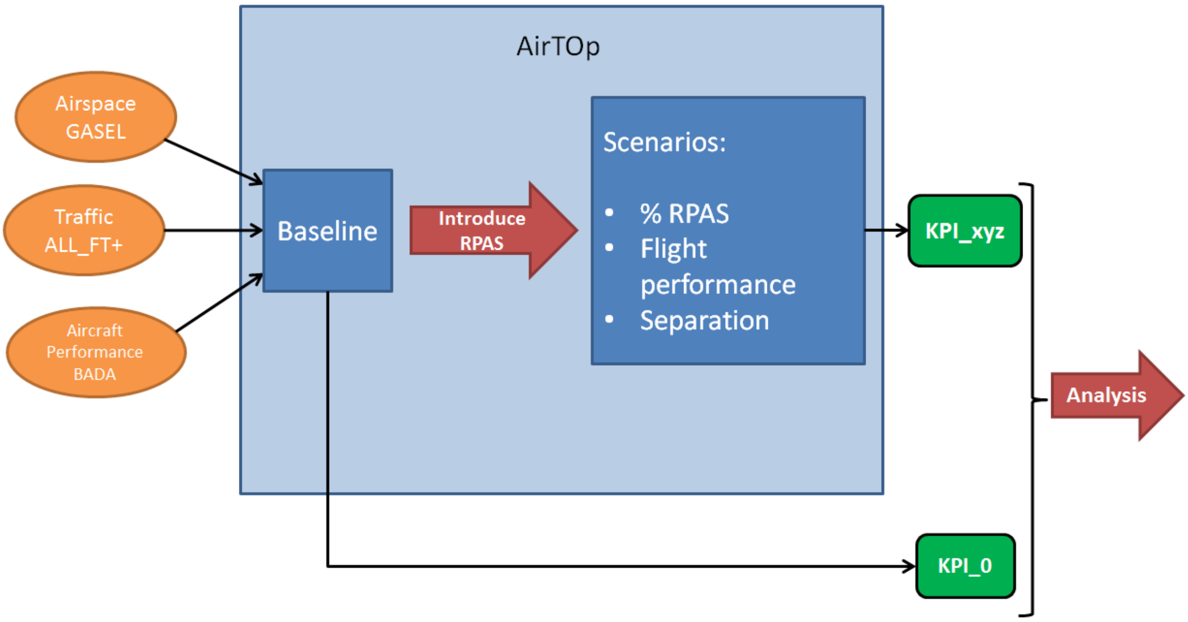
The different percentages of RPAS present in the scenario aims to represent different stages of RPAS integration in ATM, up to the 20% by 2050 predicted by the SESAR Joint Undertaking outlook study [1].

In order to cope with the particular characteristics of RPAS which pose a threat to the high levels of safety achieved nowadays in ATM, increasing separations requirements will be imposed to RPAS ranging from 0%

to 100% increase in the horizontal separation minima.

From the experiment matrix it follows that a total of 80 different scenarios will be simulated.

Figure 4.26: Experimental set-up diagram



4.8. Hypothesis

It is almost certain that the integration of RPAS Operations with manned aviation will disrupt the normal performance of the airspace. Here below a set of hypothesis is gathered describing what the expected results of the simulations are and what the relation between the RPAS modeled characteristics and the selected metrics will be:

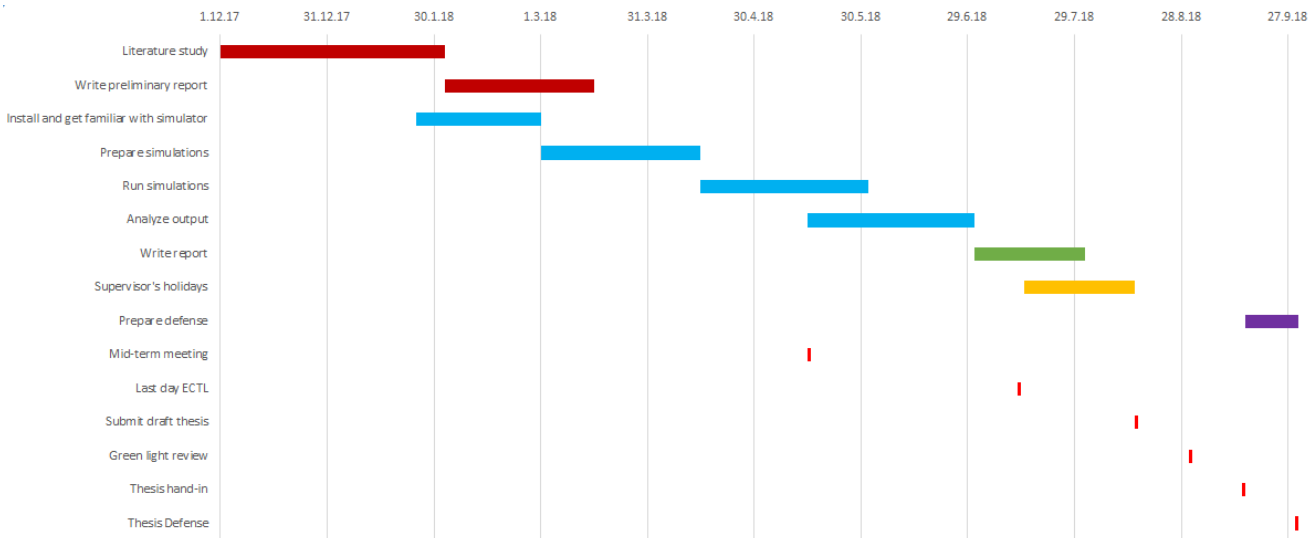
- The presence of RPAS in the airspace is expected to negatively affect the performance of the airspace, in terms of the following Key Performance Areas, as follows:
  - **Safety:** A higher number of conflicts are expected in the scenarios with RPAS compared to the baseline scenario. In addition, those conflicts will be more severe as a consequence of the limited RPAS flight performance and the imposed increased separation requirement for RPAS. Safety is expected to be the most negatively affected Key Performance Area.
  - **Efficiency:** More time will be spent on the airspace, on average, due to the lower speeds of RPAS. The average distance flown inside the sector could increase too as a consequence of the resolution of the conflicts. In terms of fuel consumption, nothing can be hypothesized as two opposing effects are expected: increased times and distances flown against the lower consumption of the RPAS models used in the simulation.
  - **Capacity:** The workload of the Air Traffic Controller will increase as more conflicts are expected to occur. The airspace will be become more overloaded as flights will spend more time in it.
- The independent variables are expected to have the following influence on the airspace performance:

- As the **percentage of RPAS** in the airspace is increased, the performance of the airspace measured in terms of Safety, efficiency and Capacity, will decrease.
- Increasing the **separation requirement** for RPAS will worsen the airspace performance.
- Airspace performance will be more negatively affected by those RPAS whose **flight performance** (in terms of vertical and horizontal speeds) is less similar to manned aircraft. The reference for "manned aircraft" being the most common aircraft on the airspace at issue: Airbus A320 and Bombardier CRJ-900.

5
Project Planning

This MSc project is divided into smaller work activities which are depicted in the following Gantt chart:

Figure 5.1: Project Gantt Chart



The project can be divided into 3 main groups of activities (represented in the Chart with different colors for clarity):

- Research and project planning (red)
- Experiment related work (blue)
- Writing of report (green)

The research and project planning group of activities encompasses all the work related with the gathering of information, literature review and definition of the experiment. It has 2 main deliverables: Research Plan for the course Research Methodologies and Preliminary Report for Literature Study.

Simulation related work consists of many activities related to the simulations such as: installing the simulator, getting familiar with it and learning how to use it, obtaining the input data, adjusting the input data to the desired form and running the simulations.

After the simulations are performed the data obtained from them has to be analyzed and conclusions drawn. This is a key activity of the project. Since there are several scenarios to simulate, and when the majority of them have been simulated, a simple analysis of results could be performed in parallel.

Although the writing of the thesis report is planned for only one period towards the end of the project, some parts of the report could be written while performing other activities in parallel.

With all of this in mind, these are the deliverables and milestones:

- 1st of December – Kick off meeting
- 2nd of February – Research Plan (Research Methodologies)
- Mid-March – Preliminary Report (Literature Study)
- Mid-May – Mid-Term meeting
- 13th of July – Last day of traineeship at EUROCONTROL.
- From Mid-July until Mid-August – TU Delft supervisors on vacation.
- Mid-August – Thesis report draft
- End of August – Green light review
- Mid-September – Thesis hand-in
- End of September – Thesis Defense

It is important to note that this is just an initial plan and that the dates of the milestones could change as the project progresses.

Bibliography

[1] *European Drone Outlook Study. Unlocking the value for Europe.* SESAR Joint Undertaking, November 2016.

[2] ICAO. *Remotely Piloted Aircraft System (RPAS) Concept Of Operations (CONOPS) For International IFR Operations.* International Civil Aviation Organization, 2011. URL `https://www.icao.int/safety/UA/Documents/RPAS%20CONOPS.pdf`.

[3] EUROCONTROL. Eurocontrol´s official website. URL `https://www.eurocontrol.int/`.

[4] ICAO. *Doc 10019, Manual on Remotely Piloted Aircraft Systems (RPAS).* International Civil Aviation Organization, Montreal, first edition edition, 2015.

[5] FAA. *Integration of Civil Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) Roadmap.* Federal Aviation Administration, U.S. Department of Transportation, first edition edition, November 2013.

[6] M. Lissone and D. Colin. *RPAS ATM CONOPS.* EUROCONTROL, 2017.

[7] ERSG. *Roadmap for the integration of civil Remotely-Piloted Aircraft Systems into the European Aviation System.* European RPAS Steering Group, European Commission, June 2013.

[8] EASA. *Concept of Operations for Drones. A risk based approach to regulation of unmanned aircraft.* European Aviation Safety Agency.

[9] *U-Space Blueprint.* SESAR Joint Undertaking, European Commission, Belgium, 2017. URL `https://www.sesarju.eu/sites/default/files/documents/reports/U-space%20Blueprint%20brochure%20final.PDF`.

[10] Sesar joint undertaking website - corus project. URL `https://www.sesarju.eu/projects/corus`.

[11] Drones helsinki declaration, November 2017. URL `https://ec.europa.eu/transport/sites/transport/files/2017-drones-declaration-helsinki.pdf`.

[12] Eurocontrol website - podium project. URL `http://www.eurocontrol.int/news/u-space-steps-podium`.

[13] Metropolis website. URL `https://homepage.tudelft.nl/7p97s/Metropolis/`.

[14] Altitude angel website, press release, March 2018. URL `https://www.altitudeangel.com/blog/nats-enters-strategic-partnership-with-altitude-angel`.

[15] Airmap website, press release, March 2018. URL `https://www.airmap.com/switzerland-u-space-skyguide-demo/`.

[16] B. Korn, S. Tittel, and C. Edinger. Stepwise integration of uas in non-segregated airspace - the potential of tailored uas atm procedures. In *2012 Integrated Communications, Navigation and Surveillance Conference*, pages P1–1–P1–8, April 2012. doi: 10.1109/ICNSurv.2012.6218440.

[17] T. L. Martin and D. A. Campbell. Rpas integration within an australian atm system: What equipment and which airspace. In *2014 International Conference on Unmanned Aircraft Systems (ICUAS)*, pages 656–668, May 2014. doi: 10.1109/ICUAS.2014.6842310.

[18] S. F. Ali and L. Nguyen. Uas c2 data link performance for safe automatic flight guidance and control operation. In *2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC)*, pages 1–6, Sept 2016. doi: 10.1109/DASC.2016.7778017.

[19] *RPAS C2 link Required Communication Performance (C2 link RCP) concept.* Joint Authorities for Rulemaking of Unmanned Systems, October 2014. URL http://jarus-rpas.org/sites/jarus-rpas.org/files/storage/Library-Documents/jar_02_doc_jarus_rpas_c2_link_rcp_-_10_oct_2014_1.pdf.

[20] Edward Londner. Interoperability of horizontal and vertical resolution advisories. In Proceedings of the USA/FAA Air Traffic Management R&D Seminar, editor, *Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)*, 2015.

[21] David P Thipphavong, Andrew Cone, and Seungman Lee. Ensuring interoperability between uas detect-and-avoid and manned aircraft collision avoidance. In Proceedings of the USA/FAA Air Traffic Management R&D Seminar, editor, *12th USA/Europe Air Traffic Management Research and Development Seminar (ATM2017)*, 2017.

[22] Rtca website, 2018. URL https://www.rtca.org/content/sc-228.

[23] *Approach To The Introduction Of RPAS In BADA 3 Aircraft Performance Model.* EUROCONTROL EXPERIMENTAL CENTRE, eec technical note no. 15/11/06-50 edition, December 2015. EEC Technical Note No. 15/11/06-50.

[24] C. Wargo, G. Hunter, K. Leiden, J. Glaneuski, B. Van Acker, and K. Hatton. New entrants (rpa/space vehicles) operational impacts upon nas atm and atc. In *2015 IEEE/AIAA 34th Digital Avionics Systems Conference (DASC)*, pages 1–37, Sept 2015. doi: 10.1109/DASC.2015.7311593.

[25] Ricardo Román Cordón, Francisco Javier Saez Nieto, and Cristina Cuerno Rejado. Rpas integration in non segregated airspace: the sesar approach. In *Proceedings of the SESAR Innovation Days*, pages 19–20. EUROCONTROL, November 2014. URL http://oa.upm.es/48602/.

[26] L. Ribeiro, S. Giles, R. Katkin, T. Topiwala, and M. Minnix. Challenges and opportunities to integrate uas in the national airspace system. In *2017 Integrated Communications, Navigation and Surveillance Conference (ICNS)*, pages 1–18, April 2017. doi: 10.1109/ICNSURV.2017.8012021.

