EUCLIDES CARLOS PINTO NETO

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considering the unmanned aircraft system
integration into the non-segregated airspace**

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RESUMO

Nos últimos anos, houve um crescimento, no espaço aéreo segregado, nos números do Veículos Aéreos Não-Tripulados (VANT). No entanto, embora exista interesse em integrar grandes VANT em espaço aéreo não-segregado, os desafios de segurança decorrem da inclusão de novas formas de alcançar estados inseguros no espaço aéreo. Além disso, o controlador de tráfego aéreo (ATCo) tem como objetivo oferecer níveis adequados de segurança e eficiência e resolver problemas presentes em situações complexas. Embora VANTs possam ser usados em diferentes situações e trazem várias vantagens para o espaço aéreo (por exemplo, eficiência), podem trazer incertezas devido ao fato de que os ATCos não estão familiarizados com essa tecnologia. Ao longo dos anos, esse impacto pode ser menor, e atualmente a falta de familiaridade na relação entre VANT e ATCo contribui para níveis mais altos de carga de trabalho. Além disso, a Área Terminal (TMA), que compõe o espaço aéreo controlado, é uma área de controle crítico normalmente estabelecida na confluência de rotas do Serviço de Tráfego Aéreo (ATS), nas quais as aeronaves tendem a estar mais próximas umas das outras. Assim, as operações nesta área particular são realizadas com cuidado e, para alcançar níveis desejáveis de segurança e eficiência, os procedimentos padrão são estabelecidos. Em alguns casos, no entanto, procedimentos padrão não podem ser seguidos e o sequenciamento da aeronave durante a aproximação, que é uma tarefa desafiadora por conta das restrições de manobras complexas, deve ser realizada pelo ATCo de forma a garantir separação mínima entre aeronaves e evitar voos através de cumulonimbus (CB). Finalmente, o principal objetivo de definir um segmento de chegada final é entregar o conjunto de aeronaves do setor final, da TMA, para a fase final do seu procedimento de pouso, ou seja, a aproximação final, considerando a eficiência e a segurança da operação. O objetivo desta pesquisa é propor um método paralelo baseado em enxame para otimizar o projeto final de segmentos de chegada de aeronaves, ou seja, rotas que conectem o setor final com o Fixo de Aproximação Inicial (IAF), considerando a presença de VANTs. Esse processo é conduzido a partir de duas perspectivas: a carga de trabalho do ATCo, que está relacionada à segurança, e a duração da sequenciamento, que está relacionado à eficiência. Além disso, são consideradas diferentes fases da integração de VANTs, ou seja, desde os primeiros estágios de sua integração até um estágio maduro de sua operação por meio do uso do Nível de Maturidade Tecnológica (TML), que é uma escala que mede a familiaridade entre o ATCo e a aeronave. Finalmente, as soluções consideram as restrições do espaço aéreo, como a separação mínima entre aeronaves e condições climáticas adversas, isto é, a presença de cumulonimbus (CB). Os experimentos realizados mostram que essa abordagem é capaz de criar soluções seguras e eficientes mesmo em situações com um grande número de aeronaves.

Palavras-Chave – Veículo Aéreo Não-Tripulado (VANT), Otimização, Computação Evolutiva, Espaço Aéreo (Segurança), Espaço Aéreo (Eficiência).

ABSTRACT

In the past few years, there has been a growth in Unmanned Aircraft Systems (UAS) numbers in segregated airspace. However, although there is an interest in integrating large UAS into non-segregated airspace, the safety challenges on its integration arise from the inclusion of new ways of reaching unsafe states into the airspace. Furthermore, Air Traffic Controllers (ATCo) aim to offer appropriate levels of safety and efficiency and to solve issues present in complex situations. Although the UAS technology may be used in different situations and brings several advantages to the airspace (e.g. efficiency), it may bring uncertainties due to the fact that ATCos may not be familiar with them. Throughout the years, this impact may be lower than it is nowadays due to the fact that the present lack of familiarity in the relationship between UAS and ATCo contributes to higher workload levels. Furthermore, Terminal Maneuvering Area (TMA), which composes the controlled airspace and in which the final sector is contained, is a critical control area normally established at the confluence of Air Traffic Service (ATS) routes in which the aircraft tend to be closer to each other. Thus, operations in this particular area are conducted carefully and, in order to achieve desirable levels of safety and efficiency, standard procedures are established. In some cases, however, standard procedures cannot be followed and the sequencing of the aircraft during the approach, which is a highly challenging task due to complex maneuvers constraints, must be performed by the ATCo in a manner to respect the minimum separation of aircraft and to avoid flights through cumulonimbus (CB). Finally, the main goal of defining a final arrival segment is to deliver the set of aircraft from the final sector of the TMA to the final phase of its landing procedure, i.e., the final approach, considering the operation efficiency and safety. The main objective of this research is to propose a parallel swarm-based method for optimizing final aircraft arrival segments design, i.e., routes that connect the final sector to the Initial Approach Fix (IAF), considering the UAS presence. This is conducted from two perspectives: ATCo workload, which is related to safety, and sequencing duration, which is related to efficiency. Furthermore, different phases of UAS integration are considered, i.e., from early stages of its integration to a mature stage of its operation by means of the Technology Maturity Level (TML) usage, which is a scale that measures the familiarity between the ATCo with the aircraft. Finally, the solutions consider airspace restrictions such as minimum separation between aircraft and bad weather conditions, i.e., the presence of cumulonimbus (CB). The experiments conducted show that this approach is able to build safe and efficient solutions even in situations with a high number of aircraft.

Keywords – Unmanned Aircraft Systems (UAS), Optimization, Evolutionary Computing, Airspace (Safety), Airspace (Efficiency).

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LIST OF ABBREVIATIONS AND ACRONYMS

AA	Autonomous Aircraft
ACC	Area Control Center
ACO	Ant Colony Optimization
APP	Approach Control
ASS	Arrival Sequencing and Scheduling
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
ATS	Air Traffic Service
AWY	Airways
ATZ	Aerodrome Traffic Zone
BWC	Bad Weather Conditions
C2	Command and Control
CA	Collision Avoidance
CATD	Computationally Adaptive Trajectory Decision
CB	Cumulonimbus
CTR	Control Zone
DST	Decision Support Tools
EP	Evolutionary Programming
ES	Evolution Strategies
FAA	Federal Administration Organization
FAF	Final Approach Fix
FASO	Final Arrival Segments Optimization
FASOM	Final Arrival Segment Optimization Method
FS	Final Sector
FSST	Final Sector Simulation Tool

GA	Genetic Algorithms
GP	Genetic Programming
GS	Ground Speed
IAF	Initial Approach Fix
IAP	Instrument Approach Procedures
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organization
IF	Intermediate Fix
JSON	JavaScript Object Notation
MA	Manned Aircraft
MINO	Mixed Integer Nonlinear Optimization
NAS	National Airspace System
nm	Nautical Miles
PPSO	Parallel Particle Swarm Optimization
PSO	Particle Swarm Optimization
RPAS	Remotely Piloted Aircraft System
s	Seconds
SID	Standard Instrument Departure
STAR	Standard Instrument Arrival
TAAM	Total Airspace and Aircraft Modeller
TAS	True Airspeed
TMA	Terminal Maneuvering Area
TML	Technology Maturity Level
TRL	Technology Readiness Levels
TWR	Aerodrome Control Tower
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicles
VP	Vectoring Point

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1 INTRODUCTION

Air transportation is essential for society and it is increasing gradually due to its importance (MARQUART et al., 2003). The growth in flights number leads to a higher revenue although makes the airspace more complex. In fact, there are many challenges to be faced by authorities in the following years, especially in terms of safety and efficiency of airspace. In this context, the Air Traffic Control (ATC) plays an important role in optimizing airspace, especially considering that safety and efficiency are key aspects of airspace operation (GIRDNER, 2016). The ATC is divided into ATC units, which are “generic term meaning variously, area control center, approach control unit or aerodrome control tower” (ICAO, 2016). These units are organized in a manner to accommodate all airspace users by the creation of sectors. The role of controlling aircraft in each control sector, nowadays, is played by Air Traffic Controllers (ATCo). The ATCo that is responsible for a given sector must communicate to ATCos responsible for other sectors to provide a smooth conduction of aircraft throughout their flights, especially when the aircraft fly through different areas.

The ATCo aims to offer appropriate levels of safety and efficiency and to solve issues present in complex situations. Moreover, ATC provides Air Traffic Services (ATS) to flights through ATCo instructions. The main goals of these services include avoiding mid-air collisions, collisions with obstructions and optimizing and maintaining an orderly flow of air traffic (IVAO, 2015). The ATCo conducts the aircraft in the sector or in the set of sectors he/she is responsible for, applying techniques to improve safety and efficiency, such as vectoring. One should note that many of these professionals act collaboratively from the beginning to the end of each flight, and as flights evolve through their flight plans and reach the sectors limits, new ATCos are assigned for controlling them. However, a challenge faced nowadays is to maintain workload¹ level under an acceptable threshold.

Among the several safety threats in airspace operation, mid-air collision can be high-

¹Workload can be defined as a metric that represents the difficulty of ATCo in understanding a particular situation (MECKIFF; CHONE; NICOLAON, 1998) and can be expressed in terms of seconds.

lighted, which depends on a set of events despite issues in aircraft mechanical systems, such as high ATCo workload levels and loss of the established minimum separation. There is an effort of authorities toward such events (e.g. ATCo training for critical situations and design of safe standard procedures). Furthermore, in situations of high air traffic density, a safer measure of the capacity of a sector is based on ATCo workload (MAJUMDAR; POLAK, 2001), i.e., the number of aircraft that can be safely accommodated decreases when there is a higher workload level. As ATCo workload levels are related to safety and there is an understanding by research and operational community that airspace complexity is one of the main factors that impact on this metric (MAJUMDAR; OCHIENG, 2002), situations that these professionals are not familiar with tends to be more unsafe. Moreover, several variables compose complexity, such as traffic density and mental factors (DERVIC; RANK, 2015).

In order to improve the airspace operation, new technologies are under development, such as Unmanned Aircraft Systems (UAS) (AUSTIN, 2011) and Decision Support Tools (DST) for ATCos (e.g. Arrival and Departure managers) (NOSKIEVIČ; KRAUS, 2017). These new technologies present advantages in many aspects, such as safety, efficiency and airspace capacity. Furthermore, the DSTs aim to lead ATCos to more effective decisions, which tends to reduce the ATCos workload and, ultimately, to reduce airspace complexity (MAJUMDAR; OCHIENG, 2002). Although these technologies are used in different situations, they may bring uncertainties due to the fact that it is reasonable to consider that ATCos may not be familiar with them. Furthermore, new technologies that are being integrated into the airspace nowadays (e.g. UAS) may be common in the future, which would increase this familiarity.

In this context, the UAS, which play an important role due to the advantages they bring to the airspace (e.g. efficiency) (GANTI; KIM, 2016) and have been considered a relevant topic in the engineering community due to its applications (FASANO et al., 2016), are systems composed of sub-systems such as Unmanned Aerial Vehicle (UAV), its payloads, the control station and communications sub-systems (AUSTIN, 2011) (FASANO et al., 2016). As there are different types of UAS, such as Autonomous Aircraft (AA) and Remotely Piloted Aircraft Systems (RPAS), there are subsystems that compose some types but not others (e.g. remote piloting interfaces are present in RPAS but not in manned aircraft). For instance, the ground station in which the pilot communicates with RPASs is not part of the AAs, which are piloted by software.

In the past few years, there has been a growth in UAS numbers (GUERIN, 2015) in segregated airspace. However, there is an interest in integrating these aircraft into non-

segregated airspace. These aircraft, which have several military and civil applications, present challenges on its integration to be faced by authorities in terms of safety, i.e., new ways of reaching unsafe states are included into the airspace. For instance, bugs in software may maneuver the aircraft and lead it to undesired headings. Also, considering RPAS, failures in Command and Control (C2) link, i.e., the link the pilot uses to communicate to the aircraft, may lead to unsafe states (NETO et al., 2017b) (ICAO, 2015).

Furthermore, the relationship between UAS and ATC needs to be well-defined, due to the impacts on ATC capacity these aircraft may present. Throughout the years, this impact may be lower then it is nowadays due to the fact that the present lack of familiarity in the relationship between UAS and ATCo contributes to higher workload levels. Nowadays, as UAS only operate in segregated airspaces, ATC tends to be more concerned when controlling a gate-to-gate flight of these autonomous systems. There are different challenges to enable this integration that need to be addressed, such as specific regulations, policies and procedures, enabling technologies and standards development for dealing with UAS (GRINDLE; HACKENBERG, 2016). As the integration of UAS enables new applications and its use may increase in a future (GUPTA; GHONGE; JAWANDHIYA, 2013), developing approaches to integrate it in a safe manner is essential.

Moreover, the Technology Readiness Levels (TRL), proposed by NASA and employed for measuring the readiness of a given aircraft to operate in airspace (MANKINS, 1995), is a widely used scale. In fact, it provides an understanding of steps needed to develop an aircraft from scratch. In this context, considering the lack of familiarity of ATCo when dealing with UASs and that this familiarity may increase throughout the years, a scale that models this metric is desired. Furthermore, there is a need for measuring the familiarity of ATCos with particular aircraft. In this context, the Technology Maturity Level (TML) is proposed in this research aiming to differentiate aircraft by familiarity levels, i.e., the activities performed by ATCo varies according to the TML of each aircraft (NETO et al., 2017a). Note that, for instance, a particular UAS may have the same TRL than a particular Manned Aircraft (MA) but they may present different TMLs.