[27] Alejandra Hertfelder Chisvert. Impact of rpas operations on the atm network minimum performance and operational requirements for the en-route phase. Master's thesis, Delft University of Technology, July 2017.

[28] Woodrow Bellamy III. Drones came too close to airplanes 1,800 times in 2016, March 2017. URL http://www.aviationtoday.com/2017/03/17/drones-came-close-airplanes-1800-times-2016/.

[29] *NEST User Guide 1.6.* EUROCONTROL, 2013-2017. Internal Document.

[30] *USER MANUAL FOR THE BASE OF AIRCRAFT DATA (BADA) REVISION 3.14.* EUROCONTROL Experimental Centre, eec technical/scientific report no. 17/05/29-143 edition, June 2018.

[31] Aci europe airport traffic report, January 2018. URL https://www.aci-europe.org/. Accessed in February.

[32] European aeronautical database - ead. URL https://www.ead.eurocontrol.int/fwf-eadbasic/restricted/user/aip/aip_overview.faces.

[33] *Annex 11 - Air Traffic Services.* International Civil Aviation Organization (ICAO), thirteenth edition edition, 2001.

[34] Lufthansa webpage, 2018. URL https://www.lufthansa.com/de/en/Seat-maps.

[35] Global hawk webpage, . URL http://www.northropgrumman.com/Capabilities/GlobalHawk/Pages/default.aspx.

[36] Mq9 reaper webpage, . URL http://www.ga-asi.com/predator-b.

[37] *Manual on Required Communication Performance.* International Civil Aviation Organization (ICAO), 2006.

[38] B.R. Elbert. *The Satellite Communication Applications Handbook*. Artech House space technology and applications library. Artech House, 2004. ISBN 9781580538084. URL https://books.google.nl/books?id=D9k5s2-mMKgC.

[39] Airtopsoft. *AirTOp User Guide*, 2015. Internal Document.

[40] *DOC 9883 Manual on Global Performance of the Air Navigation System*. International Civil Aviation Organization (ICAO), first edition edition, 2015.

III

Appendices

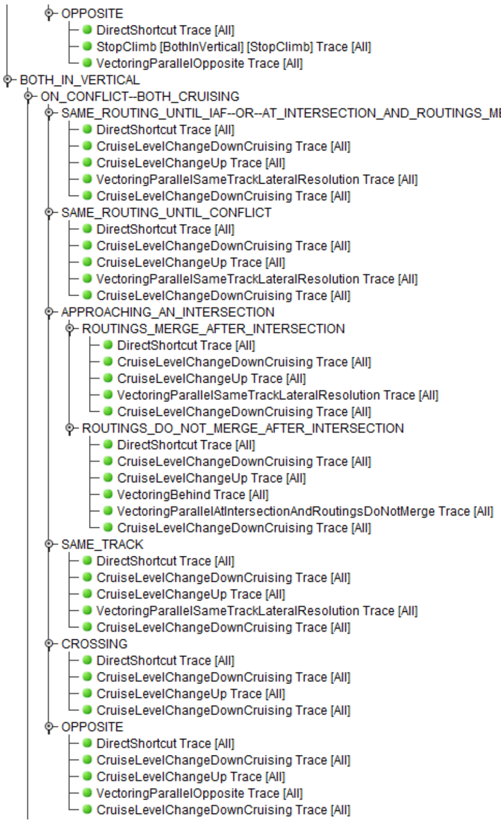
A
Conflict Resolution Tree

- ON_CONFLICT--ONE_IN_VERTICAL
  - SAME_ROUTING_UNTIL_IAF--OR--AT_INTERSECTION_AND_ROUTINGS_MERGE_UNTIL_IAF
    - DirectShortcut Trace [All]
    - StopClimb [OneInVertical] [StopClimb] Trace [All]
    - StopDescent Trace [All]
    - CruiseLevelChangeDownClimbing Trace [All]
    - FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
    - VectoringParallelSameTrackLateralResolution Trace [All]
    - VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
    - AccelerateDescent [SameRouting] [AccelerateDescent] Trace [All]
    - AccelerateClimb [SameRouting] [AccelerateClimb] Trace [All]
    - FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
  - SAME_ROUTING_UNTIL_CONFLICT
    - DirectShortcut Trace [All]
    - StopClimb [OneInVertical] [StopClimb] Trace [All]
    - StopDescent Trace [All]
    - CruiseLevelChangeDownClimbing Trace [All]
    - FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
    - VectoringParallelSameTrackLateralResolution Trace [All]
    - VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
    - AccelerateDescent [SameRouting] [AccelerateDescent] Trace [All]
    - AccelerateClimb [SameRouting] [AccelerateClimb] Trace [All]
  - APPROACHING_AN_INTERSECTION
    - ROUTINGS_MERGE_AFTER_INTERSECTION
      - DirectShortcut Trace [All]
      - StopClimb [OneInVertical] [StopClimb] Trace [All]
      - StopDescent Trace [All]
      - CruiseLevelChangeDownClimbing Trace [All]
      - FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
      - VectoringParallelSameTrackLateralResolution Trace [All]
      - VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
      - AccelerateDescent [SameTrackOrCrossing] [AccelerateDescent] Trace [All]
      - AccelerateClimb [SameTrackOrCrossing] [AccelerateClimb] Trace [All]
    - ROUTINGS_DO_NOT_MERGE_AFTER_INTERSECTION
      - DirectShortcut Trace [All]
      - StopClimb [OneInVertical] [StopClimb] Trace [All]
      - StopDescent Trace [All]
      - CruiseLevelChangeDownClimbing Trace [All]
      - VectoringBehind Trace [All]
      - VectoringParallelAtIntersectionAndRoutingsDoNotMerge Trace [All]
      - AccelerateDescent [SameTrackOrCrossing] [AccelerateDescent] Trace [All]
      - AccelerateClimb [SameTrackOrCrossing] [AccelerateClimb] Trace [All]
  - SAME_TRACK
    - DirectShortcut Trace [All]
    - StopClimb [OneInVertical] [StopClimb] Trace [All]
    - StopDescent Trace [All]
    - CruiseLevelChangeDownClimbing Trace [All]
    - VectoringParallelSameTrackLateralResolution Trace [All]
    - VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
    - AccelerateDescent [SameTrackOrCrossing] [AccelerateDescent] Trace [All]
    - AccelerateClimb [SameTrackOrCrossing] [AccelerateClimb] Trace [All]
  - CROSSING
    - DirectShortcut Trace [All]
    - StopClimb [OneInVertical] [StopClimb] Trace [All]
    - StopDescent Trace [All]
    - CruiseLevelChangeDownClimbing Trace [All]
    - AccelerateDescent [SameTrackOrCrossing] [AccelerateDescent] Trace [All]
    - AccelerateClimb [SameTrackOrCrossing] [AccelerateClimb] Trace [All]
  - OPPOSITE
    - DirectShortcut Trace [All]
    - StopClimb [OneInVertical] [StopClimb] Trace [All]
    - StopDescent Trace [All]
    - CruiseLevelChangeDownClimbing Trace [All]
    - VectoringParallelOpposite Trace [All]
- ON_CONFLICT--BOTH_IN_VERTICAL
  - SAME_ROUTING_UNTIL_IAF--OR--AT_INTERSECTION_AND_ROUTINGS_MERGE_UNTIL_IAF
    - DirectShortcut Trace [All]
    - StopClimb [BothInVertical] [StopClimb] Trace [All]
    - FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
    - VectoringParallelSameTrackLateralResolution Trace [All]
    - VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
    - FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
  - SAME_ROUTING_UNTIL_CONFLICT
    - DirectShortcut Trace [All]
    - StopClimb [BothInVertical] [StopClimb] Trace [All]
    - FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
    - VectoringParallelSameTrackLateralResolution Trace [All]
    - VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
  - APPROACHING_AN_INTERSECTION
    - ROUTINGS_MERGE_AFTER_INTERSECTION
      - DirectShortcut Trace [All]
      - StopClimb [BothInVertical] [StopClimb] Trace [All]
      - FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
      - VectoringParallelSameTrackLateralResolution Trace [All]
      - VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
    - ROUTINGS_DO_NOT_MERGE_AFTER_INTERSECTION
      - DirectShortcut Trace [All]
      - StopClimb [BothInVertical] [StopClimb] Trace [All]
      - VectoringBehind Trace [All]
      - VectoringParallelAtIntersectionAndRoutingsDoNotMerge Trace [All]
  - SAME_TRACK
    - DirectShortcut Trace [All]
    - StopClimb [BothInVertical] [StopClimb] Trace [All]
    - VectoringParallelSameTrackLateralResolution Trace [All]
    - VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
  - CROSSING
    - DirectShortcut Trace [All]
    - StopClimb [BothInVertical] [StopClimb] Trace [All]

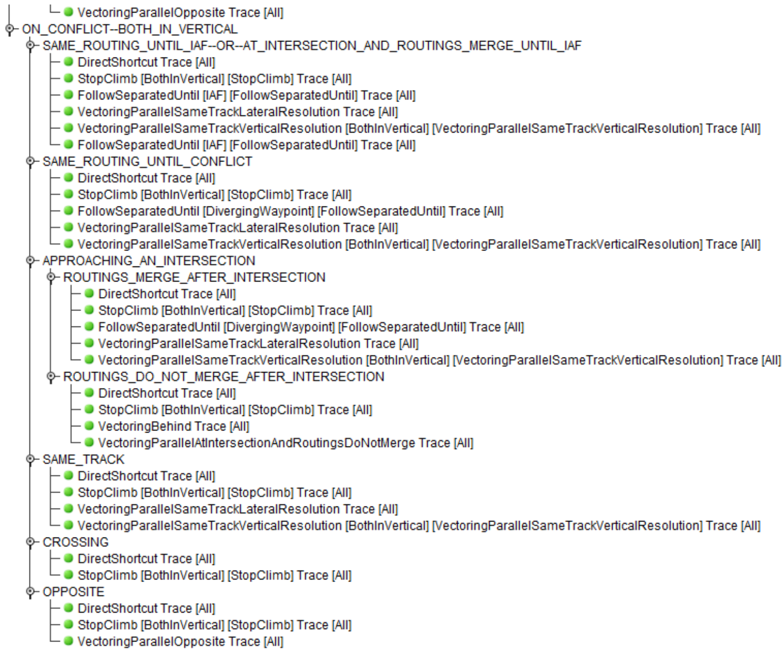
- OPPOSITE
  - DirectShortcut Trace [All]
  - StopClimb [BothInVertical] [StopClimb] Trace [All]
  - VectoringParallelOpposite Trace [All]
- ONE_IN_VERTICAL
  - ON_CONFLICT--BOTH_CRUISING
    - SAME_ROUTING_UNTIL_IAF--OR--AT_INTERSECTION_AND_ROUTINGS_MERGE_UNTIL_IAF
      - DirectShortcut Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]
      - CruiseLevelChangeUp Trace [All]
      - VectoringParallelSameTrackLateralResolution Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]
    - SAME_ROUTING_UNTIL_CONFLICT
      - DirectShortcut Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]
      - CruiseLevelChangeUp Trace [All]
      - VectoringParallelSameTrackLateralResolution Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]
    - APPROACHING_AN_INTERSECTION
      - ROUTINGS_MERGE_AFTER_INTERSECTION
        - DirectShortcut Trace [All]
        - CruiseLevelChangeDownCruising Trace [All]
        - CruiseLevelChangeUp Trace [All]
        - VectoringParallelSameTrackLateralResolution Trace [All]
        - CruiseLevelChangeDownCruising Trace [All]
      - ROUTINGS_DO_NOT_MERGE_AFTER_INTERSECTION
        - DirectShortcut Trace [All]
        - CruiseLevelChangeDownCruising Trace [All]
        - CruiseLevelChangeUp Trace [All]
        - VectoringBehind Trace [All]
        - VectoringParallelAtIntersectionAndRoutingsDoNotMerge Trace [All]
        - CruiseLevelChangeDownCruising Trace [All]
    - SAME_TRACK
      - DirectShortcut Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]
      - CruiseLevelChangeUp Trace [All]
      - VectoringParallelSameTrackLateralResolution Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]
    - CROSSING
      - DirectShortcut Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]
      - CruiseLevelChangeUp Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]
    - OPPOSITE
      - DirectShortcut Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]
      - CruiseLevelChangeUp Trace [All]
      - VectoringParallelOpposite Trace [All]
      - CruiseLevelChangeDownCruising Trace [All]

- ON_CONFLICT--ONE_IN_VERTICAL
  - SAME_ROUTING_UNTIL_IAF--OR--AT_INTERSECTION_AND_ROUTINGS_MERGE_UNTIL_IAF
    - DirectShortcut Trace [All]
    - StopClimb [OneInVertical] [StopClimb] Trace [All]
    - StopDescent Trace [All]
    - CruiseLevelChangeDownClimbing Trace [All]
    - FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
    - VectoringParallelSameTrackLateralResolution Trace [All]
    - VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
    - AccelerateDescent [SameRouting] [AccelerateDescent] Trace [All]
    - AccelerateClimb [SameRouting] [AccelerateClimb] Trace [All]
    - FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
  - SAME_ROUTING_UNTIL_CONFLICT
    - DirectShortcut Trace [All]
    - StopClimb [OneInVertical] [StopClimb] Trace [All]
    - StopDescent Trace [All]
    - CruiseLevelChangeDownClimbing Trace [All]
    - FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
    - VectoringParallelSameTrackLateralResolution Trace [All]
    - VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
    - AccelerateDescent [SameRouting] [AccelerateDescent] Trace [All]
    - AccelerateClimb [SameRouting] [AccelerateClimb] Trace [All]
  - APPROACHING_AN_INTERSECTION
    - ROUTINGS_MERGE_AFTER_INTERSECTION
      - DirectShortcut Trace [All]
      - StopClimb [OneInVertical] [StopClimb] Trace [All]
      - StopDescent Trace [All]
      - CruiseLevelChangeDownClimbing Trace [All]
      - FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
      - VectoringParallelSameTrackLateralResolution Trace [All]
      - VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
      - AccelerateDescent [SameTrackOrCrossing] [AccelerateDescent] Trace [All]
      - AccelerateClimb [SameTrackOrCrossing] [AccelerateClimb] Trace [All]
    - ROUTINGS_DO_NOT_MERGE_AFTER_INTERSECTION
      - DirectShortcut Trace [All]
      - StopClimb [OneInVertical] [StopClimb] Trace [All]
      - StopDescent Trace [All]
      - CruiseLevelChangeDownClimbing Trace [All]
      - VectoringBehind Trace [All]
      - VectoringParallelAtIntersectionAndRoutingsDoNotMerge Trace [All]
      - AccelerateDescent [SameTrackOrCrossing] [AccelerateDescent] Trace [All]
      - AccelerateClimb [SameTrackOrCrossing] [AccelerateClimb] Trace [All]
  - SAME_TRACK
    - DirectShortcut Trace [All]
    - StopClimb [OneInVertical] [StopClimb] Trace [All]
    - StopDescent Trace [All]
    - CruiseLevelChangeDownClimbing Trace [All]
    - VectoringParallelSameTrackLateralResolution Trace [All]
    - VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]


AccelerateDescent [SameTrackOrCrossing] [AccelerateDescent] Trace [All]
AccelerateClimb [SameTrackOrCrossing] [AccelerateClimb] Trace [All]
CROSSING
DirectShortcut Trace [All]
StopClimb [OneInVertical] [StopClimb] Trace [All]
StopDescent Trace [All]
CruiseLevelChangeDownClimbing Trace [All]
AccelerateDescent [SameTrackOrCrossing] [AccelerateDescent] Trace [All]
AccelerateClimb [SameTrackOrCrossing] [AccelerateClimb] Trace [All]
OPPOSITE
DirectShortcut Trace [All]
StopClimb [OneInVertical] [StopClimb] Trace [All]
StopDescent Trace [All]
CruiseLevelChangeDownClimbing Trace [All]
VectoringParallelOpposite Trace [All]
ON_CONFLICT--BOTH_IN_VERTICAL
SAME_ROUTING_UNTIL_IAF--OR--AT_INTERSECTION_AND_ROUTINGS_MERGE_UNTIL_IAF
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
SAME_ROUTING_UNTIL_CONFLICT
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
APPROACHING_AN_INTERSECTION
ROUTINGS_MERGE_AFTER_INTERSECTION
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
ROUTINGS_DO_NOT_MERGE_AFTER_INTERSECTION
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
VectoringBehind Trace [All]
VectoringParallelAtIntersectionAndRoutingsDoNotMerge Trace [All]
SAME_TRACK
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
CROSSING
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]


OPPOSITE
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
VectoringParallelOpposite Trace [All]
BOTH_IN_VERTICAL
ON_CONFLICT--BOTH_CRUISING
SAME_ROUTING_UNTIL_IAF--OR--AT_INTERSECTION_AND_ROUTINGS_MERGE_UNTIL_IAF
DirectShortcut Trace [All]
CruiseLevelChangeDownCruising Trace [All]
CruiseLevelChangeUp Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
CruiseLevelChangeDownCruising Trace [All]
SAME_ROUTING_UNTIL_CONFLICT
DirectShortcut Trace [All]
CruiseLevelChangeDownCruising Trace [All]
CruiseLevelChangeUp Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
CruiseLevelChangeDownCruising Trace [All]
APPROACHING_AN_INTERSECTION
ROUTINGS_MERGE_AFTER_INTERSECTION
DirectShortcut Trace [All]
CruiseLevelChangeDownCruising Trace [All]
CruiseLevelChangeUp Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
CruiseLevelChangeDownCruising Trace [All]
ROUTINGS_DO_NOT_MERGE_AFTER_INTERSECTION
DirectShortcut Trace [All]
CruiseLevelChangeDownCruising Trace [All]
CruiseLevelChangeUp Trace [All]
VectoringBehind Trace [All]
VectoringParallelAtIntersectionAndRoutingsDoNotMerge Trace [All]
CruiseLevelChangeDownCruising Trace [All]
SAME_TRACK
DirectShortcut Trace [All]
CruiseLevelChangeDownCruising Trace [All]
CruiseLevelChangeUp Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
CruiseLevelChangeDownCruising Trace [All]
CROSSING
DirectShortcut Trace [All]
CruiseLevelChangeDownCruising Trace [All]
CruiseLevelChangeUp Trace [All]
CruiseLevelChangeDownCruising Trace [All]
OPPOSITE
DirectShortcut Trace [All]
CruiseLevelChangeDownCruising Trace [All]
CruiseLevelChangeUp Trace [All]
VectoringParallelOpposite Trace [All]
CruiseLevelChangeDownCruising Trace [All]


ON_CONFLICT--ONE_IN_VERTICAL
SAME_ROUTING_UNTIL_IAF--OR--AT_INTERSECTION_AND_ROUTINGS_MERGE_UNTIL_IAF
DirectShortcut Trace [All]
StopClimb [OneInVertical] [StopClimb] Trace [All]
StopDescent Trace [All]
CruiseLevelChangeDownClimbing Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
SAME_ROUTING_UNTIL_CONFLICT
DirectShortcut Trace [All]
StopClimb [OneInVertical] [StopClimb] Trace [All]
StopDescent Trace [All]
CruiseLevelChangeDownClimbing Trace [All]
FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
APPROACHING_AN_INTERSECTION
ROUTINGS_MERGE_AFTER_INTERSECTION
DirectShortcut Trace [All]
StopClimb [OneInVertical] [StopClimb] Trace [All]
StopDescent Trace [All]
CruiseLevelChangeDownClimbing Trace [All]
FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
ROUTINGS_DO_NOT_MERGE_AFTER_INTERSECTION
DirectShortcut Trace [All]
StopClimb [OneInVertical] [StopClimb] Trace [All]
StopDescent Trace [All]
CruiseLevelChangeDownClimbing Trace [All]
VectoringBehind Trace [All]
VectoringParallelAtIntersectionAndRoutingsDoNotMerge Trace [All]
SAME_TRACK
DirectShortcut Trace [All]
StopClimb [OneInVertical] [StopClimb] Trace [All]
StopDescent Trace [All]
CruiseLevelChangeDownClimbing Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [OneInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
CROSSING
DirectShortcut Trace [All]
StopClimb [OneInVertical] [StopClimb] Trace [All]
StopDescent Trace [All]
CruiseLevelChangeDownClimbing Trace [All]
OPPOSITE
DirectShortcut Trace [All]
StopClimb [OneInVertical] [StopClimb] Trace [All]
StopDescent Trace [All]
CruiseLevelChangeDownClimbing Trace [All]


VectoringParallelOpposite Trace [All]
ON_CONFLICT--BOTH_IN_VERTICAL
SAME_ROUTING_UNTIL_IAF--OR--AT_INTERSECTION_AND_ROUTINGS_MERGE_UNTIL_IAF
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
FollowSeparatedUntil [IAF] [FollowSeparatedUntil] Trace [All]
SAME_ROUTING_UNTIL_CONFLICT
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
APPROACHING_AN_INTERSECTION
ROUTINGS_MERGE_AFTER_INTERSECTION
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
FollowSeparatedUntil [DivergingWaypoint] [FollowSeparatedUntil] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
ROUTINGS_DO_NOT_MERGE_AFTER_INTERSECTION
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
VectoringBehind Trace [All]
VectoringParallelAtIntersectionAndRoutingsDoNotMerge Trace [All]
SAME_TRACK
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
VectoringParallelSameTrackLateralResolution Trace [All]
VectoringParallelSameTrackVerticalResolution [BothInVertical] [VectoringParallelSameTrackVerticalResolution] Trace [All]
CROSSING
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
OPPOSITE
DirectShortcut Trace [All]
StopClimb [BothInVertical] [StopClimb] Trace [All]
VectoringParallelOpposite Trace [All]

B

Steps to reproduce the simulation scenarios in AirTOp

This appendix contains a set of steps to be followed in order to reproduce the experiment. For the creation of the baseline scenario the following steps were performed:

1. Open a new project from the default AirTOp project template.
2. Load the GASEL files (AIRAC cycle 1711) containing the airspace structure.
3. Load BADA files (Revision 3.14).
4. Run the action *"Calculate/update Aircraft Type Profile"* located in the Tools/Aircraft/Profiles menu. This action needs to be run so as the simulator will employ the imported BADA files and for internal flight performance related calculations.
5. Using EUROCONTROL's NEST, obtain the traffic data of the 25th of October of 2017, filter and select those flights which crossed Munich TMA. Generate the traffic file in $ALL-FT+$ format so AirTOp can read it.
6. Load the traffic file and select the option "Initial Trajectory".
7. Set the reference time to Departure time and leave all the other options by default.
8. Run the action *"Calculate Flight Plan Estimated Times"* located in the Tools/Traffic menu and select V3 estimate. This action will use the imported Flight Plans to calculate the departure times of the simulated aircraft.
9. Create the "ATC Sectors" (North and South) that form Munich TMA from the imported polygons (GASEL files) so that Air Traffic Controllers can be assigned to them and the conflict detection and resolution and the calculation of the workload can be performed.
10. Assign controllers to the sectors by running the action *"Create Missing Radar Controllers"* in the Tools /Actors/Controllers menu. These controllers are assigned the default controller workload schema.
11. Create an adjacent fake sector the North and South sectors so that the aircraft can be controlled before entering the TMA. This is done because unless the aircraft are controlled, no conflict is detected so it could happen that several aircraft enter the TMA already in a conflict or even an event of loss of separation, which is not a realistic scenario. So those conflicts are solved before entering the area of interest.
12. Prepare the simulation to detect and solve conflicts by activating the corresponding simulation adapters (*Conflict Detection Adapter* and *Conflict Resolution Adapter*).
13. Open AirTOp reporting tool located in the Report menu y running the action *"Report Events, Plots and Statistics"* and then *"Create Defaults"*.

14. Some metrics can be obtained from the Default reports already defined by AirTOp which are stored in the "*report*" folder once the simulation finishes. Particularly: the number of Conflicts and Events of Loss of Separation are obtained from the "*Conflict.csv*", the Workload of the ATCo's is recorded in *ATC _SECTOR _RADAR _CONTROLLER _WORKLOAD _CALCULATED.cvs* and the flight Delay in *FLIGHT _ENDED _ENDED.cvs*.
15. For other metrics new reports were defined. The new reports contained the following Object Properties: Airspace Efficiency Distance Difference As Percentage, Distance Flown In Specified Airspace, Fuel Burned In Specified Airspace, Flight Duration In Specified Airspace and Capacity Percentage.
16. Define a condition that will detect RPAS if *Aircraft Type* equals *RP01* (this will be needed later when creating the other simulation scenarios).
17. Save.

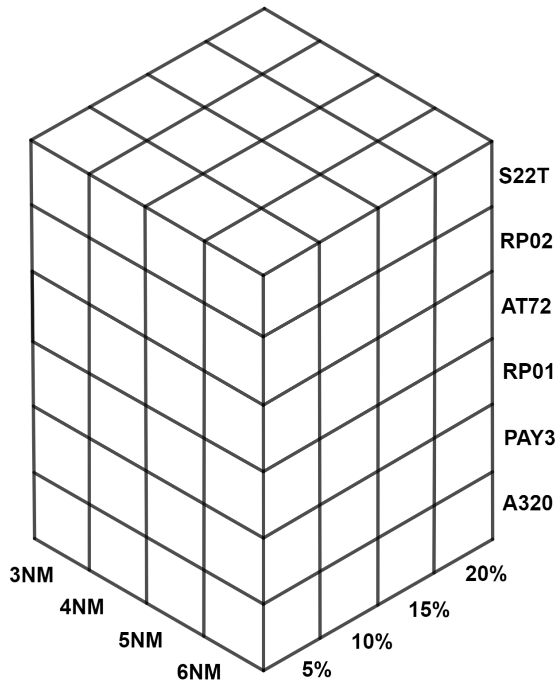


Figure B.1: Experiment Matrix

Each cell of the experiment matrix (Figure B.1) is a different simulation scenario and those scenarios are created from the Baseline scenario as follows:

1. Open a new project from the default AirTOp project template.
2. Save the project and name it after one of the cells from the experiment matrix.
3. Delete all files contained in the project folder (not the *project.prj* that is saved outside of the project folder) and copy paste the files from the baseline project folder into the new project.
4. In the aircraft folder inside the project folder there is a file called aircraft.csv that contains the list of all the flight plans call-signs (first column) and which aircraft operates them (second column). In order to have RPAS operating those flights in the simulation, a fixed percentage of elements of that column (5, 10, 15 or 20 depending on the cell of the experiment matrix) have to be modified to "RP01". A random list should be generated each time in order to make all measurements independent from each other (for this thesis project, Excel was used to randomize the aircraft list). Save the file.

5. Modify the RP01 BADA files so that they contain the Flight Performance parameters of the corresponding aircraft according to the experiment matrix (RP02, A320, PAY3...). Do not change the name of the files.

6. Reopen the project in AirTOp, re-import the BADA files and redo the actions *"Calculate/update Aircraft Type Profile"* and *"Calculate Flight Plan Estimated Times"* so that the new parameters regarding flight performance and departing times are calculated.

7. In order to tune the new separation minima for RPAS go to the *"Simulation Adapters"* menu and select *Conflict Detection Adapter*, a window containing the adapter parameters will be opened. Select the field *"Min Lateral Separation (Opt)"* and introduce a Separation Matrix defining the Separation Minima between RPAS and NO RPAS (the corresponding value from the Experiment Matrix if RPAS, and 3NM if NO RPAS). For this it is necessary to use the previously defined condition that check whether an aircraft is an RPAS or not.