Furthermore, the Terminal Control Area (TMA), which composes the controlled airspace, is a critical control area normally established at the confluence of Air Traffic Service (ATS) routes in the vicinity of one or more major aerodromes (ICAO, 2001) in which the aircraft tend to be closer to each other. In general, TMA is the most resource-constrained component of the air transportation system due to the number of aircraft that can operate simultaneously and the number of airports (KHADILKAR; BALAKRISHNAN, 2016). Its complexity increases according to the airspace configuration (e.g.

traffic density and weather conditions). Thus, operations in this particular area are conducted carefully and, in order to achieve desirable levels of safety and efficiency, standard procedures are established, such as the Standard Instrument Departure (SID) and the Standard Instrument Arrival (STAR).

However, there are situations in which standard procedures (e.g. STAR) cannot be followed, for instance, in case of high traffic density. In these cases, a highly challenging task due to complex maneuvers constraints performed by the ATCo is the sequencing of the aircraft during the approach, considering the arrival segment and the final approach (ICAO, 2006) (AHMED; ALAM; BARLOW, 2017). In order to accomplish this, the ATCo must conduct the aircraft in a manner to avoid conflict, i.e., to avoid disrespect to the minimum separation of aircraft, and to avoid flights through cumulonimbus (CB), which are cloud formations that present a real impact on aviation (FROMM et al., 2005). Finally, the main goal of defining a final arrival segment is to deliver the set of aircraft from the final sector of the TMA to the final phase of its landing procedure, i.e., the final approach, considering the operation efficiency and safety.

1.1 Motivation

Establishing final arrival segments for achieving optimized aircraft operation in terms of safety and efficiency is not a simple task. From the safety perspective, the ATCo workload related to the conflict avoidance during this phase, i.e., aircraft minimum separation to other aircraft and to the cumulonimbus (CB), must remain in acceptable levels once an increase in this metric may present impacts on safety levels. From the efficiency perspective, the set of aircraft must be delivered to the airport as soon as possible. In this context, depending on the scenario, the ATCo must act quickly in order to avoid the airspace of reaching unsafe states. As the number of aircraft increases, the situation becomes more complex and, consequently, more difficult to be controlled by the ATCo.

On the other hand, integrating UAS into non-segregated airspace is a challenge nowadays. According to ICAO (ICAO, 2005a), “the airspace will be organized and managed in a manner that will accommodate all current and potential new uses of airspace, for example, Unmanned Aerial Vehicles (UAV) and that any restriction on the use of any particular volume of airspace will be considered transitory”. Furthermore, although rules for UAS flights are defined for segregated airspace (ICAO, 2015), the increasing interest in the usage of UAS for different applications (military and civilian) leads to a need for integrating them into non-segregated airspace. In order to accomplish this, safety levels

must not be compromised (ICAO, 2015).

Toward the challenges faced in the final sector in complex situations, the presence of UAS is an important player. Due to lack of familiarity, it is reasonable to consider that the ATCo may feel uncomfortable in controlling autonomous aircraft, which is a result of the uncertainty on UAS operation (ZŁOTOWSKI; YOGEESEWARAN; BARTNECK, 2017). However, the arrival procedure is a critical and complex task even without the UAS presence, and definition sequencing solutions for both Manned Aircraft (MA) and UAS, especially during the early stages of UAS integration into non-segregated airspace, may lead to higher ATCo workload levels. Furthermore, there is a lack of simulation methods that include the UAS into the final sector and include complex situations (e.g. bad weather conditions).

Finally, measuring the familiarity of ATCo with a particular aircraft (e.g. UAS) is difficult. Not only due to the fact that UAS do not operate into non-segregated airspace nowadays, but also due to the relationship between familiarity and cognition. Measuring the familiarity enables better sequencing solutions in arrival procedures, especially from the ATCo workload perspective, i.e., from the safety perspective.

1.2 Objectives

The main goal of this research is to propose a parallel swarm-based method for optimizing final aircraft arrival segments design considering the UAS presence. This optimization is conducted from two perspectives: (1) ATCo workload, which is related to safety, and (2) aircraft delivery duration, which is related to efficiency. Also, different phases of UAS integration are considered, i.e., from early stages of its integration to a mature stage of its operation. Finally, the solutions consider airspace restrictions such as minimum separation between aircraft and bad weather conditions, i.e., the presence of cumulonimbus (CB). In order to accomplish this, the specific steps of this work are:

1. To propose a novel approach to model the familiarity of ATCo with a particular aircraft (e.g. UAS). This approach aims to measure the impacts a particular aircraft presents to the ATC in terms of ATCo workload, i.e., safety;
2. To identify aspects of aircraft sequencing during the arrival segment design. These aspects involve characteristics of final sector and final arrival segments, such as sector size and minimum separation of aircraft (which is related to safety);

3. To identify aspects of aircraft operation. These aspects involve operation characteristics, such as speed, position and heading changes and incident detection (e.g. loss of minimum separation, which is related to safety);
4. To propose a simulation model for the final sector that considers the integration of UAS into non-segregated airspace, the presence of bad weather conditions, and the evaluation of (1) ATCo workload and (2) sequencing duration. Finally, the feasibility of solutions is also evaluated;
5. To propose interfaces for using the simulation model into external applications. This enables external application (e.g. optimization applications) to use the simulation to validate the feasibility and fitness of solutions by the usage of the provided Application Programming Interface (API);
6. To proposed an appropriate approach of representing sequencing solutions into algorithms by the usage of structured files. This approach is considered for applications that employ the simulation tool. One should note that, internally, this representation is converted to the simulator solution objects;
7. To propose a parallel swarm-based method for optimizing the final arrival segments definition considering the UAS presence and the airspace restrictions. The main goal of this method is to identify a set of solutions with different fitness to be further selected according to an objective function;
8. To propose a filtering method for selecting the best solution presented by the optimization method considering an objective function. This objective function identifies the importance of reduction of ATCo workload and reduction of sequencing duration.

1.3 Contribution

The main contributions of this research are:

1. A novel approach to measuring the integration of UAS into non-segregated airspace;
2. A formal model to represent and simulate the final sector of the Terminal Maneuvering Area (TMA);
3. An optimization method for aircraft sequencing considering the UAS presence;

4. Interfaces for applying both simulation and optimization models into external applications.

Along with the expected results of this work, the proposed goals are important for academic and industry communities. In academia, we have scientific contributions in terms of the inclusion of the UAS into the non-segregated airspace in an optimization manner. In Information Technology (IT) and aviation companies, by analyzing appropriate manners to sequencing aircraft and considering a proper approach to measure the UAS impacts on ATC, we expect to contribute in three different ways:

1. To present an alternative perspective for regulatory authorities in order to enable the UAS integration into non-segregated airspace;
2. To facilitate the understanding of ATCos toward priorities when dealing with manned and unmanned aircraft;
3. To support the critical decision-making process on final approaches considering the UAS integration according to the priority associated with safety and efficiency.
4. To present alternative aspects to be taken into account by avionic designers in constructing UAS considering the safety aspects of its integration (e.g. components redundancy in order to elevate the TML of particular UAS in specific regions).

This benefits can be reached by employing the proposed approach to the airspace operation planning.

1.4 Outline

This work is organized as follows: Firstly, Chapter 2 presents the related works. Secondly, Chapters 3, 4 and 5 present the background concepts, i.e., the aspects of airspace operation, Unmanned Aircraft Systems (UAS) and combinatorial optimization, respectively. Thirdly, Chapter 6 presents the aspects of UAS integration into non-segregated airspace. Chapters 7 and 8 present, respectively, the Final Sector Simulation Tool (FSST), which is the contribution in terms of simulation modeling, and the Final Arrival Segment Optimization Model (FASOM), which is the optimization model proposed. After that, Chapter 9 shows the evaluation method adopted in this research. Then, Chapter 10

presents the case studies proposed and the discussion on the results achieved, respectively. Finally, Chapter 11 presents the conclusions of this research as well as future directions.

2 RELATED WORKS

This chapter presents the literature review conducted in order to identify research gaps toward UAS integration into non-segregated airspace and the optimization of its operations. Firstly, works related to approaches of including and measuring impacts of UAS integration into non-segregated airspace are presented. Then, works related to airspace simulation methods that may include UAS are also analyzed. Finally, a literature review on arrival segments design optimization approaches for UAS operations is conducted.

2.1 Unmanned Aircraft Systems (UAS) Integration into Non-Segregated Airspace

This section presents works related to approaches of including and measuring impacts of Unmanned Aircraft Systems (UAS) integration into non-segregated airspace from different perspectives. The works presented in this section are classified according to the presence of the following aspects: large aircraft, impacts on ATCo workload, levels of familiarity and mixed aircraft (UAS and MA operating together).

Shmelova et al. (SHMELOVA; BONDAREV; ZNAKOVSKA, 2016) present an approach based on statistical data to deal with the problem of Unmanned Aerial Vehicles (UAV) flights considering different tasks in emergency situations, which are special situations and tend to increase the Air Traffic Controller (ATCo) workload. Also, an analysis of the emergency type is conducted and a sequence of actions is defined. The authors present a motivation for the development of their research, which includes the lack of algorithms to recommend actions for the UAV operator in emergency situation, problems in the decomposition of the decision making process and lack of structure of Distributed Decision Support System (DDSS), which aims to recommend actions to appropriate aircraft from a global perspective, for remotely piloted aircraft. Furthermore, models are developed by the authors in order to determine the optimal landing site in specific situations and search for optimal flight routes. However, this effort only considers emergency

situations and the proposed model does not consider a complex airspace, i.e., airspace with many aircraft. Finally, impacts on ATCo workload due to UAS presence and lack of familiarity of ATCo with this new technology are not taken into account.

Pastor et al. (PASTOR et al., 2014) aim to evaluate the interaction between a Remotely Piloted Aircraft System (RPAS) and the Air Traffic Management (ATM) considering that a RPAS is being operated in shared airspace, i.e., along with traditional aircraft into National Airspace System (NAS). This evaluation employs human-in-the-loop real-time simulations, that allows simulating activities from both the RPAS Pilot-in-Command (PiC) and the Air Traffic Controller (ATCo), and from three different perspectives: the separation management, the contingency management and the capacity impact in the overall ATM system. The experiments conducted, which were realistic and without excessive complexity, presented recommendations to improve the evaluation, e.g., preliminary analysis of traffic to prevent separation conflicts and improvement of ADS-C flight intent communication mechanism. However, this research does not consider complex airspace scenarios in terms of the number of aircraft.

The authors in (ALLIGNOL et al., 2016) propose a geometrical horizontal detect and avoid algorithm for UASs operation, based on ADS-B-equipped aircraft information, in Terminal Control Areas (TMA), considering a constant speed. In this approach, recorded commercial traffic trajectories and random conflict scenarios with UASs were employed. The main goal is to show the applicability of the algorithm in ensuring the separation with traditional aviation, i.e., this research considers a mix of manned and unmanned aircraft. Also, six different missions, such as flying straight or turning and climbing or descending are considered. Other important aspects observed were the influence of the various parameters on the separation achieved and the number of maneuvers required, i.e., the strategy used selects the best directions respecting the range of heading degrees allowed. The conducted experiments showed the effectiveness of the proposal, which maintains the heading nearly constant and changes it in a robust manner if the minimum separation threshold is greater than the current separation between the UAS and a given aircraft. One should note that these methods were tested on 2850 realistic traffic scenarios, which were issued from data recorded in a French Terminal Control Area (TMA). However, although there is a considerable effort in the detect and avoid process, the authors do not consider UAS as large aircraft. Finally, the ATCo workload (e.g. the additional cognitive workload related to UAS operation) is not evaluated.

The authors in (KORN; TITTEL; EDINGER, 2012) focus on possible guidelines of UAS integration in non-segregated airspace. The main objective in this approach is to

maintain the level of safety of UAS and traditional aircraft nearly the same, which may lead the authorities to implement new airspace rules such as additional separation to unmanned traffic. The authors also consider the usage of Airborne Collision Avoidance System (ACAS) maneuvers and avoidance logic. In this work, the authors conducted the experiments considering series of simulations that present reduction in conflict potential (UAS and traditional traffic). The reduction of impact on airspace operation, considering the UAS integration, is also highlighted due to the fact that its integration into non-segregated airspace is a challenge in terms of future acceptance of these autonomous systems. In this context, hazardous situations related to UAS operation are stated, such as UA leaving cleared planned route, ATC has no position information and loss of communication. Furthermore, the reader should note that UAS flights can be conducted with low interference considering a proper mission planning although ATC needs to control these autonomous systems, which tends to increase the workload of the ATCos. The authors also suggest that the presence of specialized UAS controllers, which could share the duty of controlling the airspace among many ATCos. However, although workload is a concern of this paper, a workload evaluation is not conducted. Also, the workload related to the operation of UAS does not include the additional cognitive workload present especially in early stages of UAS integration. Also, different levels of familiarity of ATCo with these systems are not considered.

An approach for safety and risk assessment in unmanned aerial system (UAS) operations, which employs stochastic fast-time simulation and is conducted in non-segregated airspace, is presented in (FORTES; FRAGA; MARTIN, 2016). Considering that the integration of UAS in the NAS is a concern to airspace regulators, the main goal of this research is to calculate fatality risk and to measure how different aspects and phases of UAS operations increases the risk. In order to accomplish this, the authors model and simulate UAS operations over a specific hazardous region applying different stochastic parameters (e.g. altitude, performance variation and latency). Note that the risk analysis considers fatalities and is based on published ground impact models, which enable the usage of fast-time simulation to assess specific situations. Furthermore, the method adopted in this research, which compared different risk analysis models, is important in order to highlight mitigation actions for all stakeholders in the safety assessment. However, although this paper presents a discussion on the importance of measure accurately risks of fatalities in UAS operations, some aspects are not considered. For instance, the workload associated with the presence of UAS into airspace is not faced. Thus, the level of familiarity of ATCo with this technology is not considered.

In (BRANCH et al., 2016), the effectiveness of geo-fencing systems (such as static and dynamic design) for UAS, which defines geographical boundaries in specific areas of airspace, is analyzed. The authors also compare the geo-fencing effectiveness to the current and traditional proposed regulations on collision avoidance systems. In order to accomplish this, Monte Carlo simulations are employed, considering growth and incident rates based on the incident data. In this context, there are plenty of UAS (more than 1 million) available to operate within the National Airspace (NAS) but there is a need to safely integrate them into the NAS. This process must be conducted in a manner to optimize the relationship between cost and safety. Furthermore, UAS is considered disruptive technology to be included in NAS and operations cost reduction is a motivator of such integration. Although even considering the substantial growth of these aircraft in the past few years and, so forth, the step-wise increase of operational tests and global acceptance, the number of incidents has also grown. This growth has been due to different reasons, such as the disobedience of planned altitude and location by UAS. The experiments showed that UAS operations conducted into regulated thresholds, i.e., to specific geographical areas, provide a cost-effective method that respects safety levels and eliminates 98% of the UAS incidents as reported by FAA. However, this research does not consider aspects related to ATCo operation, such as workload.

Gimenes et al. (GIMENES et al., 2014) propose guidelines to support UAS regulations for integration of fully autonomous UASs into the Global Air Traffic Management (GATM) System, and, consequently, into shared airspace. These guidelines are proposed facing three different perspectives: the aircraft itself, the Piloting Autonomous System (PAS) and the integration of autonomous UASs into non-segregated airspace. Considering that there are social and economic interests in UAS applications, enabling this technology to operate along with Manned Aircraft (MA) has considerable potential. The main issue of this integration is that UAS operations into non-segregated airspace should be regulated by aeronautical authorities, although defining these rules is difficult due to the fact that there is not a deep understanding on UAS operation as well as how they behave in case of failures (e.g. contingency operations). Throughout the paper, the authors present the guidelines with different focuses. For instance, towards the “aircraft focus”, although it is not in the scope of this paper, the authors state that it “should be submitted to at least the same processes and criteria of developing, manufacturing and certification regarding avionic systems of manned aircraft, aiming to reach the same safety levels”. Furthermore, the authors highlight that the UAS concept should be based on aeronautical precepts and that the possibility of integrating UASs into airspace depends on specific regulations.

However, this research does not consider the ATCo evaluation and the impact of UAS operation on ATCo performance.

In (RAMALINGAM; KALAWSKY; NOONAN, 2011), the authors present a discussion on the integration of UAS into non-segregated airspace. This problem is faced as a complex system-of-systems problem, considering a level of difficulty higher the technical challenges related to the development, implementation and validation of this technology. Considering that the system design itself is a complex problem, the authors emphasize that the operation of UAS into NAS depends on aviation regulatory authorities, but this sort of regulation is not simple to be defined. The main challenge identified is to design UASs with high safety standards that behaves such as manned aircraft (e.g. transparency). As UAS numbers had increased tremendously in the last few years due to the distinct capabilities and cost advantages compared to manned aircraft in most situations, enabling these aircraft to operate alongside manned aircraft is desirable. Throughout this paper, different regulations are presented, such as regulations followed in Australia. Furthermore, this paper shows an analysis of reasons for the difficulty in integrating UAS into non-segregated airspace. However, although this research considers workload as an important aspect of UAS inclusion, it does not propose an approach to evaluate it. Finally, the evolution in terms of familiarity of the relationship UAS-ATCo is not considered.

In (KAMIENSKI; SEMANEK, 2015), the authors aim to identify potential ways of mitigating issues related to different UAS challenges. Also, a revision of some of the pros and cons of these different approaches and recommendations for changes in procedures, automation, and policy. The impacts presented by an integrated UAS operation on ATC is not fully clear yet even in less congested areas, but there is a need to integrate this aircraft in terms of cost reduction and efficiency. The MITRE Corporation, which is the corporation of the authors of this research, has been using a techniques to identify the impacts of UAS on ATC in the past years, which has shown that, for instance, the process of filing of flight plans, the usage of latitude/longitude waypoints instead of named fixes or waypoints and possible delays or loss of communication have considerable impact. More specifically, the authors state that the impacts are presented in five major areas: UAS flight planning and automation, the UAS control link (delays and loss), UAS-specific information and procedures, ATC training, and UAS interaction with the future NAS. However, although this research highlights challenges of ATC in terms of UAS integration and considers ATCo workload as an impacted metric, the level of familiarity of ATCo with a specific aircraft is not considered, i.e., there is not a workload evaluation process that highlights the difference between UASs of different familiarity (from the

ATCo perspective).

The authors in (MCFADYEN; MARTIN, 2016) deal with the problem of integrating UASs above urban environments, i.e., into low altitude airspace. This integration also includes major Terminal Manoeuvring Areas (TMA) and helicopter landing sites. A set of data-driven modeling techniques are employed to assess existing air traffic as starting for UAS operation. In order to accomplish this analysis, the authors exploit low altitude air traffic data sets in order to discover existing no-fly zones and an alternative geometric approach to defining exclusion zones, which is applied to a real region (Australia), including one International airport and helicopters landing areas. Considering that determining adequate exclusion zones for unmanned aircraft in an urban environment is an important task and that regulations may, in some cases, include UAS in these areas without considerable reduction of risks of collision, the main goal of this research is to propose an approach to define exclusion zone appropriately. The results achieved showed that there is a need for more rigorous scientific approaches to safely integrate these autonomous aircraft into shared and urban airspaces. However, although this is a work that constitutes an important and unique contribution to UAS integration into urban environment, aspects such as workload measurement during the definition of these areas are not considered.

The authors in (CLOTHIER; DENNEY; PAI, 2017) propose a manner to create a Risk Informed Safety Case (RISC) applied to the context of safety assurance of small UAS operation. This approach aims to facilitate safe and cost-effective operations of small UAS by presenting the comprehensive measures considered in order to eliminate, reduce, or control the safety risk. The RISC proposed is composed by barrier models of safety, which support the development of safety measures, and structured arguments, which provide assurance of safety in operations (through, for instance, appropriate evidence). The authors also propose a model for small UAS operational risk, which considers, for instance, specific hazards (e.g. mid-air collision) and operational risks, which depends on the small UAS. Ultimately, this paper shows key safety-related assurance concerns to be addressed and the development of a layered framework for reasoning about those concerns, which can be useful for regulators and various stakeholders in justifying confidence in operational safety in the context of the absence of the relevant aviation regulations for small UAS. However, although the authors focused on proposing an approach to deal with the current state, i.e., a lack of presence of UAS into shared airspace, this research does not measure the impact of these aircraft into ATCo operation (e.g. workload) and, ultimately, into safety levels. Finally, different levels of familiarity of aircraft to the ATCo are not taken into account.

In (WASHINGTON et al., 2017), a new framework for system safety certification under conditions of uncertainty is proposed considering a Bayesian approach to the modeling of average probability of failure conditions. As nowadays the debates over the development of appropriate system safety requirements for UAS is heated, an interesting point of view is to approach this analysis by determining the allowable average probability per flight hour of failure conditions. Due to the lack of knowledge and data to inform the assessment of failure probabilities of UAS, a level of uncertainty may be considered during the system safety assessment (SSA) process, which presents many advantages. The conducted experiments showed the suitability in terms of safety measures provided by the proposed approach. Thus, other sources of uncertainty are intended to be considered in future works. Finally, the authors state that using a constant failure rate model is challenged by the usage of a Weibull distribution, which seems to be a more appropriate representation of UAS failure occurrence. However, although there is an effort in order to estimate UAS failures and an interesting approach that relates uncertainty into safety assessment that can be applied to small and large UASs is presented, this research does not focus on aspects related to ATCo operation, such as communication to UAS.

Romero et al. (ROMERO; GOMEZ, 2017) discuss on present and future of Remotely Piloted Aircraft System (RPAS) in terms of regulation of aeronautical authorities. This discussion considers different countries (e.g. Colombia, Malta and Japan) aiming to understand the integration of RPAs into non-segregated airspace from the ATCo perspective. An analysis of the existing classification types of RPAS (classes one, two and three) is conducted. Moreover, the results of the integration of three RPAS in non-segregated airspace, successfully performed in a real setting, from the air traffic control center in Barranquilla (Colombia) are presented. Note that there were not losses of separation with other aircraft or between RPAS and that one of the authors of this paper, who is an air traffic controller of Barranquilla, coordinated the different entities who participated in the implementation of this successful operation of integrating RPA into non-segregated airspace. Finally, a proposal is made to integrate this type of aircraft into non-segregated air spaces, which considers airspaces classification, RPA classification (in terms of navigation performance) and contingency operation. However, although this paper is an outstanding contribution due to the integration of RPAS into shared airspace into a real setting, the authors do not consider future scenarios in which RPAS may be represented by commercial aircraft. Finally, different types of aircraft in terms of ATCo familiarity are not considered.

The basis to implement a risk model and general methodologies to investigate RPAS safety, according to the operational scenarios defined by European Aviation Safety Agency

(EASA) is proposed in (GRIMACCIA et al., 2017). The authors conducted an analysis of results achieved in experimental flights of multiple RPAS. As the modern aeronautical scenario is being adapted to accommodate new key elements, including the Remote Piloted Aircraft Systems (RPAS), initially used for military purposes only, this new sort of aircraft is ready to become a new airspace user in civilian applications and, even considering that it cannot operate into non-segregated airspaces nowadays, there is a potential growth expectation in terms of investments on this technology. This research points the hazards related to RPAS operation into non-segregated airspace, such as failures in Command and Control (C2) link, ATCo performance referred with high workload situations, pilots performance with high workload situations, external factors (e.g. emergencies) and jamming. Moreover, the authors highlight that a requirement for disclosing the airspace to RPAS is the implementation of a specific Safety Management System (SMS) for every aeronautical operator. Finally, the preliminary risk analysis presented in this research highlights many possibilities to be further investigated in future works. However, although this approach can be easily extended from small to large RPAS, this research does not focus on different levels of maturity that each aircraft may present in the relationship with the ATCo, which may have a considerable impact on workload.

Perrottet (PERROTTET, 2017) explores the challenges related to the application of Performance Based Navigation (PBN) in UAS operation, which include GNSS navigation, layered PBN procedures to UAS performance characteristics, and the capability of performing instrument procedures (in case of failures in communication link). The main goal of this integration is to enable UAS to fly without limitations airspace shared with other aircraft. However, the primary focus of integrating these aircraft has been on identifying a way to compensate the lack of a human pilot onboard, which technologies such as Detect and Avoid (DAA) and Datalink technologies. The author also states that safety and efficiency are two key metrics of airspace and that they may or may not be inherently linked as in manned aviation, i.e., UASs may provide a more independent relationship between safety and efficiency for specific operations. Finally, this new balance between safety and efficiency must aim to maintain the high level of safety observed in today's NAS, which is a requirement in order to turn the advantages provided by UAS reasonable. However, although the authors deal with the problem of integrating UAS into shared airspace, this research presents an overview of challenges faced. One should note that large aircraft are also considered, but that aspects such as ATCo workload are not taken into account.

In (SESSO et al., 2016), the authors propose a qualitative approach for assessing the safety of UAS operations when using Automatic Dependent Surveillance-Broadcast

(ADS-B) systems considering a new testing platform, which is called PiP-E-SEC, as a possible approach for this safety evaluation. The focus of this research is on the influence of data integrity, which is considered as a safety-related parameter. The increase in UAS numbers is pressing authorities to design airspace rules to integrate this airspace into non-segregated airspace safely although safety issues arise when both manned and unmanned aircraft coexist in the airspace. Furthermore, surveillance and, consequently, data integrity play important roles in controlling these aircraft. In this context, the positional information provided by the ADS-B, which is essential to UASs control systems operation, interacts with the Sense and Avoid Systems (S&AS) of the UAS in order to avoid exposure to unsafe situations. Finally, the authors discuss on the usage of a methodology previously applied on manned systems for assessing safety on and state that the adoption of the presented methodology and tools makes enables the identification of appropriate scenarios for the insertion of UAS along with manned aircraft, maintaining the same safety. However, this research does not consider impacts of positional errors of aircraft with different levels of maturity. For instance, the impacts of positional error of UAS in early stages of its integration as well as in long-term stage are not considered.

Oztekin et al. (OZTEKIN; FLASS; LEE, 2012) propose a systems-level approach to analyze the safety impact based on risk controls of introducing new technologies into the NAS, such as UAS, considering Safety Management Systems (SMS) principles and existing regulatory structure. Furthermore, the authors present a methodology to identify minimum safety baselines for safe operations in the NAS and show its applicability through a proof-of-concept study. In this context, UAS emerge as a viable technology for potential civil and commercial applications in the NAS although it brings the need for a deeper analysis of safety impact. A detailed outline of the concepts and methodologies used for constructing a proof-of-concept study for the proposed approach, which considers related hazards and underlying causal factors, is also presented. Finally, the safety baseline proposed in this research identifies a set of minimum risk controls for conducting safe operations. As future steps, the authors intend to focus on identifying the UAS-specific components of the developed safety baseline in order to identify hazards related specifically to the UAS domain. However, although this research considers scenarios with both manned and unmanned aircraft, aspects such as ATCo workload are not taken into account.

An architecture that provides data and software services to enable a set UAS platforms to operate in non-segregated airspace (including, for instance, terminal, en route and oceanic areas) is presented in (HEISEY et al., 2013). The authors present the general

architecture and a Sense and Avoid (SAA) testbed implementation in order to quantify the benefits. This architecture, which is based on a Service Oriented Architecture (SOA) with open standards, aims to support UAS operations by offering a set of services to meet their specific requirements, such as command, control and data management. This proposed approach is considered a guidance and offers architectural best practices. Finally, even considering that an SOA architecture makes some aspects of certification more challenging, this approach presents some advantages and can be implemented in a manner to meet performance requirements. One should note that certification may be more straightforward considering the usage of formal service contracts, with comprehensive interface and quality of service specifications, and governance process in this SOA architecture. However, this research does not provide specific services considering different levels of maturity of each aircraft. Also, although this contribution focuses on integrating UAS into non-segregated airspace, aspects such as impacts on ATCo workload are not considered.