8. Save the project

C

Results and Statistical Analysis

This appendix contains the entirety of results and statistical analysis.

In order to have a more sound analysis of results statistical test of significance were be performed. This type of statistical tests determine whether there is a statistically significant difference between two or more data-sets. Having an statistically significant difference implies that the variation of the data is partly caused by the differences in the factors (IV) of the experiment, and not simply the product of the randomness present in every phenomenon in life. Sometimes, after simply looking at the data in table or graphical form, a difference between two different experiment conditions is identified but when the statistical test is performed, the perceived difference is not significant. The opposite can occur too, when the data-sets are rather similar and apparently the IV has no effect on the DV but actually an statistically significant difference in found.

The statistical test chosen is the widely known **ANOVA** (ANalysis Of VAriance). ANOVA is a robust and powerful statistical test that checks whether two or more sets of data belong to the same normal distribution. More precisely, its main output is the probability (*p-value*) of the difference between the given data-sets simply being the product of randomness. Therefore, if the *p-value* is less than a predefined value α it can be said that there is a statistically significant difference between the two data-sets. If the data-sets come from different experiment conditions, it can be inferred that there is an effect between the Independent Variable and the measured score for the Dependent Variable. The value of $\alpha = 0.05$ will be used as it is common practice.

In order to be able to perform an Independent ANOVA test to a data-set and get meaningful results, the following four assumptions have to be met:

1. **Interval or ratio data** - This assumption concerns the Dependent Variable which has to of ratio or interval type. This assumption is met because every metric is ratio type data.

2. **Independent measurements** - This assumption is met due to the randomization introduced and the fact that one simulation run does not influence the others in any way.

3. **Normally distributed data** - In particular, for the ANOVA test, the assumption is that the residuals within each group follow a normal distribution. One could be tempted to check for normality by applying the Shapiro-Wilk or Kolmogorov–Smirnov tests for normality to each of the data-sets obtained from every scenario, but there is no use for that since there are only five data points for each scenario. Five data points can hardly be normally distributed and the statistical power of the mentioned tests with such a low number of data points is very low, so no meaningful conclusions could be drawn. On top of that, this project does not aim at analyzing every difference between every scenario, the goal is no find out the general relationships between the variables. Thus, it would only make sense to analyze the normality of the data withing groups for each variable averaging across the other two. This means that normality is sought at the different levels of the independent variables. Fortunately, since the number of data samples for this analysis is larger (120 for each level of Traffic mix and 80 for each level of flight performance) the central limit theorem can be applied. The central limit theorem states that if the number of data samples is higher than 30, the sample distribution approaches a normal distribution.

Besides all the above-mentioned, the ANOVA test is robust against violation of this assumption when the sample sizes are equal within groups and greater than 30.

4. **Homogeneity of variances** - The variances throughout the data should be roughly the same. Levene's test for equality of variances has been performed on the data and not every DV complies with it. Fortunately, that is not an issue since ANOVA is robust against the violation of this assumption when all sample sizes are equal, which is the case.

From all the above, it can be concluded that it is reasonable to apply the ANOVA test to the obtained data. Particularly, 2-way and 3-way ANOVA tests will be employed. The same assumptions of the One-way Independent ANOVA apply to **Independent Factorial ANOVA**. Factorial ANOVA test is meant for experiment designs where there is **more than one Independent Variable**. Factorial ANOVA is utilized to find out whether there is a **significant interaction effect between two or more Independent Variables** regarding the Dependent Variable. Factorial ANOVA is a good choice when dealing with more than one IV, since the significant differences found applying One-way ANOVA could be caused by the interaction between the Independent Variables and not just due to the sole effect of each variable separately.

Factorial ANOVA's output is the *p-value* of every source of variation from every combination of Independent Variables. Thus, from 3-way ANOVA **seven p-values** are obtained: **main effect of IV1, main effect of IV2, main effect of IV2, interaction IV1*IV2, interaction IV1*IV3, interaction IV2*IV3, and IV1*IV2*IV3.** A significant interaction between two Independent Variables means that for different levels of one of the IVs, how the second Independent Variable affects the Dependent Variable changes. A triple interaction is more complex to understand, but it can be seen if one visualizes the three-dimensional experiment matrix: fot the different levels of the third IV the 2-way interaction between the other two IVs is not the same.

Higher order interactions can imply that the lower order interactions are meaningless, even if their p-values are significant, because the significance found can be due to the interaction with a third (or second) Independent Variable. In those cases, a closer look is needed. In particular for this experiment design, finding a significant p-value in the 3-way interaction means that a 2-way ANOVA is needed at every level of the third IV. If a significant 2-way interaction is found, nothing can be said about the main effects of the IVs regarding the DV in question, so a 1-way ANOVA test ought to be performed at every level of the second IV. When performing this 1-way ANOVA the so called **simple effects** are found, simple effects are those of the IVs at every level of another IV. **Main effects** are simply the effect the Independent Variables have on the Dependent Variables averaging across all other variables.

No common post-hoc test will be employed, instead lesser order ANOVAs will serve to gain a more detailed insight into the relationship between the variables. It is not in the scope of this project to go down to the individual scenario level and analyze the effect of the Independent Variables for each scenario and Dependent Variable. A more high level understanding of the relationship between the variables is sought.

The shortcoming of statistical analysis is that the more statistical test are run, the higher the probability of committing Type I error. Type I error is when a false negative occurs, this means that the null hypothesis is rejected incorrectly. For ANOVA, whose null hypothesis is that the means of the distributions of each data-set are equal, it means that a significant difference is found when in reality there is none. When consecutive tests are performed on the same data, testing the same family of hypothesis, the more likely it is to erroneously find a statistical significance, this is called Family Wise Error. In statistics, the definition of "family" is rather ambiguous. For this project a conservative approach is taken: a family is defined as the set of hypothesis whose analysis aims to answer one of the research questions. Thus, three families can be identified which corresponds to the hypothesis testing for each Key Performance Area: Safety, Efficiency and Capacity. I.e.: testing the hypothesis that RPAS Flight Performance has an effect on the number of Conflicts is equivalent to saying that RPAS Flight Performance affects Safety.

In order reducing the Family Wise Error-rate is applying a correction that reduces the α level. One such method is the Bonferroni Correction which divides the initial α by the number of tests performed per family so that this new more restrictive α is ensures the Family Wise Error Rate stays at the required level. The Bonferroni correction is too conservative and subtracts statistical power to the whole statistical analysis performed for each KPA, that is why the more sophisticated Holm-Bonferroni method will be used. The Holm-

Bonferroni method also ensures that the FWER stays at the required level while reducing the loss of statistical power (risk of incorrectly accepting a null hypothesis or not detecting a true statistical difference).

In this section the results are presented and analyzed in a structured way. For the sake of clarity the metrics are grouped by their corresponding Key Performance Area: Safety, Efficiency and Capacity. First, the graphs are presented and analyzed and then the necessary statistical analysis are performed. The *p-values* are presented in tables where color green indicates statistical significance after applying the Holm-Bonferroni correction to α, Orange color means statistical significance to the $\alpha = 0.05$ level and red is used for no significant values.

C.1. Safety

The obtained data for the Safety metrics: of Conflicts, Events of Loss of Separation, Lateral Separation and Vertical Separation are shown in figures C.1 to C.12, from which the following relationships between Independent and Dependent Variables are identified:

- **Conflicts:**
  - Fewer conflicts are computed in those scenarios where the RPAS Flight Performance is better (closer to the Flight Performance of the A320 which is the most common aircraft at the selected location and date). The three best performing aircraft remain very close to the values of the baseline, while the three worse performing aircraft register substantially more conflicts. S22T and RP02 present a specially high number of Conflicts, around 50% more than the baseline. By looking at the differences among the aircraft and keeping table **??** in mind, TAS and ROC both play a more relevant role than ROD.
  - Increasing the percentage of RPAS in the airspace increases the numer of Conflicts for the three worse performing aircraft while for the three best performing aircraft it is the opposite, the number of Conflicts decreases. This could mean that there is an interaction between Flight Performance and Traffic Mix for the number of Conflicts.
  - An increase in Separation Minima translate in an slightly increase in number of Conflicts for every aircraft except for the case of the A320, which remains constant.
- **Events of Loss of Separation:** Counterintuitively, for some of the RPAS scenarios (AT72, RP02 and S22T) the number of Events of Loss of Separation is higher than the number of Conflicts, this is most likely due to the fact that when a Conflict is solved by the simulated ATCo, a different Event of Loss of Separation involving a different pair of aircraft is generated, which the simulator cannot solve. There is no previous Conflict situation, so it is not registered as such.
  - The three worse performing aircraft produce a substantially higher Events of Loss of Separation than the three best performing aircraft. While in the scenarios with A320 and RP01 RPAS register values similar to the baseline of around 20 Events, on the S22T scenarios between 80 and 140 Events of Loss of Separation took place, which is several times the Baseline value. Again, TAS and ROC seem to be the main factors within Flight Performance.
  - The larger the percentage of RPAS present in the airspace the more Events of Loss of Separation occur, with the exception of A320 and RP01 which remain constant. The largest gradient corresponds to the S22T scenarios which register around 75 Events with 5% RPAS and around 140 with 20% RPAS.
  - Increasing the Separation Minima slightly increases the Events of Loss of Separation registered in the airspace.
- **Lateral Separation:**
  - Regarding Flight Performance, PAY3 and AT72 in general scored slightly higher (safer) values than the baseline, A320 and RP01 slightly worse and RP02 and S22T substantially worse. Thus, it seems

that TAS is more relevant than ROC and ROD. The largest difference, between AT72 and RP02, accounts for 1NM when the Separation Minima is 6NM and 0.5NM when it is 3NM.

- The effect of the Traffic Mix on Lateral separation is subtle, as the percentage of RPAS increases the Lateral Separation decreases. It seems that when the Flight Performance is worse, the decrease in Lateral Separation as percentage of RPAS increases is accentuated, which is symptom of a interaction between the two IVs.

- As the Separation Minima imposed on the RPAS increases Lateral Separation decreases so slightly that it may not be significant.

- **Vertical Separation:**

  - Unexpectedly, the Vertical Separation score for every RPAS Flight Performance is better than the baseline, being PAY3 the best and A320 (and the Baseline) the worst. The fact that PAY3 scores the est and A320 and RP01 so poorly could be an indication that ROD is a more relevant factor for this metric than TAS and ROC. The difference between PAY3 scenarios and the Baseline is of almost 250ft.

  - Vertical separation seems to be affected in different ways by Traffic Mix, which could indicate an interaction between these two variables.

  - A similar diverse effect is observed for Separation Minima, so there could also be an interaction between the Independent Variables Separation Minima and Flight Performance for the Dependent Variable Vertical Separation.

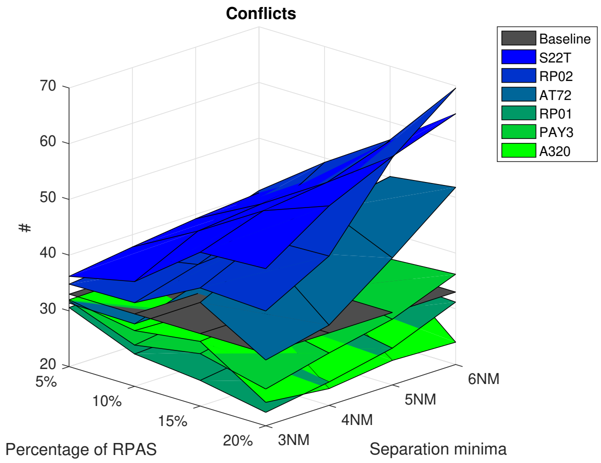


Figure C.1: Number of conflicts for every scenario

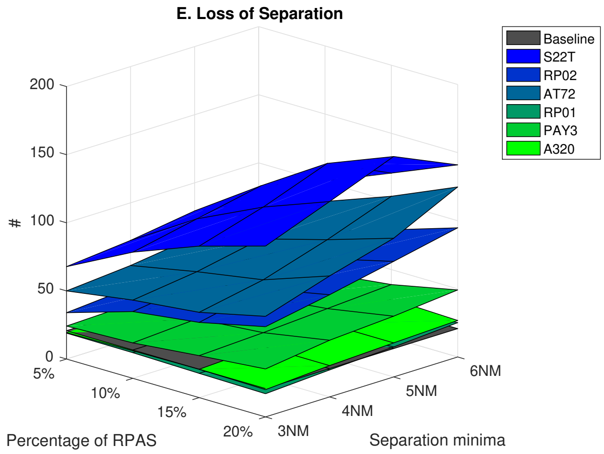


Figure C.2: Events of Loss Of Separation for every scenario

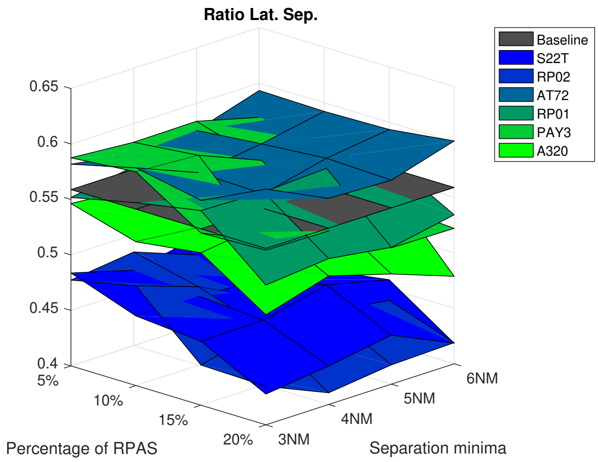


Figure C.3: Lateral separation at Closest Point in ELOS (ratio) for every scenario