Wargo et al. (WARGO et al., 2017) presents an integrated view on how enabling technologies can support the Remote Pilot in Command (PIC) and the UAS operations into congested terminal airspace operations. There is a desire, nowadays, for integrating large and small UAS (e.g. RPAS) into the complex terminal environment and into the airport surface. The new surveillance technologies that are under development, as well as the access to the NAS system information via System Wide Information Management (SWIM), are manners for improving the remote UAS Pilot in Command's (PICs) performance and, consequently, to conduct UAS operations safely in the terminal environment. Through this resources, vendors are able to get data feeds for, for instance, flight planning, airport status and weather information. All of these information streams provide better Situational Awareness (SA) and a better understanding of the relationship of UAS to other aircraft movements for remote pilots, which enables more efficient operations. Furthermore, there are other enabling technologies presented in this paper, such as vision technologies, control techniques and specific pilot alerts. Finally, the authors have proposed an approach that would include additional information to the flight control cockpit-like displays that are used by the remote pilots. In addition to this research and instead of dealing with the piloting performance, our proposal investigates the relationship between the UAS and the ATCo and the respective familiarity level.

In (WANG et al., 2017), the authors present advantages and disadvantages of four architecture alternatives for enabling FAA Next-Gen National Voice System (NVS), which are Legacy Analog, UAS Gateway Connected to Remote Radio Node (RRN), UAS Gate-

way Connected to AVN and UAS Gateway over FAA Telecommunication Infrastructure (FTI). Considering the architecture choice, UAS Gateway design and functional requirements development are presented. As UAS technology advances and operations become feasible and cost-effective, architectures that support seamless interaction between UAS and the ATC are needed. These architectures should include a UAS network Gateway for managing Air Traffic Voice Node (AVN) within the airspace via a networked Ground-to-Ground (G/G) connection. In this context, there are several functional requirements that must be considered, such as latency, security, access, communication, frequency and fault. On the other hand, the main components of the NVS include the ATC Voice Node (AVN), that connects pilot and ATC, and Local Radios (LRs), which is used in tower operations. Finally, as currently technologies adopted in UAS operations introduce long latency and may be unavailable at times, enabling UAS integration into the NextGen voice system is important. In conclusion, the authors highlight that 1-to-1 deployment of UAS Gateways to AVN and the deployment “access gateways” to provide a point of entry for the UAS PIC is the recommended option. However, although this research is an important contribution in terms of integration of UAS considering an appropriate communication, the relationship of these aircraft with the ATC is not taken into account.

Finally, this section presented the works related to UAS integration into non-segregated airspace. Different aspects are covered by each research, but, in order to identify the similarities and differences, Table 1 presents all works, which are classified as follow:

- **Large Aircraft (LA):** Indicates if the research considered large UAS in the proposed approach;
- **Impacts on ATCo Workload (ATCoW):** Indicates if the impacts related to UAS operation on ATCo workload are considered;
- **Levels of Familiarity (LF):** Indicates if the proposed integration approach takes the familiarity of ATCo with the particular aircraft into account;
- **Mixed Aircraft (MixA):** Indicates if UAS operations are considered along with manned aircraft operations.

This table shows that most of the related works consider a mix of manned and unmanned aircraft. Furthermore, many works consider UAS as a large aircraft. On the other hand, although the impacts of UAS on ATC performance are important to be measured and reduced, only two related works consider the integration from the ATCo perspective.

Also, none of the listed works treat all the criteria presented in the Table differently to the proposal of this research.

Table 1: Works related to integration of UAS into non-segregated airspace.

Related Work	LA	ATCoW	LF	MixA
(SHMELOVA; BONDAREV; ZNAKOVSKA, 2016)	X	X	X	✓
(PASTOR et al., 2014)	X	✓	✓	X
(ALIGNOL et al., 2016)	X	X	X	✓
(KORN; TITTEL; EDINGER, 2012)	✓	X	X	✓
(FORTES; FRAGA; MARTIN, 2016)	✓	X	X	✓
(BRANCH et al., 2016)	X	X	X	✓
(GIMENES et al., 2014)	✓	X	X	✓
(RAMALINGAM; KALAWSKY; NOONAN, 2011)	✓	X	X	✓
(KAMIENSKI; SEMANEK, 2015)	✓	X	X	✓
(MCFADYEN; MARTIN, 2016)	X	X	X	✓
(CLOTHIER; DENNEY; PAI, 2017)	X	X	X	✓
(WASHINGTON et al., 2017)	✓	X	X	✓
(ROMERO; GOMEZ, 2017)	X	X	X	✓
(GRIMACCIA et al., 2017)	X	✓	X	✓
(PERROTTET, 2017)	✓	X	X	✓
(SESSO et al., 2016)	✓	X	X	✓
(OZTEKIN; FLASS; LEE, 2012)	✓	X	X	✓
(HEISEY et al., 2013)	✓	X	X	✓
(WARGO et al., 2017)	X	X	X	✓
(WANG et al., 2017)	X	X	X	✓

Source: The author.

2.2 Airspace Simulation

This section presents works related to airspace simulation methods that may include UAS. In order to identify research gaps, many aspects are analyzed. The works presented in this section are selected as related works according to the presence of the following aspects: the presence of UAS, cognitive impact of different aircraft, bad weather conditions, conflicts avoidance, Air Traffic Controller (ATCo) and vectoring and workload evaluation.

In (MCFADYEN et al., 2016), the authors present two simulation tools focused on

unmanned aircraft operations within shared airspace considering the safety perspective. To accomplish this, a fast pair-wise encounter generator is proposed to simulate the See and Avoid environment, which is demonstrated through statistical performance evaluation of an autonomous See and Avoid decision and control strategy collected in experiments. Also, an unmanned aircraft mission generator is presented, which helps to visualize the impact of multiple unmanned operations. The authors intend to use these analysis tools in exploring some of the fundamental and challenging problems faced by civilian unmanned aircraft system integration and consider that these simple simulation tools can be valuable when assessing a future aerospace environment. Finally, future works are pointed out, such as the application of their strategy in random walk style mission. However, this work does not include Air Traffic Controller (ATCo) aspects in simulation, such as workload. Also, autonomous aircraft does not present a relative cost due to the lack of familiarity the airspace operators (e.g. ATCo) present with this new technology.

Scala et al. (SCALA; MOTA; DELAHAYE, 2016) propose a methodology for developing an airport arrival and departure manager tool. Optimisation and simulation techniques are employed for improving the robustness of the solution. The main goal is to help air traffic controllers in managing the inbound and outbound traffic without incurring in conflicts or delays, i.e., this tool is able to help them in making the right decisions in a short time. The decisions taken in the present methodology for each aircraft are related to entry time and entry speed in the airspace and push back time at the gate. Finally, this approach presents a smooth flow of aircraft both in the airspace and on the ground. The experiments, which considered the Paris Charles de Gaulle Airport as the case study, showed that conflicts were sensibly reduced. However, although the number of conflicts is reduced in this simulation tool considering this approach, Unmanned Aircraft Systems (UASs) are not taken into account. Also, the uncertainty related to autonomous control systems (such as the airport arrival and departure manager tool) are not considered.

Farlik (FARLIK, 2015) proposes the concept of air force simulator operational architecture. Considering that military live training in the airspace is expensive and that information technologies have evolved in the past years, simulation becomes a feasible alternative in training building military simulation centers with a high level of realism may be useful in this sense. In order to train a wide spectrum of personnel together (e.g. pilots and ATCos), simulation capabilities are merged to single robust simulation environment, which considers, for instance, cooperation. Finally, although the simulation of air defense operations with all its aspects is a complex process, this paper stated the essential conceptual operational architecture of the proposed air defense simulator, helping to

structure future simulator architecture according to military requirements. However, this paper presents a set of recommendation but does not include the UAS presence, which may be feasible in the future.

The authors in (HU; LIAO; PAOLO, 2016) present a simulation study on Air Traffic Control (ATC) strategies aiming to use global traffic information in order to improve the decision-making process in local ATC. Considering that ATC is a decentralized system, the control sectors face the challenge of using all available information to manage local air traffic in a safe, smooth and cost-efficient manner. The strategy adopted means how to define and apply various local ATC rules (e.g. first-come-first-served rule) to the coming-in traffic, i.e., traffic that will enter in the local sector and whose information is available in global ATC. Finally, a simple ATC network model is set up and a software simulation system is proposed and the simulation results showed that applying an inappropriate set of rules can cause heavy traffic congestion, while an appropriate strategy (based on global information) can significantly reduce delays, improve safety, and increase the efficiency of using airspace. The authors also indicate future directions of this research, such as introducing more ATC rules and study the effect of each of them, collaborating with the ATC industry to modify and improve the simulation systems and designing proper ATC strategies. However, although the proposed strategy considers the ATC, UAS operation is not considered. Also, different costs, in terms of workload, for different aircraft are not considered.

In (MEHLITZ et al., 2016), the authors present a framework for facilitating rapid development and deployment of distributed simulations based on Java virtual machines called Runtime for Airspace Concept Evaluation (RACE). Developing large, distributed, human-in-the-loop airspace simulations may be not simple, including sophisticated interactive visualization. This framework utilizes the actor programming model and open source components (e.g. Akka and WorldWind). Finally, the authors highlight three main contributions, which are the provision by actors of the basis for extensibility and scalability, seamless combination of a functional programming (scala) and actors and the minimal core of RACE with the maturity of its third-party system basis allow applications that go beyond simple simulations. However, although this framework allows adaptations and extensions, it does not consider the UAS presence and its interaction with Air Traffic Controllers (ATCo). Finally, this research is not focused on the final sector of Terminal Manoeuvring Areas (TMA).

AgentFly system is presented in (VOLF, 2015) as fast-time simulation tool. The authors state the this tool is appropriate for National Airspace System (NAS)-wide ex-

periments and cognitive behavioral of Air Traffic Controller (ATCo) is considered. The United States NAS, for instance, is very complex and lots of information need to be shared, from specific regions to the whole NAS. Also, increases in air traffic lead to impacts on the difficulty faced by ATCo in avoiding unsafe and inefficient operations. An alternative to the real operation is real-time Human-In-The-Loop (HITL) simulation, which provides valuable feedback on the behavior of human operators but presents a limited flexibility and high cost. Thus, AgentFly is proposed as a fast-simulation tool and can be used to perform different experiments, varying the number of aircraft, in order to facilitate the analyses of specific situations in airspace (e.g. conflict avoidance). Several simulations were conducted and important metrics were measured. The presents results showed that this tool is appropriate to be used as a tool for large-scale experiments, providing detailed data for further analysis. However, although this paper considers the Remotely Piloted Aircraft Systems (RPAS) integration as possible implementation (including many aspects of their operation as landing) and a human behavior model, which considers workload, additional cognitive workload related to UAS is not taken into account. Finally, the workload during arrival segment execution is not computed using vectoring points and different costs in terms of workload if considering different aircraft (e.g. traditional aircraft and UAS).

The authors in (HOEKSTRA; ELLERBROEK, 2016) aim to make ATM research results more comparable by sharing tools and data using a fully open-source and open-data approach to air traffic simulation. The main challenges were to achieve a high fidelity (e.g. aircraft performance) and to increase the adoption by the community by keeping the program as simple as possible. Consideration an adoption of this platform by many users, this can be considered a useful tool in terms of innovation and applications development (e.g. providing specific methods for different problems). The paper describes the difficulties faced when using a fully open-data and open-source policy in this area. However, this work does not consider the UAS presence and its impacts on ATCo workload.

Tra et al. (TRA et al., 2017) present conflict rate models to determine the intrinsic safety of airspace designs, which consider conflicts between aircraft in different flight phases. Fast-time simulations were performed for several different layered airspace concepts, considering unstructured airspaces. The results indicate that the models are able to estimate the conflict rate for high traffic densities. When comparing the different layered airspace concepts tested, the model predicted, and the simulation results, a clear safety improvement when the heading range is reduced can be noted. Thus the models can be used to study the effect of airspace design parameters on the safety of airspace con-

cepts. However, although this research considers structured and unstructured airspaces, the presence of UAS is not taken into account.

In (ALAM; ABBASS; BARLOW, 2008), the authors introduce the Air Traffic Operations and Management Simulator (ATOMS), which is an air traffic and airspace modeling and simulation system for free-flight concepts. This tool simulates end-to-end airspace operations and air navigation procedures for conventional air traffic. A multiagent-based modeling paradigm for modular design and easy integration of various air traffic sub-systems is adopted. Also, advanced Air Traffic Management (ATM) concepts that are envisioned in free flight are prototyped in this research, including Airborne Separation Assurance (ASA), Cockpit Display of Traffic Information (CDTI) and weather avoidance. The presented results showed that advanced ATM concepts present an appropriate scenario for free flights. However, this research does not consider ATCo workload and the impact of the UAS presence on it. Also, it does not consider a vectoring point-based workload evaluation.

The authors in (PAVLINOVIĆ et al., 2017) focus on simulation-based Air Traffic Controller (ATCo) training using the Beginning to End for Simulation and Training (BEST), which is a simulation tool adopted in training organizations in Europe. Although BEST simulator covers all levels and types of training (e.g. basic, validation and conversation refresher), this research is focused on the basic part of the initial training. Furthermore, insights into challenges the candidates face when mastering the techniques of performance-based training are presented. ATCos are responsible for guiding aircraft through the airspace and, throughout the whole education and later work, their extensive training (which considers practical exercises performed on computer devices) is divided into three phases. They are the initial training (basic and rating training), unit training (transitional, pre-on-the-job and on-the-job training) and continuation training (conversion and refresher training). Moreover, BEST simulator meets all the objectives and requirements prescribed for the provision of basic ATCo training. However, this research does not consider the aspects related to UAS integration (e.g. increase on cognitive workload) and different levels of aircraft in terms of ATCo familiarity are not considered.

Young et al. (YOUNG et al., 2013) proposes an approach to describe the process of creating and using weather polygons for simulation and analysis activities using the Federal Aviation Administration (FAA)'s Concept Analysis Branch, including an example study focused on weather impacts on flights efficiency and tested in a fast-time simulation environment. Considering that weather has substantial impacts on the National Airspace System (NAS) and that most simulation and analysis tools are unable to rep-

resent weather activity effectively, the development of capabilities that benefits some operational improvements cannot be quantified, i.e., the weather may impact negatively on solutions that improve the airspace efficiency consider good weather conditions. The FAA's Concept Analysis Branch (ANG-C41) developed a tool to create weather polygons, which is a concise model to store and process and can be modeled as restricted airspace that moves across the NAS, that considers high fidelity weather data. This enables the measurement of the impact of operational improvements on weather-related flight delays and, thus, an analysis of the efficiency of current weather avoidance operations was conducted using weather polygons in algorithms to calculate the distance of each flight from weather at different severity levels as well as to identify flights which rerouted to avoid moderate to severe convective weather. Finally, capability enables the FAA to represent the impact of convective weather on NextGen operational improvements. However, although this research is broad in terms of weather simulations, this does not include UAS operation in bad weather avoidance. Furthermore, ATCo workload related to this process is not considered.

McGovern et al. (MCGOVERN; KALISH, 2009) propose and present an overview of a Monte Carlo-based stochastic airspace simulation tool as well as its formulation as programming languages, environments, and other development tools. The main objective is to provide a documented, lifecycle-managed, multi-processor capable, stochastic simulation capability in order to enable the analysis of procedures and equipment for aircraft flight into shared airspace. Thus, selection, design, and implementation of the mathematical models, as well as verification and validation processes, are conducted. Considering that real experiments are expensive and unfeasible, modeling and simulation are often used to study the physical world. Furthermore, navigation aids, surveillance systems, pilots, aircraft, Air Traffic Controllers (ATCos), and weather are desirable features for a useful simulation tool, and in this research, the authors consider all of them and a Graphical User Interface (GUI) integrating world-wide photo-realistic airport depictions and real-time three-dimensional animation. Finally, this paper focus on the interaction of components into shared airspace and the software tool and its formulation was presented. However, this work does not consider the UAS integration into airspace and its impacts on ATCo operation as well as the ATCo workload.

The authors in (HOMOLA et al., 2016) developed a simulation component, considering the UAS Traffic Management (UTM) paradigm, that supports near and long-term live flight testing and exploration. The capabilities of the simulation tool are depicted in this work. In this context, NASA has started to work collaboratively in research with the

Federal Aviation Administration (FAA) and other stakeholders (government, industry, and academia) to explore the concepts and requirements of safe and scalable operations of small Unmanned Aircraft Systems (UAS) in low-altitude airspaces. Finally, a powerful research and development platform capable of addressing the multitude of questions is developed considering that the UTM laboratory is ideally suited to progress the state of UTM research and knowledge. However, although this research considers the UAS presence and its control, large aircraft (e.g. traditional aircraft) are not taken into account. Also, the control of manned and unmanned aircraft are performed by different agents and the aircraft are not included into high-altitude shared airspace.

Different utilization modes of Closely Spaced Parallel Runways (CSPRs), which are employed in the construction of parallel runways, are analyzed in (LI et al., 2015), considering different threshold. This analysis is conducted using the simulation software SIMMOD, which was applied to build simulation models for different utilization modes of runways with a staggered threshold. This systematic analysis aimed to evaluate quantitatively airport capacity and, consequently, operational efficiency. The authors showed through experiments that, considering the existing air traffic control operation rules, CSPRs usage enables the airspace to support from 765 to 815 movements in each peak day. Also, 55 movements are supported in each peak hour. If the runway threshold is staggered in terms of the approach direction and bypass taxiway is provided, i.e., considering adaptations of runway due to air traffic state (e.g. dynamic change to reduce arrival delay), the mode landing on the inside runway and taking-off from the outside runway shows up as the most efficient mode, which increases the operation efficiency by about 5%. However, this research explores capabilities of a widely used simulation tool in order to build simulation models. Also, the focus is on evaluating landings and take-offs, which is different from final approach although has a substantial impact on this previous phase. Finally, the presence of autonomous control systems is not considered, as well as their impacts on personnel performance.

In (SUN; ZHANG; CAI, 2009), a new 4D trajectory generation method is proposed. This method is based on historical radar data processing, considering traffic flow theory to generate the flight states and introducing the interacting multiple models smoother and spline interpolation to determine the intermediate flying status. 4D trajectory generation, which is one the most fundamental functions in the airspace simulation system, is currently based on the partitioning of the flight, i.e., the entire flight is divided into several parts enabling the usage of models to generate the flying states. However, in the method proposed in this research the problems of generating the initial state of an air-

craft and depicting the 4D flying status are addressed. The results presented in this work, obtained from the simulated trajectories and real trajectories by the MATLAB software, showed that the method is valid and practical. However, the authors do not consider the interaction of these aircraft with the ATCo. Also, problems related workload aspects, as well as bad weather conditions, are not faced. Finally, although the authors consider real data, the standard curve rate employed in aviation is not highlighted.

Bucceroni et al. (BUCCERONI et al., 2016) propose a system for integrating Unmanned Aerial System (UAS) visual observers into the distributed simulation capability of the Federal Aviation Administration (FAA). This distributed simulation, which employs large-scale virtual reality systems, is used to demonstrate terrain surrounding flight tests in virtual environments and the generation of the observer's views (ground- and air-based). Basically, three situations are considered: stationary ground-based monitoring, mobile air-based monitoring and seaborne monitoring. As large-scale distributed visualizations are routinely used by organizations (industry and government), this approach is beneficial and has considerable importance in the research associated with the FAA's current work on adapting itself to Next Generation Air Transportation System, considering that this new system will include UAS into shared airspace. Thus, locally caching real-world terrain with data provided was integrated into a graphical interface to give the operator the UASs position and information from multiple perspectives in a distributed simulation. However, the simulation tool proposed in this research does not include interaction between the aircraft operator and the Air Traffic Controller (ATCo). Finally, this is a work conducted aiming the future integration of UAS into shared airspace but it does not consider the impacts these autonomous systems have on personnel performance (e.g. workload).

Borener et al. (BORENER et al., 2015) present Unmanned Aircraft Systems (UAS) modeling and simulation, which consider a use case scenario that is consistent with the FAA's concept of operations for integration of UAS into shared airspace and employs sensing (using actual radar track traffic data) and medium fixed wing UAS. The proposed simulations offer functionality related to UAS operations, such as 'detect and avoid', mission profiles, positional variance, performance variance, fuzzy conflicts, variation in time spent in communication, and deviation from planned or intent profiles. The simulations, which are based on the RAMS plus fast-time simulator tool, aim to evaluate the separation indices and the number and severity of the separation events. The experiments, conducted in a simulated Houston Metroplex Environment, showed that multiple UAS would considerably increase the likelihood of separation event and separation critically

indices and the usage of the "return to departure land site" contingency operation in case of failures in UAS communication link has a considerable impact on separation events. A difficulty faced by researchers, though, is the lack of historical data of UAS operation. However, this research does not include the interaction between UAS and ATCo, and, consequently, the workload is not taken into account.

The authors in (KOPARDEKAR et al., 2009) describes the results of a Dynamic Density (DD) human-in-the-loop simulation. The DD model adopted aims to measure the complexity of a given airspace area and measures presented at the US/Europe ATM 2003 Seminar were used in this research. Thus, the simulation included Reduced Vertical Separation on the Cleveland Air Route Traffic Control Centre's airspace and the considered traffic was actively controlled during throughout simulation. Due to the difficulty related to real-world simulation, i.e., it may be not feasible to conduct experiments with real aircraft, simulations were adopted in this research. One should note that human-in-the-loop simulations may offer a more accurate data on, for instance, airspace capacity evaluation. The simulated experiments employed six Certified Professional Controllers (CPCs) and one Operations Supervisor from Cleveland and were conducted in the high fidelity Display System Replacement (DSR) Laboratory. The experiments showed the DD metric performed better than the aircraft count, which is a usual complexity measure. However, although this research has valuable results in terms of simulation and airspace capacity and considered specialists in Air Traffic Control (ATC), UAS are not considered in the approach. Finally, cognitive factors (e.g. lack of familiarity of ATCo with a specific aircraft) are not taken into account.

In (HORIO et al., 2012), the LMI ACAS (Airspace Conflict Analysis Simulation) tool is presented. This is a 3-dimensional simulation modeling tool and its application meets the analytical requirements. The benefits of implementing a multidimensional visualization are also presented. The conducted case study, which employs the ACAS tool for a safety risk assessment based on conflicts probability, demonstrates the capacity of the framework to evaluate safety risk is demonstrated. Also, a set of concerns that include traffic growth, Next Generation Air Transportation System (NextGen) technologies, dynamic airspace sector reconfiguration and the integration of UAS into shared airspace are considered. As the NextGen is under development, modeling complex diverse future scenarios is important, thus better solutions can be provided in term of specific metrics (e.g. safety). Some causes and consequences related to risk analysis are pointed. For instance, an increase in passenger demand leads to a higher traffic density. Considering that ACAS is not meant to be a NAS-wide simulation of all aspects of flight, this research

aims to propose an agile tool for exploring NextGen aviation concepts and technologies from the safety perspective. However, this research does not include cognitive workload associated with special aircraft operation (e.g. UAS).

In (HONG et al., 2016), numerical simulations are used in order to demonstrate the effectiveness of the proposed conflict management approach, which ensures conflict avoidance among aircraft and transition of aircraft into adjacent airspace. Complexity is also modeled as aircraft heading and speed deviations in a given sector to avoid conflicts. Considering more than one sector, a specific architecture is proposed for planning aiming to minimize complexity for the neighbor sectors. More specifically, the conflict avoidance problem can be seen as a mixed integer Linear Programming (LP) subject to maneuver constraints. Thus, the aircraft can find the optimal solution by solving the LP problem and resolve conflicts among the aircraft and reduce the air traffic complexity of the neighbor sectors. Moreover, the proposed conflict management algorithm can identify the optimal conflict resolution maneuver of aircraft in near real-time considering multi-sector environments. The authors intend to investigate the relationship between the maneuver constraints and traffic complexity in future works. However, although this research is interest from the conflict avoidance perspective, it does not deal with fully autonomous or remotely piloted aircraft. Finally, ATCo operation and impacts of the proposed approach in his/her workload are not considered.

In this section, the works related to airspace simulation were presented. Different aspects are covered by each work, but, in order to identify the similarities and differences, Table 2 presents all works, which are classified as follows:

- **Unmanned Aircraft System (UAS):** Indicates if UAS are considered in a given research. One should note that Remotely Piloted Aircraft Systems (RPAS), as a sort of UAS, are also considered.
- **Cognitive Impact of Different Aircraft (CIDA):** Indicates if the impacts related to special aircraft (e.g. UAS) operation on personnel performance.
- **Bad Weather Conditions (BWC):** Indicates if the proposed simulation tool deals with the challenges imposed by bad weather conditions.
- **Conflicts Avoidance (CA):** Indicates if conflict avoidance is prioritized in the given simulation tool.
- **Air Traffic Controller (ATCo):** Indicates if ATCo operation is one simulation focus.

- **Vectoring (Vc):** Indicates if aircraft are controlled by Vectoring Points (VP).
- **Workload (Wl):** Indicates if the workload of ATCo is evaluated in the simulation tool.

This table shows that most of the related works deal with collision avoidance problem in simulation and many consider the ATCo operation. Few works include weather conditions, vectoring and workload evaluation in experiments. Thus, UAS appears in few works. Finally, none of the listed related works treat the cognitive impact on, for example, workload due to the lack of familiarity of ATCo with a new aircraft (e.g. UAS). Also, none of the listed works listed treats all the criteria presented in the Table. Note that all the criteria are considered in the proposal of this research.

Table 2: Works related to airspace simulation.

Related Work	UAS	CIDA	BWC	CA	ATCo	Vc	Wl
(MCFADYEN et al., 2016)	✓	X	X	✓	X	X	X
(SCALA; MOTA; DELAHAYE, 2016)	X	X	X	✓	✓	X	X
(FARLIK, 2015)	X	X	X	✓	✓	X	✓
(HU; LIAO; PAOLO, 2016)	X	X	X	✓	✓	✓	✓
(MEHLITZ et al., 2016)	X	X	✓	✓	✓	X	X
(VOLF, 2015)	X	X	X	X	✓	X	✓
(HOEKSTRA; ELLERBROEK, 2016)	X	X	✓	✓	✓	✓	X
(TRA et al., 2017)	X	X	X	✓	X	✓	X
(ALAM; ABBASS; BARLOW, 2008)	X	X	✓	✓	X	X	X
(PAVLINOVIĆ et al., 2017)	X	X	X	✓	✓	✓	X
(YOUNG et al., 2013)	X	X	✓	✓	X	X	X
(MCGOVERN; KALISH, 2009)	X	X	✓	X	✓	X	X
(HOMOLA et al., 2016)	✓	X	✓	✓	✓	✓	X
(LI et al., 2015)	X	X	X	✓	✓	X	X
(SUN; ZHANG; CAI, 2009)	✓	X	X	✓	X	X	X
(BUCCERONI et al., 2016)	✓	X	X	X	X	X	X
(BORENER et al., 2015)	✓	X	✓	✓	X	X	X
(KOPARDEKAR et al., 2009)	X	X	✓	✓	✓	✓	✓
(HORIO et al., 2012)	✓	X	✓	✓	✓	X	✓
(HONG et al., 2016)	X	X	X	✓	✓	✓	X

Source: The author.