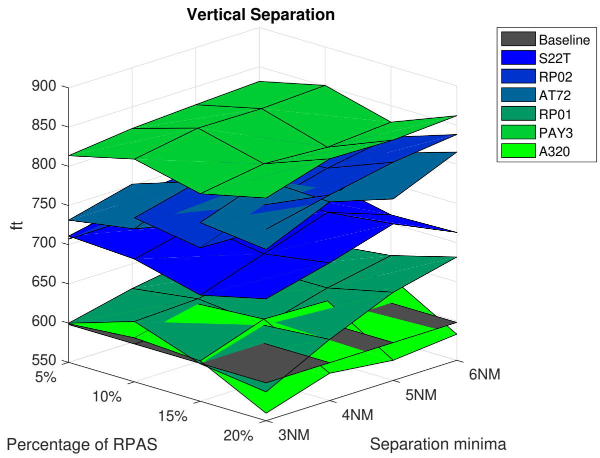


Figure C.4: Vertical Separation at Closest Point in ELOS for every scenario

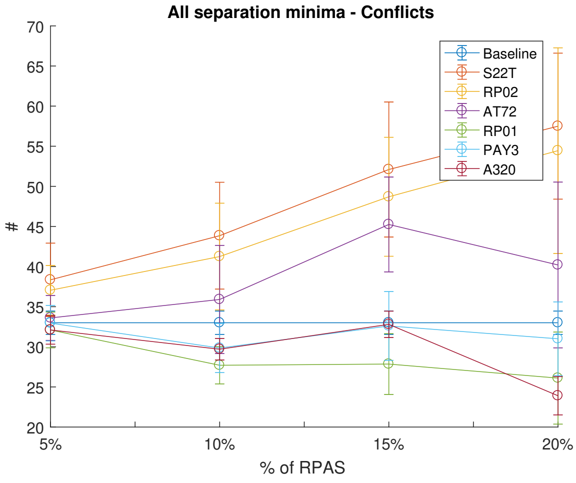


Figure C.5: Number of conflicts against Traffic Mix

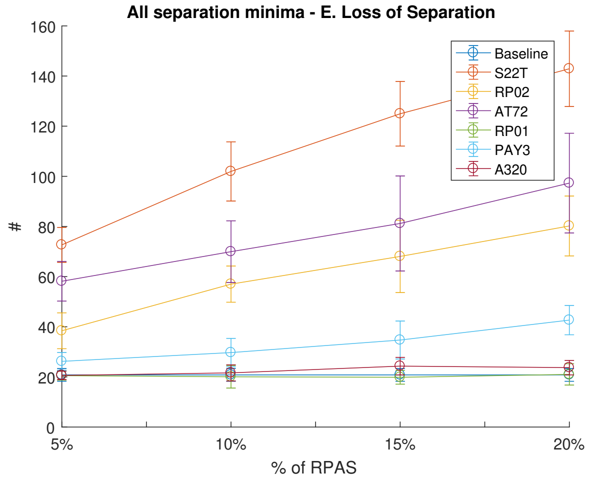


Figure C.6: Events of Loss Of Separation against Traffic Mix

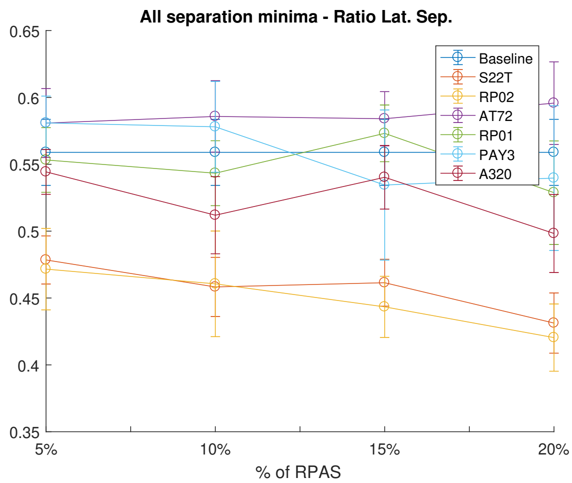


Figure C.7: Lateral separation at Closest Point in ELOS (ratio) against Traffic Mix

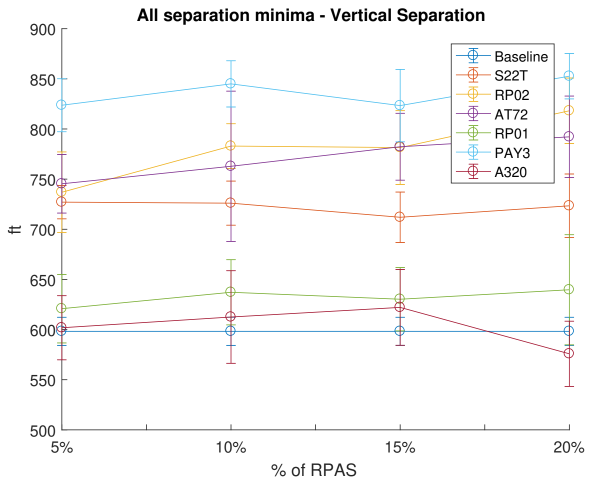


Figure C.8: Vertical Separation at Closest Point in ELOS against Traffic Mix

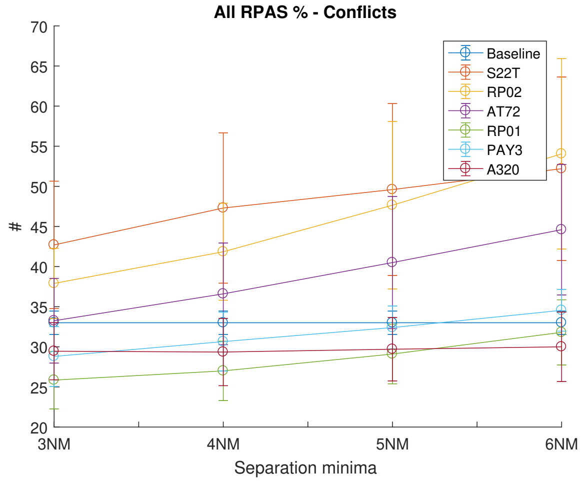


Figure C.9: Number of conflicts against Separation Minima

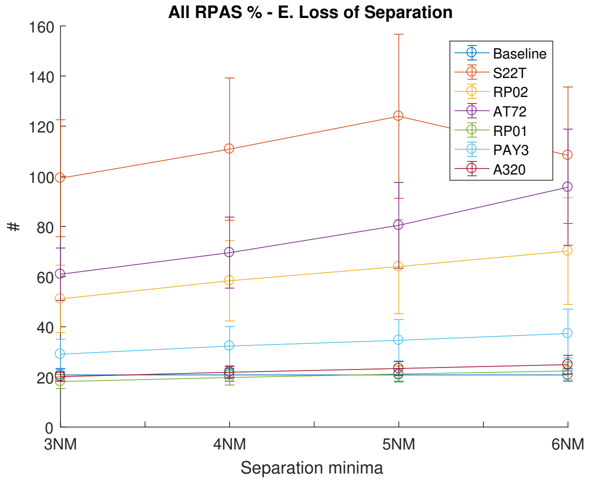


Figure C.10: Events of Loss Of Separation against Separation Minima

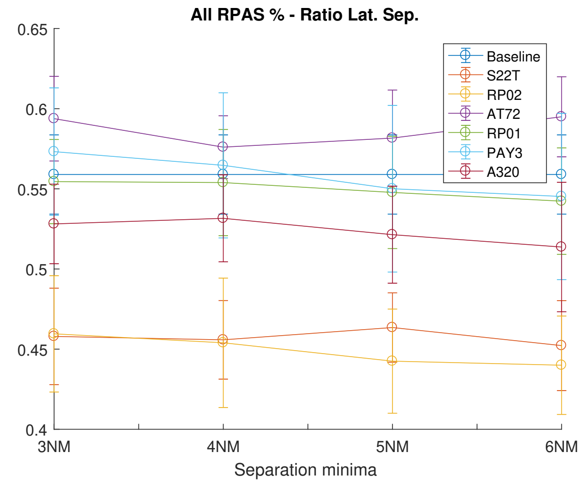


Figure C.11: Lateral separation at Closest Point in ELOS (ratio) against Separation Minima

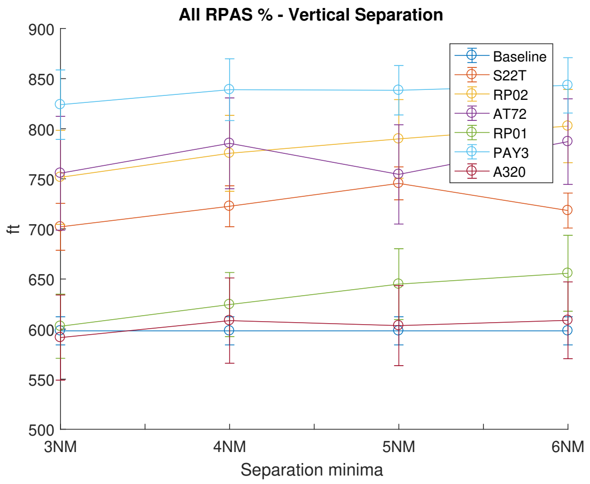


Figure C.12: Vertical Separation at Closest Point in ELOS against Separation Minima

C.1.1. Statistical Analysis

A 3-way ANOVA is performed on the data in order to find out whether the differences and effects found from eye-balling the graphs between the IVs and the DVs are statistically significant. The seven p-values of the 3-way ANOVA for each of the Safety Dependent Variables are shown in table C.1. By looking at the last row of the table it can be noted that there is no significant 3-way interaction between the three Independent Variables for any of the Safety metrics. Not having a 3-way interaction means that the p-values for the lower level interactions are meaningful since their significance is not dependent on a third IV.

Causes of variation	Conflicts	E. Loss of Separation	Lateral Separation	Vertical Separation
	Safety metrics			
Separation Minima	0.0000	0.0000	0.0053	0.0000
Traffic Mix	0.0000	0.0000	0.0000	0.0000
Flight Performance	0.0000	0.0000	0.0000	0.0000
SM*TM	0.0000	0.0000	0.3880	0.9380
SM*FP	0.0000	0.0000	0.3279	0.0033
TM*FP	0.0000	0.0000	0.0000	0.0000
SM*TM*FP	0.8033	0.4898	0.9999	1.0000

Table C.1: p-values 3-way ANOVA Safety

There is a highly significant 2-way interaction between all three pairs of IVs for both **Conflicts** and **Events of Loss of Separation**. Thus, although the main effects of each of the Independent variables separately seems to be significant (first three rows of table C.1), they may not be actually meaningful because they may be caused solely due to the effect of the interactions between variables. Therefore, the simple effects have to be analyzed. In order to accomplish that, a One-way ANOVA is performed in order to test the simple effects of the Independent Variables grouping the data by each of the other two IV's levels.

In order to determine whether the effect of **Separation Minima** is significant, the simple effects have to be analyzed by grouping the data by Traffic Mix and Flight Performance levels. The results of the 1-way ANOVAs for both Dependent Variables are displayed in table C.2.

As can be seen, when the data is grouped into Traffic Mix levels, Separation Minima has no significant effect on the number of Conflicts if the Holm-Bonferroni correction is applied. It also has no significant effect on the number of Events of Loss of Separation even without applying the correction to the α level.

When the data is grouped in Flight Performance levels, it can be concluded that Separation Minima has a significant effect on the number of Conflicts at Flight Performance group but S22T and A320. Regarding Events of Loss of Separation, the only significant simple effects are found at RP02 RP01 and S22T scenarios.

Hence, it can be concluded that, in general, **Separation Minima has no significant effect** by itself on **Conflicts** and **Events of Loss of Separation**, only when interacting with Traffic Mix and Flight Performance.

	Traffic Mix levels				Flight Performance levels					
	5%	**10%**	**15%**	**20%**	**A320**	**PAY3**	**RP01**	**AT72**	**RP02**	**S22T**
Conflicts	0.0041	0.0057	0.0136	0.0019	0.0254	0.0000	0.0000	0.0000	0.0000	0.9574
E. Loss of Separation	0.6087	0.5477	0.3698	0.2968	0.0561	0.0076	0.0000	0.0136	0.0005	0.0000

Table C.2: 1-way ANOVA simple effects Separation Minima on Conflicts and E. Loss of Separation

Regarding the effect of **Traffic Mix** on the Dependent variables Conflicts and Events of Loss of Separation the same procedure as before is followed and the p-values obtained for the 1-way ANOVAs are shown on table C.3. There it can be seen that when the data is grouped by Separation Minima levels, the Traffic Mix has no significant effect on Conflicts or Events of Loss of Separation.

When the data is grouped by Flight Performance, Traffic Mix is a significant factor regarding Conflicts for every level ut AT72 and, regarding Events of Loss of Separation, for every level but RP02.

Thus, **Traffic Mix is not a significant factor** by itself regarding **Conflicts** and **Events of Loss of Separation**, but it is in combination with the other two Independent Variables.