2.3 Airspace Arrival Segments Optimization

This section shows a literature review conducted toward optimization approaches for arrival segments design considering the UAS presence. The proposals are analyzed from different perspectives in order to highlight the difference between them and our approach. In order to select and classified the related works present in this section, the consideration of the following aspects in each approach are taken into account: non-segregated airspace, final arrival segment design, complex situations, bad weather conditions, minimum separation, UAS presence and time as a constraint.

Alonso-Ayuso et al. (ALONSO-AYUSO et al., 2016) presents an approach that employs a mixed integer linear approximation to a Mixed Integer Nonlinear Optimization (MINO) model for the conflict resolution problem in air traffic management, i.e., for providing aircraft configurations in order to avoid conflicts, which is the loss of the minimum separation between two given aircraft. The problem is solved considering an initial position of a set of aircraft and applying changes to their position, velocity and heading angles. Thus, a multi-criteria scheme and a Sequential Mixed Integer Linear Optimization (SMILO) approach are also presented. This is due to the achievement of solutions in short computing time. Furthermore, a comparison between the results obtained by using the state-of-the-art MINO solvers and SMILO performance in a broad testbed is also considered, which showed that the both presented similar solutions but the proposed approach requires a very small computing time. Finally, the authors highlight that for large-size instances (e.g. above 5 aircraft) the computing time is higher than the one required by real-life operational applications and that other meta-heuristics able to reduce even more the computing time without deteriorating the SMILO solution as future research line. However, this research does not consider the operation of UAS into the non-segregated airspace. In addition to this outstanding contribution, our research includes bad weather conditions, which have a considerable impact on aviation, and ATCo workload related to each maneuver. Furthermore, we consider the inclusion of UAS into non-segregated airspace and how they impact the final arrival segments optimization from safety and efficiency perspectives.

The authors in (GAO; ZHANG; GUAN, 2012) present a cooperative multi-aircraft Conflict Resolution (CR) method based on co-evolution. The paths are composed by sub-populations considered in a Particle Swarm Optimization (PSO) implementation, in which the fitness is evaluated by cooperation among individuals from different sub-population and is adopted for its advantages such as fewer parameters and computation

and faster convergence. One should note that each particle is seen as a point of D-dimension space. Further, an encoding method with adaptive searching mechanism is introduced to improve the searching efficiency. Compared with Genetic Algorithms (GA) currently being used for conflict resolution path optimization, the results achieved by this approach achieved higher system efficiency, which is a manner to measure how similar a given path is to the smallest possible path. Considering 2, 4 and 6 aircraft, the proposed approach outperformed the GA approach. However, although this research employs the PSO successfully, this research does not consider the fitness evaluation and particle update processes to be conducted in parallel for each particle, which can improve the performance considerably. Also, bad weather conditions are not taken into account. Finally, the UAS presence and arrival segments definition are not considered.

Ahmed et al. (AHMED; ALAM; BARLOW, 2017) present an evolutionary method for optimizing the aircraft path planning algorithm in Terminal Maneuvering Area (TMA). This method, which provides near optimal aircraft arrival sequences, aims to deliver the aircraft to the Final Approach Fix (FAF). In order to accomplish this, the paths are built to conduct the aircraft from the Initial Approach Fix (IAF) to the FAF considering intermediates waypoints called Intermediate Fix (IF). The classic Genetic Algorithm (GA)-based optimization technique with conflict detection and resolution used in this effort minimizes the inter-arrival time. Furthermore, conflict-free path planning to an Air Traffic Controller (ATC) is also obtained. One should note that conflict between any two aircraft is detected based on their future arrival time at the waypoint. The results show that the proposed approach provides a near optimal solution compared to the traditional GA-based algorithm, which does not consider airspace constraints (e.g. speed). In addition to this outstanding effort, we propose a method that optimizes the final arrival segment definition, i.e., instead of delivering the aircraft from the IAF to the FAF, our objective is to deliver the aircraft from the final sector of the TMA to the IAF. Furthermore, besides considering conflict avoidance into the path planning strategy, we also consider bad weather conditions as well as the UAS presence.

In (SAMÀ et al., 2017c), the authors proposed a mixed integer linear programming formulations to optimize, at real-time, the take-off and landing operations at a busy Terminal Maneuvering Area (TMA) in case of traffic congestion by investigating the trade-off aspects between performance indicators of practical interest. This method also considers safety constraints with high precision. As TMAs are becoming problematic, especially in the major European airports, due to the fact that there is a limited possibility of building new infrastructures, alternative solutions (e.g. optimization models) are desired. The

real-time problem of effectively managing aircraft operations is challenging especially due to the inclusion of safety regulations into the optimization model and several performance indicators. This inclusion leads to the achievement of feasible and reasonable solutions in terms of safety and efficiency even considering that there is no well-recognized objective function and traffic controllers often use simple scheduling rules. The experiments performed considering simulated scenarios in the two major Italian airports, Milano Malpensa and Roma Fiumicino. In this context, a set of random landing and take-off aircraft disturbances is built. In the optimization process, practical-size instances are solved to (near) optimality by employing a commercial solver. Finally, a computational analysis enables the selection of solutions that presents considerable quality in balancing the various indicators trade-off. However, this research focuses on scheduling and does not consider the presence of UAS and the impact of the inclusion of this new technology into the ATC. Furthermore, in addition to this research, our proposal conducts the aircraft from the final sector to the Initial Approach Fix (IAF).

Samà et al. (SAMÀ et al., 2017a) deals with the TMA aircraft scheduling problem, which requires conflict-free schedules for all aircraft whereas the overall aircraft delays are minimized. Furthermore, this research also deals with the aircraft landing trajectory optimization problem, which requires landing trajectory that minimizes the travel time or the fuel consumption for each aircraft. In this context, a framework for the lexicographic optimization of both problems is proposed, which solves the two problems sequentially based on a defined lexicographic order of importance for the performance indicators, i.e., the most important performance indicator defines the first problem to be optimized. Note that the second problem is solved considering some outputs of the solution of the first problem. The experiments, performed on simulated Milano Malpensa airport instances and considering different optimization lexicographic orders and performance indicators, show the existence of performance gaps between the optimized indicators of the two problems, which highlights the multi-objective nature of the problem when different lexicographic optimization approaches are considered. However, some aspects such as bad weather conditions are not taken into account in this research. In addition to this research, our approach considers the inclusion of UAS into the non-segregated airspace. Furthermore, bad weather conditions are also considered in our proposal.

A number of algorithmic improvements implemented in the AGLIBRARY solver, which is a state-of-the-art optimization solver for complex routing and scheduling problems, in order to improve the possibility of finding good quality solutions quickly is presented in (SAMÀ et al., 2017b). Intelligent decision support systems for the real-time

management of landing and take-off operations, which can be effective in helping ATCos at busy Terminal Control Areas (TMAs), aims to optimize the aircraft sequencing. This problem, which can be faced as a mixed integer linear program, is strongly NP-hard and heuristic algorithms are typically adopted in practice to compute good quality solutions in a short computation time. In this context, the framework proposed in this paper starts from a feasible initial solution for the aircraft scheduling problem with fixed routes, computed via a truncated branch-and-bound algorithm, and, further, metaheuristics (e.g. variable neighbourhood search, tabu search and hybrid schemes) are applied to improve the solution by re-routing some aircraft in the TMA. Finally, the results presented showed that the metaheuristics achieve solutions of remarkable quality quickly compared with a commercial solver. However, parallel implementations of the metaheuristics, which may reduce the execution time considerably, are not considered. Finally, UAS presence is not taken into account.

The authors in (ARANTES et al., 2017) apply heuristic and genetic algorithms approaches for the path planning problem for UAVs. This approaches consider emergency landing procedures and aim to mitigate the probability of reaching unsafe situations. The path re-planning, which can be caused by several factors such as equipment failures and leads missions to be aborted by executing an emergency planned landing, is introduced through a mathematical formulation. In this context, path planning approaches that employ greedy heuristic, which aims to find feasible paths quickly, genetic algorithm and multi-population genetic algorithm, which tends to return better quality solutions, are introduced and evaluated considering large set (600 maps) of scenarios. The experiments, conducted by using FlightGear simulator, showed that all methods were able to land the aircraft appropriately for about 67% of scenarios considered. The type of landing executed by the UAV was evaluated under two situations. First, The UAV landing is evaluated taking into account the chance to save the UAV without putting a risk on people, properties or itself. Next, the UAV landing is evaluated taking into account the emphasis on saving people and properties, without to care about UAV damages. Finally, statistical analysis reveals that the strategy of combining the greedy heuristic with the genetic algorithms is suitable for this problem. Although this paper deals with path planning, it is not focused on non-segregated airspace. Furthermore, the presence of the ATC is not taken into account.

A framework and a formulation for solving path planning problem for multiple heterogeneous UAVs with uncertain service times for each vehicle–target pair is presented by Sundar et al. (SUNDAR et al., 2017). The vehicles, which differ in their motion

constraints and are located at distinct positions in the beginning of the mission, consider a penalty related to the duration of their total service time. The main goal is to find a tour of each vehicle that starts and ends at its respective position. This considers that every target is visited and serviced by some vehicle and the sum of the total travel distance and the penalty applied to all vehicles are minimized. Furthermore, the authors present the theoretical properties and advantages of using a two-stage stochastic as problem formulation to solve this problem instead of using a deterministic expected value formulation. Finally, extensive numerical simulations that compared these two formulations also corroborate the effectiveness of the proposed approach. However, although this research can be adapted to be applied to problems related to non-segregated airspace (e.g. aircraft rerouting), this is aimed to be applied to segregated airspace missions. Furthermore, aspects such as bad conditions are not taken into account. Finally, arrival segment constraints are not taken into account.

In (FRONTERA et al., 2017), a fast algorithm that finds collision-free 3D paths for small UAS in urban environments is introduced and, further, combined with an algorithm that computes approximate Euclidean shortest paths. This algorithm uses a method for reducing the number of obstacles present in the pathfinding process considering that the studied environments are expressed as three-dimensional scenarios and the objects as vertical polyhedra. The reader should note that this approach aims to reduce the computation time in a more practical situation, i.e., the algorithm proposed is not efficient in complex situations. Thus, there are situations in which the algorithm does not perform well, for instance, scenarios that include tall objects. Experimental cases showed that this approach is competitive both in terms of speed and solution quality if compared to solutions present in the literature for more realistic scenarios. Furthermore, the authors intend to extend this method for more complex scenarios in future works. However, this research does not consider application into the non-segregated airspace. Also, evolutionary approaches (e.g. Particle Swarm Optimization) are not explored as an alternative to solving complex situations. Finally, some important factors that present impacts on aviation for segregated and non-segregated airspace, such as the bad weather conditions are not taken into account.

In (SHAKHATREH et al., 2017), an approach that employs a single UAV for providing wireless coverage for indoor users inside a high-rise building under disaster situations (e.g. earthquakes) considering the failures in cellular networks is proposed. In order to accomplish this, the authors assume that the locations of indoor users are uniformly distributed in each floor. Furthermore, a Particle Swarm Optimization (PSO) algorithm

to find an efficient 3D placement of a UAV that minimizes the total transmit power required for the coverage. The experiments, which considered 50 of population size, 50 of maximum iteration number, and 20 users in each floor, showed that the proposed approach minimizes the total transmit power required to cover the indoor users considering a uniform distribution of users per floor. Note that the authors state that the PSO is chosen due to the intractability of the problem given its characteristics. In conclusion, this research adopts a traditional implementation of the PSO algorithm and adapts it to the problem. However, changes that may improve the time spent in finding an appropriate solution in terms of feasibility and fitness, e.g., polarization, are not taken into account. On the other hand, this effort focus on small UAS, i.e., the non-segregated airspace is not considered. Finally, complex situation and bad weather conditions are not included in this approach.

Jiang et al. (JIANG; ZHOU; YE, 2017) establish the model of task assignment for UAV in logistics regarding the Vehicle Routing Problems with Time Windows (VRPTW). In the past few years, there has been a growth in research achievements in logistics and UAV separately, whereas the research achievement on the combination of these areas steadies stable. Effective logistics system and task assignment are important in reducing the operation cost and improving transport efficiency. In this context, the model proposed in this research considers different constraints, such as weight coefficients, time-windows constraints and the constraints of the UAV. Furthermore, the Particle Swarm Optimization (PSO) algorithm is used for solving the task assignment problem due to its suitability for dealing with complex combinatorial optimization problems. Note that the PSO implementation presents some modifications due to the fact that the original PSO algorithm is only suitable for the continuous space optimization problem and, in this paper, the task assignment for UAV is integer linear programming problem. The conducted experiments showed that the PSO is efficient to solve the problem of task assignment for UAV and, in comparison with a traditional Genetic Algorithm (GA), this approach presented a higher success rate and a lower average running time. In addition to this research, although we do not deal with an integer linear programming problem, we adopt in our proposal the PSO algorithm in order to solve the vectoring problem in a parallel manner in order to achieve a higher efficiency.

A new optimization problem for solving conflicts is presented by Hong et al. (HONG et al., 2017). This method allows aircraft to change both their heading angle and speed in order to optimize their trajectory. The performance index is expressed in terms of the variation of the aircraft arrival time that is caused by conflict resolution maneuvers,

i.e., higher performance indices are computed in situations in which this time variation is low. In order to accomplish the conflict resolution and a proper flow management, metering constraints (e.g. aircraft arrival time) are introduced together with separation constraints. In this context, the optimal solution is obtained by utilizing Particle Swarm Optimization (PSO) and numerical and Monte Carlo simulations are conducted to evaluate the performance of the proposed algorithm. Due to the considerable ease of PSO in solving complex nonlinear problems, several performance indices and constraints are considered without the limitations of linear approximation or complex procedure, which may involve a certain level of imprecision. The simulations results showed a significant reduction in the variation of the aircraft arrival time as well as the magnitude of the maneuvers, i.e., heading angle and speed changes. In addition to this interesting application of the PSO algorithm, our proposal considers the optimization of arrival segments considering the UAS presence. Thus, in order to achievement a quicker response of the algorithm execution, we consider a parallel algorithm architecture.

Marinakis et al. (MARINAKIS et al., 2017) deal with the Constrained Shortest Path problem, which is a well known NP-hard problem, by proposing a new hybridized version of Particle Swarm Optimization (PSO) algorithm, which is a population-based swarm intelligence method, with Variable Neighborhood Search (VNS), which is an algorithm applied in order to optimize the particles' position. Although in the proposed algorithm, a different equation for the velocities update of particles is considered and a new neighborhood topology is employed, an issue of applying the VNS is the identification of the suitable local search method for a given problem. In this sense, a number of continuous local search algorithms are used and tested in a number of modified instances from and, further comparisons with classic versions of PSO. Finally, the experiments showed that the proposed algorithm very satisfactory efficiency and results. As future directions, the authors highlight the application of this methodology to more difficult problems. In the proposal of the present research, in order to improve the PSO efficiency and in addition to this research, parallel evaluation of each particle fitness as well as the velocity updates are conducted in a parallel manner. Finally, the reader should note that this research is more theoretical and is not applied directly to the airspace optimization such as our proposal.

In (YANG et al., 2016), the authors present an optimization algorithm for solving the problem of arrival aircraft trajectory, which aims in finding best solutions of vertical flight profile considering the Required Time of Arrival (RTA) and constraints of Terminal Maneuvering Area (TMA), and aircraft performance. Firstly, the Base of Aircraft Data

(BADA), which is an open-source database toward aircraft performance aspects and is used in simulation tools, is used in order to identify the aircraft aerodynamic and fuel consumption. Then, a method for optimizing the trajectories is proposed based on an Improved Particle Swarm Optimization (IPSO), in which the inertia of particles decreases from 1 to about 0.5 as long as they get closer to near-optimal solutions, with Successive Quadratic Programming (SQP). During the optimization process, the IPSO is employed in finding a near optimal solution and, then, the SQP is used in order to enable a quicker finding of an accurate solution. Furthermore, this approach is compared to standard PSO, which shows that its performance is an effective method for trajectory optimization problem. However, this proposal is not focused on aspects of UAS integration during the optimization process. Finally, although fixed weights are employed in our proposal, the parallel architecture considered tends to improve the algorithm efficiency.

Girish (GIRISH, 2016) proposes a Hybrid Particle Swarm Optimization-local search (HPSO-LS) algorithm, in a rolling horizon framework, for dealing with the Aircraft Landing Problem (ALP), which consists of the allocation of arriving aircraft to runways and the assignment of a landing time to each aircraft. The main goal of this research is to minimize the penalty costs due to delays in landing times. Note that the rolling horizon framework is used as an online optimization strategy in which a fixed time horizon is taken into account. The presented results showed that the proposed algorithm is effective in solving the problem and comparing with existing approaches from the literature (e.g. PSO variants) in scenarios that involve up to 500 aircraft and 5 runways, the RH-HPSO-LS showed to be a more appropriate technique for this problem. As future works, the author intends to improve the approach approaches in order to reduce the computational time requirements for enabling real-world applications, i.e., real-time applications. However, this effort does not cover the final arrival segments design from the final sector. Also, although the techniques employed are interesting for finding good solutions, the optimization is not built considering aspects of UAS integration into the non-segregated airspace.

Ribeiro et al. (RIBEIRO et al., 2016) propose a framework that integrates performance preferences of landing aircraft in Continuous Descent Arrival (CDA) operations that deals with the management of building flight trajectories, which are optimized reduce fuel burn and emissions during the descent/approach phase. This approach is special interesting due to the fact that the maximization of airspace efficiency and capacity, which needs to be addressed considering local airspace requirements and constraints, are related to optimization of air traffic trajectories. The authors highlight that the Air Traffic Con-

trol (ATC) agent, which is responsible for conducting the air traffic to specific trajectories, employs a Particle Swarm Optimization (PSO) algorithm in order to build feasible and safe solutions for arrival sequencing. The results showed that considering the data from Brasilia International Airport (SBBR), the proposed approach enabled 77% of the air traffic to accomplish their desired time window flying. Finally, as future intentions, the authors aim to deal with en-route trajectory conflicts and capacity constraints. However, some aspects such as bad weather conditions are not taken into account in this research. In addition to this effort, our proposal considers a parallel implementation of the PSO algorithm. Also, the presence of UAS is considered. Finally, we also consider bad weather conditions.

The authors in (MURATA et al., 2016) focus on the aircraft landing optimization problem considering both the landing routes and the landing order of aircraft. The main goal is to minimize the occupancy time of airport, which leads to an increase in the airspace efficiency. This approach considers dynamical situations such as weather condition changes and other aircraft' landing routes changes. To deal with this problem, the hierarchical evolutionary computation is proposed, which generates candidates of the main landing route of all aircraft. Furthermore, good combination of landing routes of all aircraft is considered in order to minimize an occupancy time of airport. The experiments showed that robust landing routes and order are generated by the proposed strategy. However, the obtained results have only been obtained from one simple grid map which simulates the flying area of the aircraft and further careful qualifications and justifications (e.g. other maps or a different number of aircraft) represent future intentions of the authors. Furthermore, our proposal considers complex situations in which feasible solution in terms of efficiency and, especially, in terms of safety are required. Finally, the UAS integration, which may be an important airspace user in the next years, is considered.

Narayan et al. (NARAYAN et al., 2009) proposes a novel approach for optimization 3D flight trajectories considering real-time planning deadlines for small UAS operating in challenging environments, i.e., environments with obstacles. In this approach, which generate feasible solutions, sets of candidate smooth flight trajectories are generated and, considering that in typical small UAS operations multiple objectives may exist, a multi-objective optimization is employed due to the fact that it may allow the discovery of solutions that better reflects overall mission requirements. Note that, in this context, real-time planning constraints may be imposed during the optimization process in order to avoid obstacles in the immediate path and this approach considers a novel Computa-

tionally Adaptive Trajectory Decision (CATD) optimization system to manage, calculate and schedule parameters associated with trajectories building to ensure that the feasible solutions are offered taking processing duration as constraint. In conclusion, the authors point that this approach may potentially more efficient use of the computational time available. However, this research is intended to be applied to segregated airspaces. Furthermore, weather conditions are not taken into account.

The authors in (JI; FANG; YAN, 2014) propose an online method based on Estimation of Distribution Algorithm (EDA), which has become a hot topic in field of evolutionary computing, for the real-time Aircraft Arrival Sequencing and Scheduling (ASS) optimization problem. This problem, which is considered a hot topic in Air Traffic Control (ATC) contributions, has been proven to be an NP-hard problem. Although many efforts have been made by modeling this problem in a static case, the air traffic environment in the airport is dynamic and constantly changing. Considering that new aircraft are arriving at the airport continually, the corresponding adjustments should be considered for the scheduling definition. In this context, the method focuses on aircraft that have already arrived at the TMA but have not been assigned to land. The experiments conducted highlighted that the method is effective in achieving appropriate solutions for the ASS optimization problem. However, this contribution does not include the operation of UAS into non-segregated airspace and all challenges it brings to the sequencing problem. Furthermore, bad weather conditions are not taken into account. Finally, the fitness evaluation does not consider the impacts of a given sequencing solution into the ATC.

Bennell et al. (BENNELL et al., 2017) deal with the scheduling of aircraft landings on a single runway. The time window constraints for each aircraft's landing and the minimum separation between consecutive aircraft and, consequently, consecutive landings are two important metrics for the sequencing problem. Note that the separation between aircraft depends on specific factors, such as the weight classes. Thus, a multi-objective formulation that considers both the runway metrics (throughput, earliness and lateness) and the cost of fuel related to aircraft maneuvers and additional flight time is employed in order to achieve the landing schedule. This proposal also considers both the static/off-line problem, in which details of the arriving flights are provided in advance and the dynamic/online problem, in which the flight arrival information becomes available over time. The experiments conducted showed that, for both static and dynamic problems, efficient runway throughput results were achieved considering the employment of different meta-heuristics. In addition to this research, we consider the UAS presence and the impacts of this new technology into the ATCo operation.

In this section, the works related to air traffic sequencing optimization were presented. Different aspects are covered by each work, but, in order to identify the similarities and differences, Table 3 presents all works, which are classified as follow:

- **Non-segregated airspace (NSA):** Indicates if the optimization method is intended to be applied in situations of non-segregated airspace.
- **Final Arrival Segment Definition (FASD):** Indicates if the proposed method is focused on the final arrival segments design.
- **Complex Situations (CS):** Indicates if the optimization method is developed considering the sequencing of many aircraft, which constitute a complex situation.
- **Bad Weather Conditions (BWC):** Indicates if the proposed solution takes bad weather conditions into account.
- **Minimum Separation (MS):** Indicates if the proposed method applies minimum separations for each aircraft in order to maintain the safety levels.
- **UAS Presence (UAS):** Indicate if the proposed solution considers the presence of the UAS and its impacts on sequencing.
- **Time as a Constraint (TC):** Indicate if processing duration is analyzed in the approach, i.e., if the problem faced is a real-time problem.

This table shows that many related works consider the non-segregated airspace, minimum separation and complex situations. However, only one of them considers bad weather conditions. Note that all works that consider the UAS presence do not integrate them into the non-segregated airspace and, consequently, all works that deal with non-segregated airspace do not include the UAS. Finally, note that our proposal considers all the criteria presented in this table, differently to the listed works.

2.4 Concluding Remarks

Toward the increasing desire to integrate the UAS integration into the non-segregated airspace, a safe integration must be conducted. The literature review shows that there is a gap regarding the familiarity of the personnel with this new technology and few works consideres the ATCo workload, which are important aspects of the airspace operation. There are many perspectives of safety operation, e.g., unsafe failures of UAS components

Table 3: Works related to air traffic sequencing optimization.

Related Work	NSA	FASD	CS	BWC	MS	UAS	TC
(ALONSO-AYUSO et al., 2016)	✓	X	✓	X	✓	X	✓
(GAO; ZHANG; GUAN, 2012)	✓	X	✓	X	✓	X	X
(AHMED; ALAM; BARLOW, 2017)	✓	✓	✓	X	✓	X	X
(SAMÀ et al., 2017c)	✓	X	✓	X	✓	X	✓
(SAMÀ et al., 2017a)	✓	✓	✓	X	✓	X	X
(SAMÀ et al., 2017b)	✓	✓	✓	X	✓	X	✓
(ARANTES et al., 2017)	X	X	X	✓	X	✓	✓
(SUNDAR et al., 2017)	X	X	X	X	✓	✓	✓
(FRONTERA et al., 2017)	X	X	X	X	X	✓	✓
(SHAKHATREH et al., 2017)	X	X	X	X	X	✓	X
(JIANG; ZHOU; YE, 2017)	X	X	✓	X	X	✓	✓
(HONG et al., 2017)	✓	✓	✓	X	✓	X	X
(MARINAKIS et al., 2017)	X	X	X	X	X	X	✓
(YANG et al., 2016)	✓	✓	✓	X	✓	X	✓
(GIRISH, 2016)	✓	X	✓	X	✓	X	X
(RIBEIRO et al., 2016)	✓	✓	✓	X	✓	X	X
(MURATA et al., 2016)	✓	✓	X	X	✓	X	X
(NARAYAN et al., 2009)	X	X	X	X	X	✓	✓
(JI; FANG; YAN, 2014)	✓	✓	X	X	✓	X	✓
(BENNELL et al., 2017)	✓	✓	✓	X	✓	X	✓

Source: The author.

may lead the airspace to an unsafe state. This research proposed a novel approach for the UAS integration from the ATC perspective. In order to accomplish this, the Technology Maturity Level (TML), which models the familiarity of ATCo with a particular aircraft, is introduced. In this context, impacts on ATCo workload of UAS, which is related to airspace safety, are measured in this research according to the TML. This approach can also be applied to Manned Aircraft (MA). Finally, one should note that this research considers only large UAS, i.e., UAS have similar performance of MA.

In terms of airspace simulation, many aspects are not taken into account simultaneously in the works present in the literature. Conversely, there are gaps regarding, for instance, the cognitive impact on the inclusion of the UAS, which is an essential aspect to be considered. Furthermore, considering the increasing adoption of new technologies into the shared airspace, there are many challenges to be accomplished. Among these technologies, Unmanned Aircraft Systems (UAS), which has military and civilian applications, play an important role. There is an understanding that Air Traffic Controllers (ATCos) may be careful when dealing with this technology due to the lack of familiarity with it, which leads to a higher workload (ZŁOTOWSKI; YOGEEESWARAN; BARTNECK, 2017). However, in a futuristic scenario, UAS may operate along with traditional aircraft. In this research, we also propose a simulation tool, called Final Sector Simulation Tool (FSST), which aims evaluate safety (from workload perspective) and efficiency in aircraft sequencing in final sector considering the UAS presence. There are some aspects taken into account in this simulation tool. They are:

- Bad weather conditions;
- TML, which models the level of familiarity of ATCo with these aircraft;
- UAS presence;
- Cognitive impacts of UAS operation;
- Collision avoidance (detection);
- ATCo operation;
- Vectoring;
- Workload evaluation.