	Separation Minima levels				Flight Performance levels					
	3NM	**4NM**	**5NM**	**6NM**	**A320**	**PAY3**	**RP01**	**AT72**	**RP02**	**S22T**
Conflicts	0.1766	0.1161	0.0272	0.0028	0.0000	0.0000	0.0000	0.0318	0.0000	0.0000
E. Loss of Separation	0.0638	0.0223	0.0132	0.0025	0.0000	0.0000	0.0000	0.0000	0.7358	0.0003

Table C.3: 1-way ANOVA simple effects Traffic Mix on Conflicts and E. Loss of Separation

	Traffic Mix levels			
	5%	10%	15%	20%
Lateral Separation	0.0004	0.0000	0.0000	0.0000
Vertical Separation	0.0000	0.0000	0.0000	0.0000

Table C.5: 1-way ANOVA simple effects Flight Performance on Lateral and Vertical Separation

	Flight Performance levels					
	A320	PAY3	RP01	AT72	RP02	S22T
Lateral Separation	0.0000	0.0000	0.3118	0.0000	0.0000	0.0000
Lateral Separation	0.1944	0.0000	0.0142	0.0012	0.4383	0.0015

Table C.6: 1-way ANOVA simple effects Traffic Mix on Lateral and Vertical Separation

Lastly, the effect of **Flight Performance** is analyzed, the p-values obtained for the 1-way ANOVAs are shown on table C.4. Here it can be seen that Flight Performance is always a significant factor for both **Conflicts** and **Events of Loss of Separation** for every level of Separation Minima and Traffic Mix. Therefore, as every simple effect is significant it can be said that **Flight Performance has a significant effect on** both number of **Conflicts** and **Events of Loss of Separation**.

	Separation Minima levels				Traffic Mix levels			
	3NM	4NM	5NM	6NM	5%	10%	15%	20%
Conflicts	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
E. Loss of Separation	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table C.4: 1-way ANOVA simple effects Flight Performance on Conflicts and E. Loss of Separation

Regarding the analysis of the Dependent Variables **Lateral Separation** and **Vertical Separation**, as seen on table C.1 the 2-way interactions SM*TM and SM*FP are not significant. Since Separation Minina is not involved in any significant interaction, it can be said that its p-value is meaningful. The p-values indicate that **Separation Minima is significant regarding Vertical Separation but not for Lateral Separation**.

A significant interaction is found between Traffic Mix and Flight Performance, thus, the simple effects are analyzed by means 1-way ANOVA tests. In tables C.5 and C.6 the p-values for the tests are shown. When the data is grouped by Traffic Mix, Flight Performance has a significant effect at every level. When the data is grouped by Flight Performance, Traffic Mix percentage is significant only for the half of the levels.

Hence, it can be said that both **Flight Performance has a significant effect on Lateral and Vertical Separation**. **Traffic Mix produces no significant effect** on the data by itself, but it does when interacting with Flight Performance.

As a summary, it can be concluded that **Flight Performance is the only Independent Variable that has a direct effect on Safety**, while **Separation Minima and Traffic Mix** in most of the cases are **significant factors when interacting with Flight Performance**.

C.2. Efficiency

The obtained scores for Distance, Trajectory Efficiency, Fuel, Time and Delay are displayed in figures C.13 to C.27:

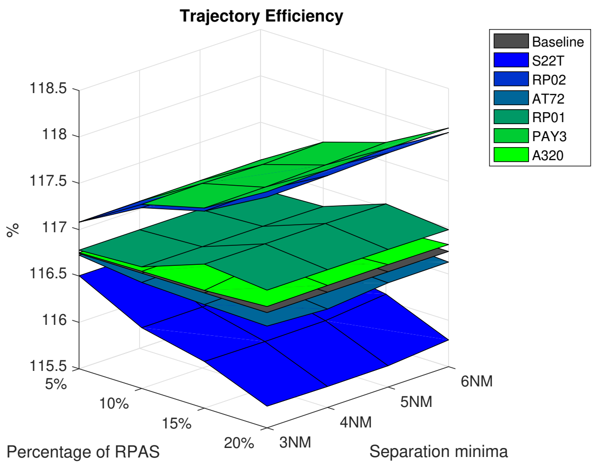


Figure C.13: Distance Efficiency in TMA for every scenario

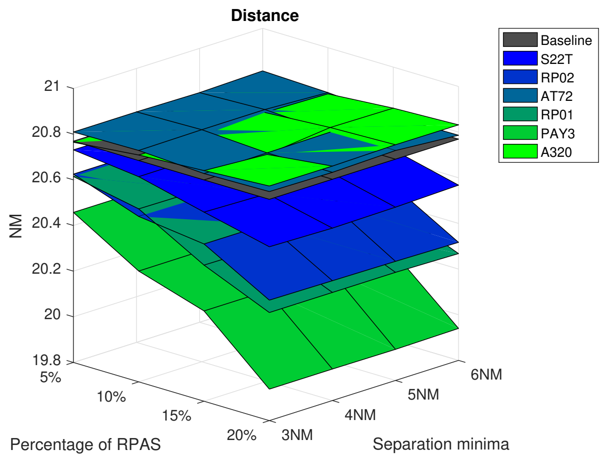


Figure C.14: Distance flown in TMA for every scenario

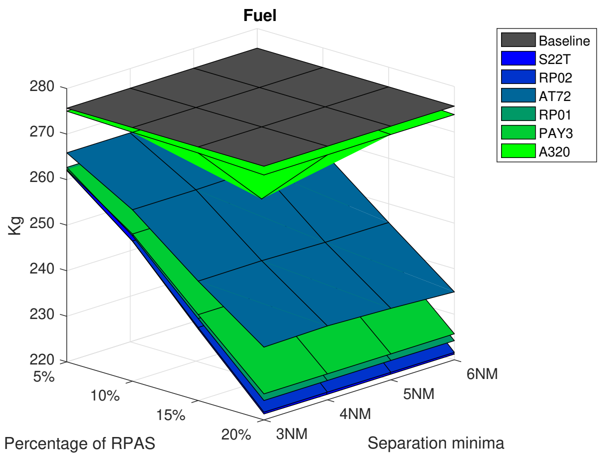


Figure C.15: Fuel consumed in TMA for every scenario

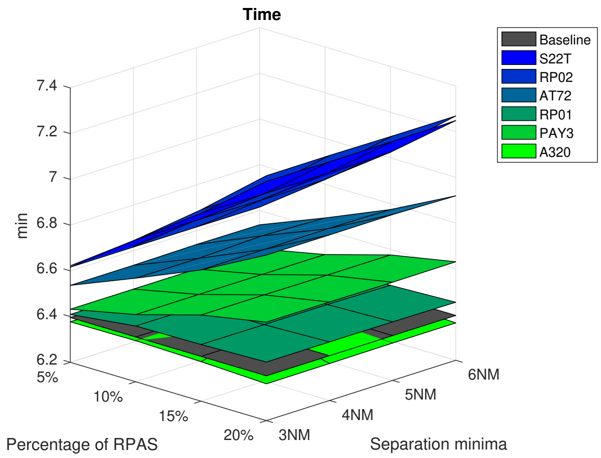


Figure C.16: Time spent in TMA for every scenario

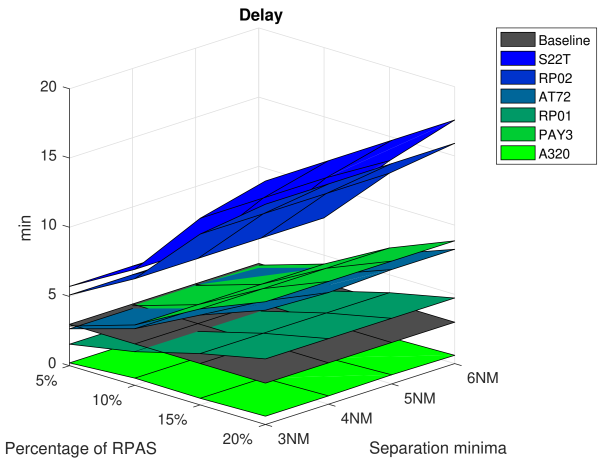


Figure C.17: Delay for every scenario

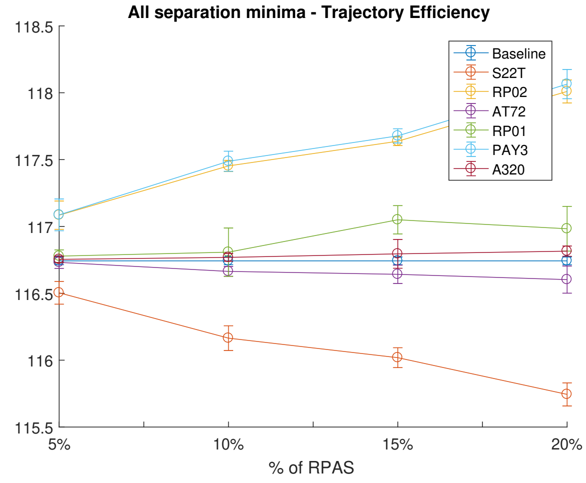


Figure C.18: Distance Efficiency against Traffic Mix

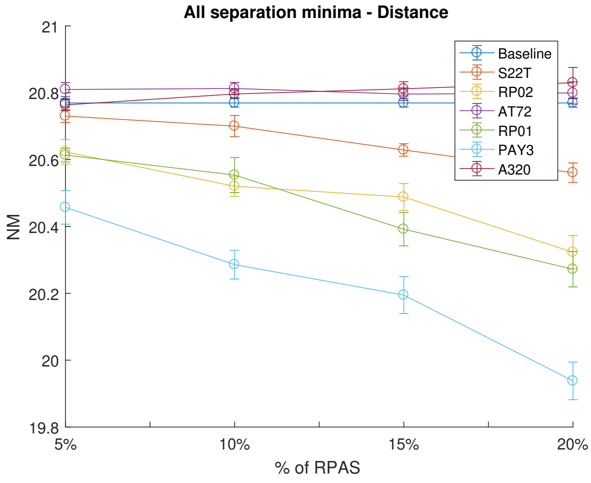


Figure C.19: Distance against Traffic Mix

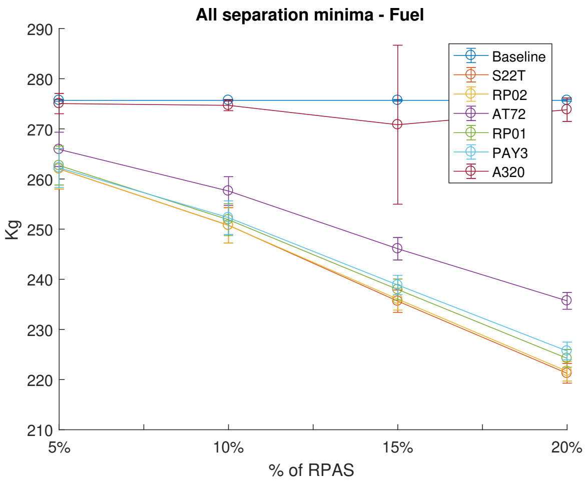


Figure C.20: Fuel against Traffic Mix

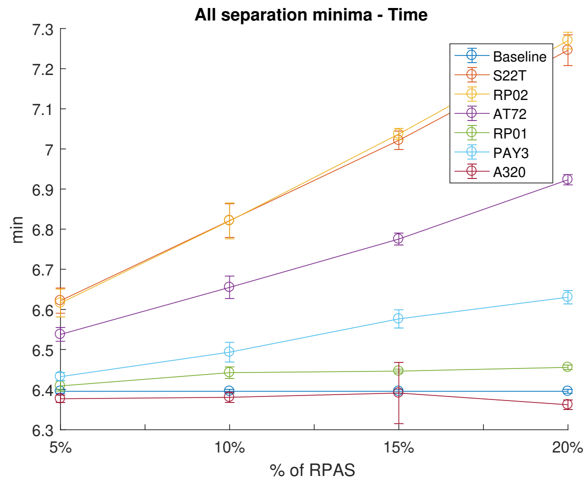


Figure C.21: Time against Traffic Mix

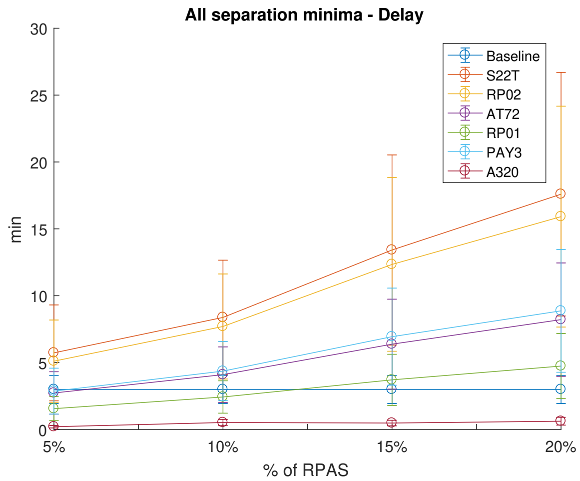


Figure C.22: Delay against Traffic Mix

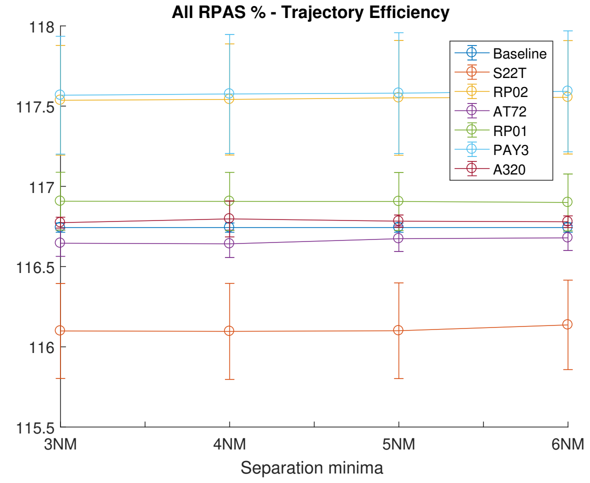


Figure C.23: Distance Efficiency against Separation Minima

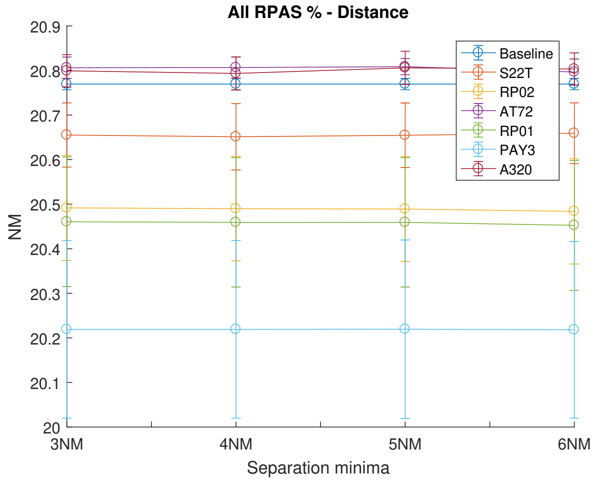


Figure C.24: Distance against Separation Minima

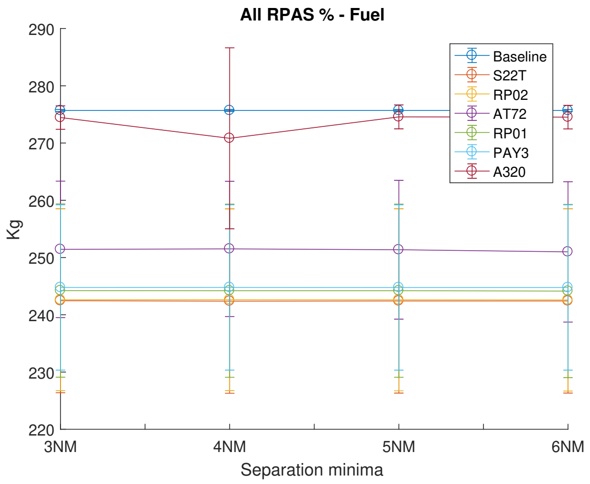


Figure C.25: Fuel against Separation Minima

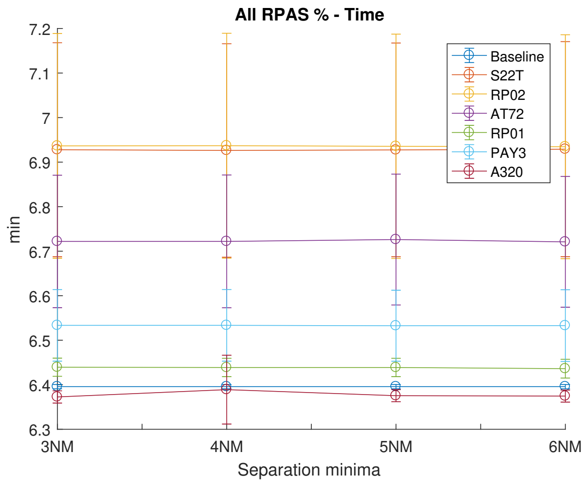


Figure C.26: Time against Separation Minima

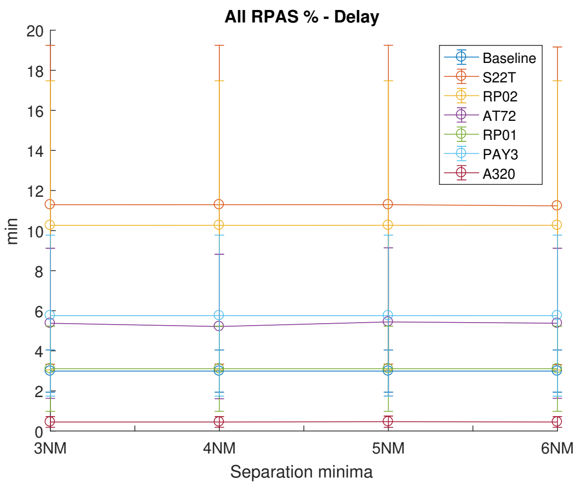


Figure C.27: Delay against Separation Minima

The following relationships between the Independent Variables and Dependent Variales are found:

- **Trajectory Efficiency:** It is worth noticing on the graphs that the maximum difference found is of only

2% which is not a big difference considering that the airspace under study is a TMA where the distances are small in the order of tenths of Nautical Miles. That means that the difference is of approximately 1NM, which, even if the statistical test determines it is significant, in practice it is not. Thus, any difference or effect that is observed in the graphical representation of the data is not very meaningful.

- For the A320, RP01 and AT72 scenarios the values obtained for Trajectory Efficiency are very similar to the Baseline. PAY3 and RP02 perform slightly worse, and S22T slightly better. Hence, no clear relationship with overall performance is observed, nor with either TAS, ROC or ROD.
- The Traffic Mix effect on Trajectory Efficiency is not consistent. There seems to be an interaction with Flight Performance that amplifies its effect, so that as the percentage of RPAS increases the differences between RP02 and PAY3 with S22T increase.
- Separation Minima does not affect Trajectory Efficiency.

• **Distance:** Logically, this metrics shows a similar behavior than the previous one. The maximum difference found is of 1NM which effectively is not worth considering when flight plans cover distances several orders of magnitude higher. Thus, any difference or effect that is observed in the graphical representation of the data is meaningful enough.

  - Almost in every scenario a shorter average Distance is traveled, being PAY3's the shortest then RP01 and RP02, then S22T and finally AT72 and A320 scoring values almost identical to the Baseline. From that, no clear effect of overall performance can be deduced, nor for the specific Flight Performance components TAS, ROC or ROD.
  - As the percentage of RPAS increases, the Distance traveled decreases.
  - Distance is unaffected by Separation Minima.

• **Fuel:**

  - As could be expected, less fuel is burned in every scenario with RPAS in it since the selected aircraft models are lighter aircraft which naturally burn less fuel. The values of A320 scenarios are very similar to those of the baseline. Not only the weight but TAS could also be a significant factor.
  - Logically, as the percentage of those lighter aircraft in the airspace is increased, the fuel consumption decreases. Traffic Mix interacts with Flight Performance regarding this Dependent Variable.
  - Fuel consumption remains constant with respect to Separation Minima.

• **Time:** The maximum difference is of less than a minute.

  - The worse the Flight Performance, the more Time is spent in the TMA. TAS is noticeably the main factor, but ROC is also relevant as the RP01 scenarios perform better that the AT72 and PAY3 scenarios.
  - As the percentage of RPAS is increased, Time increases. There is an interaction between Traffic Mix and Flight Performance.
  - No effect is found between Separation Minima and Time.

• **Delay:**

  - As the Flight Performance worsens the Delay increases. S22T and RP02 register average delays of around 11 minutes, PAY and AT72 6 inutes, RP01 3 minutes (same as the Baseline, where slight delays are introduced as a randomization factor) and A320 has virtually no Delay. TAS sees to be the main contributor within Flight Performance, but ROC is also an important factor as RP01 scenarios score better that PAY3 and AT72 ones.
  - Traffic Mix and Flight Performance are once more related and the more RPAS are introduced into the airspace the more Delay is registered.
  - No effect is found between Separation Minima and Delay.

C.2.1. Statistical analysis

This section contains the statistical analysis of results for the Efficiency metrics: **Trajectory Efficiency, Distance, Fuel, Time and Delay**.

Causes of variation	Efficiency metrics: Trajectory Efficiency	Distance	Fuel	Time	Delay
Separation Minima	0.4682	0.8703	0.6677	0.8663	0.9999
Traffic Mix	0.0000	0.0000	0.0000	0.0000	0.0000
Flight Performance	0.0000	0.0000	0.0000	0.0000	0.0000
SM*TM	0.9995	1.0000	0.8141	0.9859	1.0000
SM*FP	0.9972	0.9997	0.8622	0.9979	1.0000
TM*FP	0.0000	0.0000	0.0000	0.0000	0.0000
SM*TM*FP	1.0000	1.0000	0.9868	1.0000	1.0000

Table C.7: p-values 3-way ANOVA Efficiency metrics

The 3-way ANOVA results are equivalent significance-wise for every Dependent Variable so, for simplicity, the five DVs are analyzed simultaneously. As can be seen on table C.7 there is no 3-way interaction between the three IVs, so the 2-way interactions are meaningful and can be analyzed.

Since **Separation Minima** is not involved in any significant 2-way interaction its main effect is meaningful and, in this case, **not significant for any of the Efficiency metrics**.

The only significant 2-way interaction is the one involving Traffic Mix and Flight Performance. This fact means that although the main effects of each (Traffic Mix and Flight Performance) obtain a p-value that is statistically significant, it may not be meaningful since this effect might be due to the interaction effect between the two IVs. Hence, in order to be able to positively state something about the individual effect of each IV separately on the Dependent Variables, the simple main effects have to be analyzed. For that, a 1-way ANOVA is performed on the data grouped first by Traffic Mix levels and then by Flight Performance levels. The otained p-values for those test are gathered in tables C.8 and C.9.

	Traffic Mix levels: 5%	10%	15%	20%
Trajectory Efficiency	0.0000	0.0000	0.0000	0.0000
Distance	0.0000	0.0000	0.0000	0.0000
Fuel	0.0000	0.0000	0.0000	0.0000
Time	0.0000	0.0000	0.0000	0.0000
Delay	0.0000	0.0000	0.0000	0.0000

Table C.8: 1-way ANOVA simple effects Flight Performance on all Efficiency metrics

	Flight Performance levels: A320	PAY3	RP01	AT72	RP02	S22T
Trajectory Efficiency	0.0000	0.0000	0.0000	0.0000	0.0000	0.0091
Distance	0.0000	0.0000	0.0768	0.0000	0.0000	0.0000
Fuel	0.0000	0.0000	0.0000	0.0000	0.0000	0.3462
Time	0.0000	0.0000	0.0000	0.0000	0.0000	0.1395
Delay	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table C.9: 1-way ANOVA simple effects Traffic Mix on all Efficiency metrics

When the data is grouped by Traffic Mix levels, it can be seen in table C.8 that Flight Performance is significant for every level and metric. When grouping by Traffic Mix, it can be seen in table C.9 that Traffic Mix is significant for almost every group and metric but Distance in RP01 scenarios and Fuel and Time in S22T scenarios. From the fact that almost every simple effect is significant and the information from the graphs, it is reasonable to state that Traffic Mix and Flight Performance are interacting in a additive way, meaning that they are causing an effect in the same direction and amplifying each others effect.

It can be concluded that both **Flight Performance and Traffic Mix have a significant effect on Trajectory Efficiency, Distance, Fuel, Time and Delay**.

C.3. Capacity

The obtained scores for **Workload and Occupancy** for every scenario are shown in figures **??** to **??**.

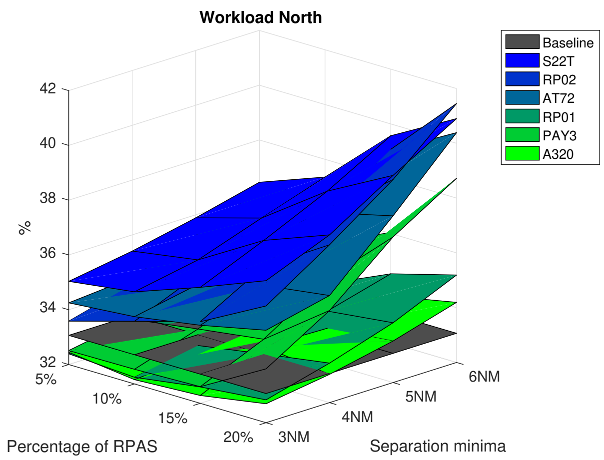


Figure C.28: Workload (Sector North) for every scenario

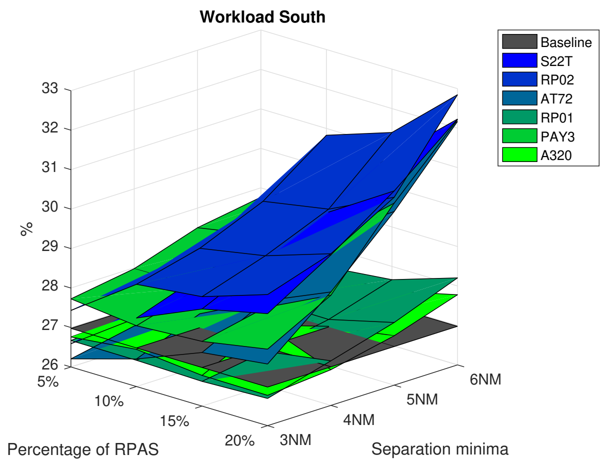


Figure C.29: Workload (Sector South) for every scenario

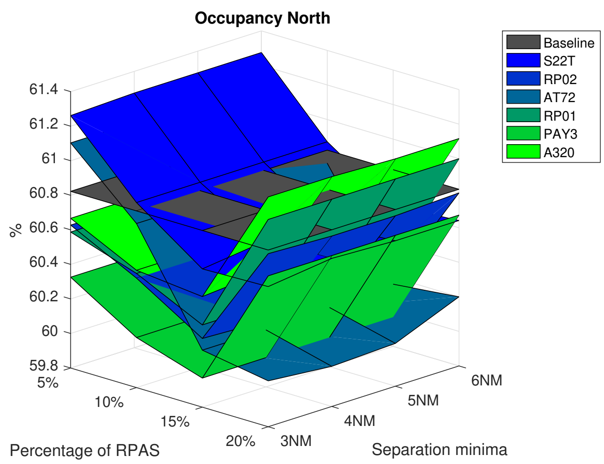


Figure C.30: Occupancy (Sector North) for every scenario

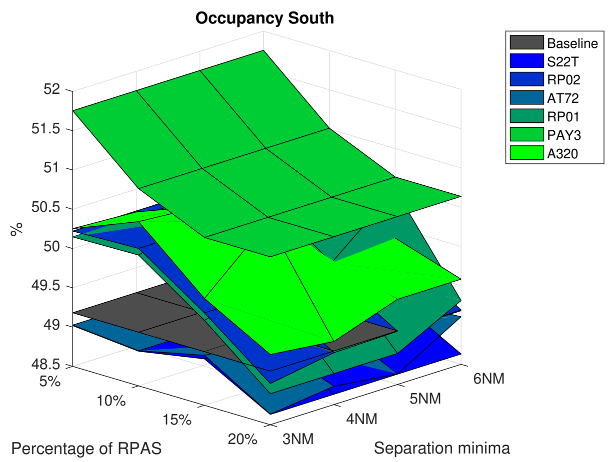


Figure C.31: Occupancy (South) for every scenario

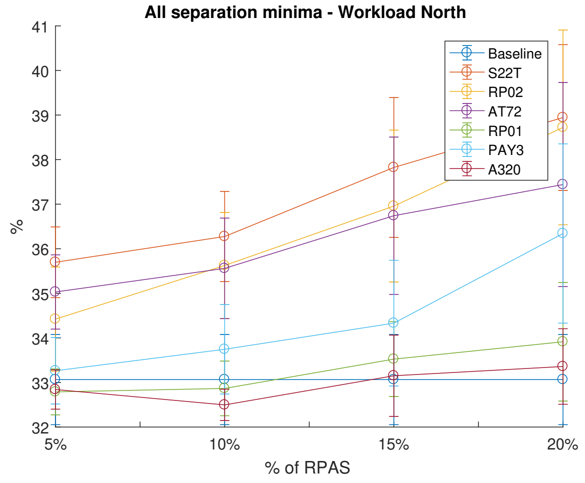


Figure C.32: Workload N against Traffic Mix

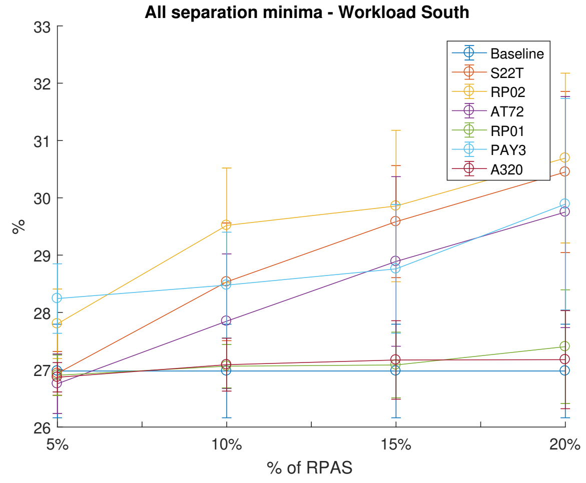


Figure C.33: Workload S against Traffic Mix

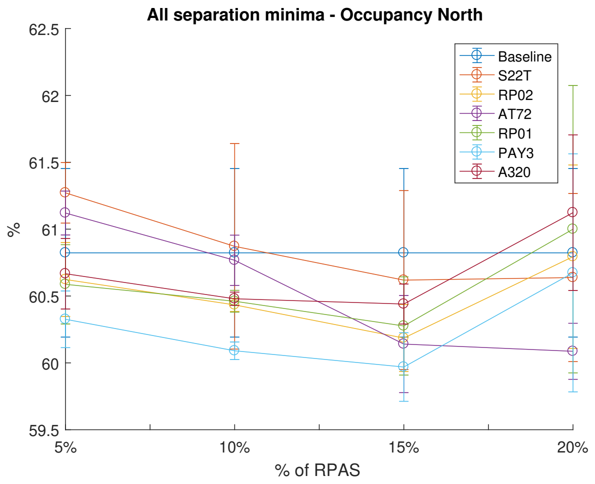


Figure C.34: Occupancy N against Traffic Mix

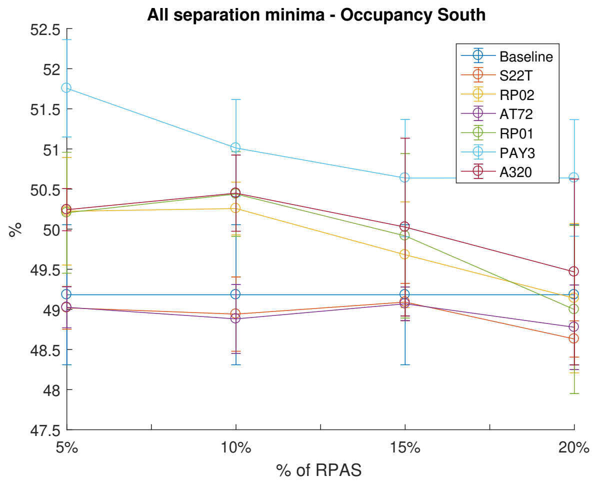


Figure C.35: Occupancy S against Traffic Mix

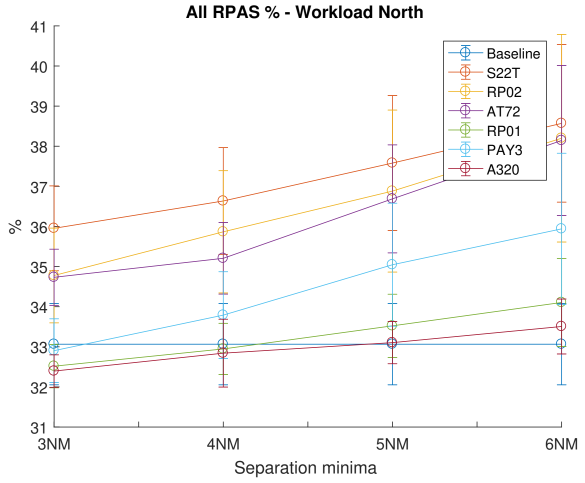


Figure C.36: Workload N against Separation Minima

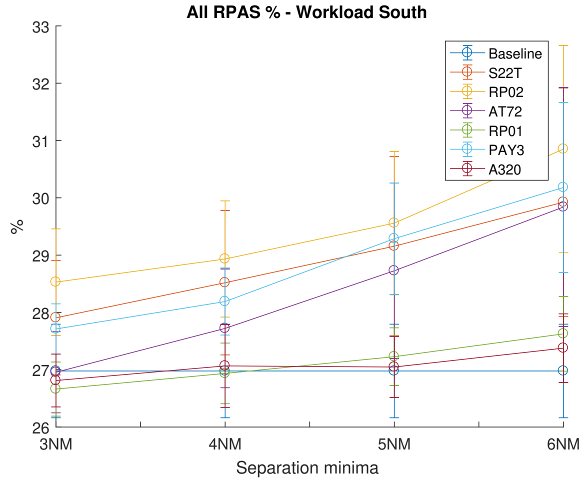


Figure C.37: Workload S against Separation Minima

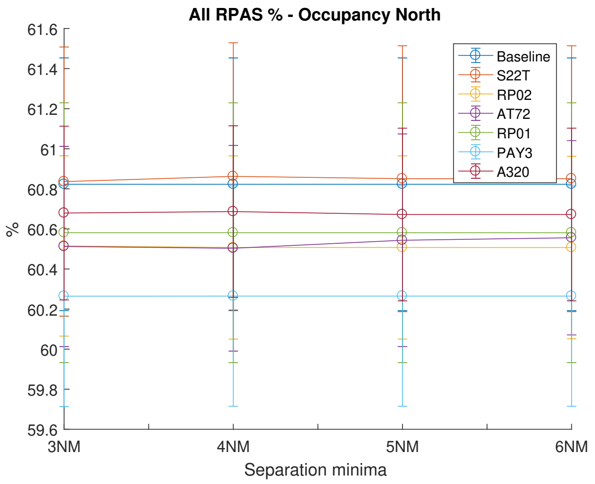


Figure C.38: Occupancy N against Separation Minima

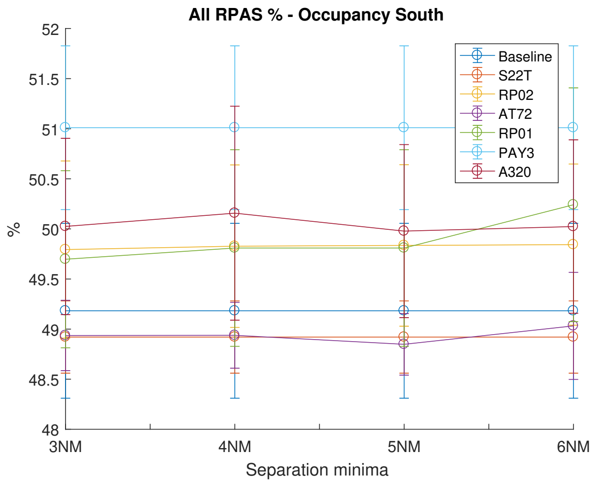


Figure C.39: Occupancy S against Separation Minima

From analyzing the figures the following effects are observed:

- **Workload (North and South):** The largest differences within the Worload scores is around 6-7% Workload, which equates to 4 minutes in an hour.
  - The worst performing aircraft (RP02 and S22T) produce the higher Workload. PAY3 and AT72 are not that far behind. And in A320 and RP01 scenarios the Workload remains at Baseline levels. TAS and ROC seem to be the main factors within flight performance since RP01 scenarios have better scores than PAY3 and AT72 scenarios.
  - Workload increases as the percentage of RPAS increases.
  - Workload increases as the Separation Minima increases.
- **Occupancy (North and South):** The variation on Occupancy is very small: around 1% for the North Sector and 3% for the South Sector. With a declared capacity for the whole TMA of 90 aircraft per hour, this means that there is from 1 to 3 more aircraft per hour, which in practice is not a big difference.
  - There is no clear orderly effect of Flight Performance on Occupancy. In the North Sector all scores are very similar to the Baseline, and in the South Sector S22T and AT72 are similar to the Baseline while the rest score slightly higher.
  - Contrary to what could be expected, as RPAS percentage increases Occupancy decreases slightly.
  - Separation Minima does not affect Occupancy.

C.3.1. Statistical analysis

Hereafter an analysis of the statistical significance of the results obtained for the Dependent Variables **Workload and Occupancy** is performed.

	Capacity metrics			
Causes of variation	**Workload N**	**Workload S**	**Occupancy N**	**Occupancy S**
Separation Minima	0.0000	0.0000	0.9996	0.5592
Traffic Mix	0.0000	0.0000	0.0000	0.0000
Flight Performance	0.0000	0.0000	0.0000	0.0000
SM*TM	0.0000	0.0000	1.0000	0.9987
SM*FP	0.0000	0.0000	1.0000	0.9718
TM*FP	0.0000	0.0000	0.0000	0.0000
SM*TM*FP	0.9883	0.9273	1.0000	1.0000

Table C.10: p-values 3-way ANOVA Capacity metrics

The obtained p-values from the 3-way ANOVA test (table C.10) show that there is no significant interaction among the three Independent Variables. Thus, the p-values for the 2-way interactions are meaningful and can be analyzed.

Regarding **Workload**, as all three 2-way interactions are significant, the significant p-value obtained for the main effect of the individual IVs is not meaningful. Several 1-way ANOVA tests ought to be performed in order to study the simple main effects:

As can be seen on table C.11 the simple effects of **Flight Performance** regarding **Workload** are **significant** for every level of Separation Minima and Traffic Mix.

	Separation Minima levels				**Traffic Mix levels**			
	3NM	**4NM**	**5NM**	**6NM**	**5%**	**10%**	**15%**	**20%**
Workload North	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Workload South	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Table C.11: 1-way ANOVA simple effects Flight Performance on Workload

As can be seen on table C.12 the simple effects of **Traffic Mix** are **significant** for almost every level of Flight Performance (with the exception of RP02 and S22T) and every level of separation Minima but 3NM.

	Separation Minima levels				**Flight Performance levels**					
	3NM	**4NM**	**5NM**	**6NM**	**A320**	**PAY3**	**RP01**	**AT72**	**RP02**	**S22T**
Workload North	0.0030	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0009
Workload South	0.0008	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0932	0.3476

Table C.12: 1-way ANOVA simple effects Traffic Mix on Workload

As can be seen on table C.13 the simple effects of **Separation Minima** regarding **Workload** are **significant** for every level of Traffic Mix and Flight Performance (except for S22T).

	Traffic Mix levels				Flight Performance levels					
	5%	10%	15%	20%	A320	PAY3	RP01	AT72	RP02	S22T
Workload North	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Workload South	0.0002	0.0000	0.0000	0.0000	0.0005	0.0000	0.0000	0.0000	0.0000	0.0308

Table C.13: 1-way ANOVA simple effects Separation Minima on Workload

To sum up, it can be said that in general **the three Independent Variables have a significant effect** on the Dependent Variable **Workload**.

Lastly, the individual and combined effect of the IVs on **Occupancy** is analyzed. As shown on table C.10, **Separation Minima** is not involved in any significant 2-way interaction which means that p-value of the main effect is meaningful, and in this case, **not significant**.

There is a significant interaction between Traffic Mix and Flight Performance. As before, the procedure of performing a One-way ANOVA test to the data grouped by the different levels of the other IV is followed:

Every simple effect of Flight Performance on Occupancy is found to be significant (table C.14), when the data is grouped by Traffic Mix levels.

When the data is grouped by Flight Performance levels (table C.15), not every simple Traffic Mix effect regarding Occupancy is significant.

Thus, it can be concluded that Flight **Performance** produces **significant effect on Occupancy** while the effect of **Traffic Mix** depends on Flight Performance and is **not significant** by itself.

	Traffic Mix levels			
	5%	10%	15%	20%
Occupancy North	0.0000	0.0000	0.0000	0.0004
Occupancy South	0.0000	0.0000	0.0000	0.0000

Table C.14: 1-way ANOVA simple effects Flight Performance on Occupancy

	Flight Performance levels					
	A320	PAY3	RP01	AT72	RP02	S22T
Occupancy North	0.0034	0.0000	0.0000	0.0001	0.0019	0.0000
Occupancy South	0.0001	0.0000	0.0635	0.0000	0.0000	0.0032

Table C.15: 1-way ANOVA simple effects Traffic Mix on Workload