Toward the optimization of final arrival segments design, considering that sequencing the air traffic during the final arrival under airspace constraints can be considered an

NP-hard problem (JI; FANG; YAN, 2014), our novel approach deals with the integration of UAS into the non-segregated airspace given the gaps identified in the literature review (e.g. consideration of important aspects, such as bad weather conditions). The focus in this research is on the final arrival segments design considering complex situations. Thus, bad weather conditions are considered and represented as cumulonimbus (CB). Furthermore, a constraint taken into account in the proposed optimization method is the processing duration. This is due to the fact that in these critical situations, the ATCo needs quick responses. Finally, the optimization is achieved by considering: (1) sequencing duration, which is related to efficiency and represented by the time spent in delivering a set of aircraft to its destination, (2) ATCo workload, which is related to safety and is represented by the activities performed by ATCo when establishing vectors for each aircraft in order to deliver them safely, and (3) employing the Particle Swarm Optimization (PSO) meta-heuristic.

3 ASPECTS OF AIRSPACE OPERATION

This Chapter presents important aspects of the airspace operation that are related to the proposal presented in this research. Firstly, the Air Traffic Control (ATC) and its responsibilities are presented. After that, the importance of the Air Traffic Controller (ATCo). Then, a discussion on risks in aviation is conducted. Furthermore, the Arrival Sequencing and Scheduling (ASS) problem is defined. Finally, a discussion on Cumulonimbus (CB) formation is conducted.

3.1 Air Traffic Control (ATC)

In order to achieve safe operations in the airspace, several actions are adopted by many professionals from the flight plan presentation, by pilots or airlines, up to the turning off of aircraft engines on destination airport. In this context, there is an appropriate airspace structure and appropriate services provided by Air Traffic Control (ATC).

The airspace is divided into regions in which two services are provided by proper Air Traffic Service (ATS) units: the service of traffic control and Flight Information Service (FIS). Furthermore, the controlled airspace is formed by Airways (AWY), Terminal Control Area (TMA), Control Zone (CTR) and Aerodrome Traffic Zone (ATZ), illustrated in Figure 1.

An ATC unit, which is a “generic term meaning variously, area control center (ACC), approach control (APP) or aerodrome control tower (TWR)” (ICAO, 2016), is assigned for each controlled airspace. Note that a CTR is “a controlled airspace extending upwards from the surface of the earth to a specified upper limit” (ICAO, 2016), whereas a ATZ is “an airspace of defined dimensions established around an aerodrome for the protection of aerodrome traffic” (ICAO, 2005b). Finally, the AWY can be defined as “A control area or portion thereof established in the form of a corridor” (ICAO, 2005b).

The air traffic services comprise three services identified as follows (ICAO, 2001):

Figure 1: Controlled airspace structure.

(a) Front view

(b) Top view

Source: Adapted from (NETO et al., 2017b)

Table 4: Controlled Airspaces and their respective ATC unit.

Controlled Airspace	ATC Unit
AWY	ACC
TMA and CTR	APP
ATZ	TWR

Source: The author.

- **Area Control (ACC) Service:** the provision of air traffic control service for controlled flights primarily in Airways (AWY);
- **Approach Control (APP) Service:** the provision of air traffic control service for those parts of controlled flights associated with arrival or departure. This control is done in Control Zone (CTR) and Terminal Control Area (TMA).
- **Aerodrome Control Service:** the provision of air traffic control service for aerodrome traffic.

As sequencing arriving traffic is one of the most complex tasks in air traffic control, in this work the TMA and its respective ATC unit, i.e., the APP, are considered in order to analyze different scenarios. The TMA is defined as a control area normally established at the confluence of Air Traffic Service (ATS) routes in the vicinity of one or more major aerodromes (ICAO, 2001), as the TMA of Miami (KMIA), illustrated in Figure 2. Note that the black lines represent airways within the TMA, whereas the blue squares inside red circles represent airports of this TMA. Furthermore, ACC, APP, TWR are responsible for, respectively, AWY, TMA and ATZ, as illustrated in Table 4.

Aircraft that operate in Instrument Flight Rules (IFR)-equipped airports when taking off and landing, fly according to the standardized procedures published as Standard Instrument Departure (SID) and Standard Instrument Arrival (STAR) and need a clearance to consider these procedures. The approach controller is responsible for departing or approaching traffic and assigns SIDs and STARs to the flights in the approaching and departing procedures. An important detail is that controlling arriving traffic includes quick decisions that mean to involve intersections between departing and arriving traffic.

3.2 Air Traffic Controller (ATCo) Workload

Regardless of the ATC unit, the ATCo is responsible for “preventing collisions between aircraft, and on the maneuvering area between aircraft and obstructions; and expediting

Figure 2: TMA of Miami (KMIA).

Source: Adapted from (AIRNAV, 2016).

and maintaining an orderly flow of air traffic” (ICAO, 2016). These professionals play an important role in the airspace operation as long as they act in order to guarantee appropriate levels of safety and efficiency and in order to solve problems that arise in complex situations.

Moreover, considering the desire in maintaining the safety levels at an acceptable rate, the capacity of each sector, i.e. the maximum number of aircraft a sector can control in a specified period while still permitting an acceptable level of ATCo workload, must be respected (MAJUMDAR; OCHIENG, 2002). Experiences of airspace capacity in high-density air traffic suggest that the most appropriate measure for airspace capacity is based on controller workload, both physical and mental (MAJUMDAR; POLAK, 2001) (NETO et al., 2017a).

The workload can be defined as a metric that represents the difficulty of ATCo in understanding a particular situation (MECKIFF; CHONE; NICOLAON, 1998), expressed

in terms of seconds and measured by the interaction of various factors (e.g. exposition time to the controlling operation, ATCo experience and ATCo current mental state) that compose the airspace complexity. The workload can be considered as a function of (1) the geometrical nature of the air traffic, (2) the operational procedures and (3) practices used to handle the traffic and the characteristics of the ATCos. Note that all of these aspects are related to complexity (MECKIFF; CHONE; NICOLAON, 1998).

Examples of variables that compose the complexity in the ATCo operation and, consequently, impact the workload level are (DERVIC; RANK, 2015): communication with other ATCos, mental factors, conflict by distance, mean flight time, conflict by time-to-go, mix of aircraft performance, emergency operations, pilot request, flights entering or exiting sector, pilot's knowledge, frequency congestion and preventing conflicts.

In other words, the workload is the time spent by the ATCo in the process of handling the air traffic in a safe and efficient manner. In fact, although measuring workload precisely is a challenge due to the mental aspects involved in the ATCo operation (SUÁREZ et al., 2014), the complexity produces an additional controller workload, i.e., the characteristics of the sector and the air traffic tends to produce an additional workload for the controller (MAJUMDAR; OCHIENG, 2002). Examples of sectors within a TMA can be checked in the Figure 3, which illustrates the sectors 1 and 6 of the TMA of São Paulo (TMA-SP) as well as the Guarulhos airport. Furthermore, there are several models that consider different variables that impact the airspace capacity such as sector geometry, traffic density and the amount of climbing or descending traffics (MAJUMDAR; OCHIENG, 2002).

One should note that the workload threshold considered in this research, i.e., the maximum acceptable workload in order to maintain the safety levels, is 80% of an hour of control team workload (MAJUMDAR; POLAK, 2001) (MAJUMDAR et al., 2005).

Although there are many proposed models for ATCo workload measurement (MAJUMDAR; OCHIENG, 2002), there is an understanding that complexity is related to the increase of this metric. This is due to the fact that the difficulty faced in complex situation demands a more careful decision-making process at a short time. Complexity, thus, can be defined as the characteristics that arise from the airspace properties as, for instance, weather, airspace restrictions, traffic density, traffic flow, aircraft performance characteristics and unusual events (TOY, 2015).

Finally, inserting new technologies into airspace (e.g. UAS) may increase ATCo workload. This depends on several factors, such as familiarity of ATCo with this technology.

Figure 3: Examples of sectors in the airspace: Sectors 1 and 6 of TMA-SP.

Source: Adapted from (DECEA, 2017).

Moreover, UAS may increase the ATCo workload due to the uncertainties in its performance in terms of understanding and execution (by the UAS) of the instructions provided (by the ATCo). On the other hand, the process of making the ATCo familiar with these technologies may reduce the workload levels in a long-term.

3.3 Risks in Aviation

As safety is a key concern in airspace operation, threats to an acceptable safety level must be treated. Among the several problems that may occur in airspace operation, aircraft collision (which is the evolution of the conflict, i.e., the evolution of the loss of separation between aircraft) can be highlighted. One should note that mid-air collisions depend on a set of events happens, such as a conflict (i.e. the minimum separation established for those aircraft is not respected). Although these events are not usual,

there is a concern about reducing collision probabilities between aircraft. On the other hand, collisions may also happen with the ground or mountains. There are some factors that may lead to this collision, such as piloting errors (e.g. during arrival procedures the pilot may not have full situation awareness and collide with the ground) and lack of fuel. Considering a deep analysis on this risks, probability of occurrence as well as severity can be derived by, for instance, calculating the probability of each event in the set of events that lead to a collision. In order to evaluate the probability, different tools can be used, such as Fault Tree Analysis (FTA) (LEE et al., 1985). One should note that the severity, i.e., the impacts of a collision in society (e.g. loss of human lives), is complex to be precisely calculated and approximations are an alternative. However, there is an effort towards proposing mitigation strategies to reduce the probabilities of these events.

In order to reduce the probabilities of occurrence of possible hazardous events, actions are taken from different perspectives. From the ATCo perspective, there is an understanding that training for specific situations is an appropriate strategy. This training may also include, for example, real-time simulations, which insert the professional in a proper environment to experience key airspace situation (e.g. loss of communication with pilots). Other aspects that may have an lead the airspace to an unsafe state and can be mitigated with training are lack of intervention, by the ATCo, in complex situations and problems in communication. Ultimately, flight plans may be a critical source of undesirable events, and a special attention on this item may reduce probabilities of reaching unsafe states. From the pilot perspective, training on maneuvering from departure to arrival is essential to avoid undesirable incidents. Thus, problems on piloting (e.g. during critical arrival maneuvers) and communication must be avoided. Note that the ATCo workload optimization tends to reduce the achievement of unsafe states into the airspace and, although this research is not focused on risk analysis, an approach to maintain the safety levels considering the UAS presence is proposed. In this research, the risks faced are the mid-air collision (i.e. collision between aircraft) and “collision” with cumulonimbus (CBs). In order to avoid hazardous states in this context, in some situations, the ATCo must operate quickly and precisely, i.e., in an optimized manner.

3.4 Arrival Sequencing and Scheduling (ASS)

Regarding the Arrival Sequencing and Scheduling (ASS), many aspects can be highlighted. Firstly, we highlight the ASS problem. Then, the aspects of the Standard Instrument Arrival (STAR) are presented. Finally, a discussion of the instrument approach

procedure is conducted.

3.4.1 Problem Definition

The sector in which the aircraft intercept the Initial Approach Fix¹ (IAF) is called the Final Sector (FS). In this sector, which is illustrated in Figure 4 highlighted by a red polygon and in which this research is focused on, the aircraft are slower than in others sector of the airspace (around 180kts²). Also, the height is reduced (around 6000ft³). In common operations, the aircraft are expected to enter in this sector with a considerable space between them, which enables the ATC to conduct them in an easier manner to the IAF. Note that the IAF is the fix the aircraft must be delivered to in order to start the final approach procedure. Finally, note that, although the IAF of the Miami International Airport is located near to the Basho notification point (i.e. a triangle that represents a location in which the pilot must inform the aircraft position to the ATC unit), the IAF is not illustrated explicitly in Figure 4 due to the fact that area chart does not illustrate IAFs.

Figure 4: Final Sector of KMIA TMA (Miami).

Source: Adapted from (AIRNAV, 2016)

However, in complex situations, this sector may receive many aircraft at the same

¹Fix can be defined as type of a point on the surface of the earth located at a specific geographical location (i.e. at a specific position) that facilitates the conduction of aircraft as well as the separation maintenance (ICAO, 2016).

²1kt = 1,852 kilometers/hour

³1ft = 0,3048m

time and with nearly-minimum separations. Also, the Final Sector (FS) may also present challenges in terms of weather conditions with the presence of cumulonimbus (CBs). These factors may turn the sequencing and scheduling of these aircraft a very challenge activity due to its complexity and the need for a quick answer.

Thus, the objective function of the Arrival Sequencing and Scheduling (ASS) problem, which aims to "minimize the makespan of the landing sequence so that to land as many aircraft as possible within a period of time", is defined in Equation 3.1, whereas the landing time can be calculated considering the Equation 3.2 (adapted from (MA et al., 2014)).

$$\min W_\pi = x_{\pi_{end}} \quad (3.1)$$

$$x_{\pi_i} = \begin{cases} e_{\pi_i} & i = 1 \\ \max\{e_{\pi_i}, x_{\pi_{i-1}} + MST_{\pi_{i-1}, \pi_i}\}, & i > 1 \end{cases} \quad (3.2)$$

The Equations 3.1 and 3.2 show that the objective of the ASS problem is to minimize the landing time of the last aircraft ($x_{\pi_{end}}$) for a given sequence (π) and that this time can be measured by finding the maximum value between the expected time spent in the landing (e_{π_i}) and the sum of the time in which the previous aircraft landed and the Minimum Separation Time (MST) of these two aircraft ($x_{\pi_{i-1}} + MST_{\pi_{i-1}, \pi_i}$). Note that, in this research, we are conducting the aircraft to the IAF but the equations 3.1 and 3.2 are applicable considering instead of landing, delivery to the IAF as the main goal.

For instance, in Figure 5, two aircraft are flying in the direction of one IAF in a sequence s , i.e., $\pi = s$. The expected time duration of the aircraft 1 is 100s ($x_{s_1} = 100s$). Suppose that the actual expected time duration of the aircraft 2 is 150s and that, in order to maintain the separation between the aircraft, the Minimum Separation Time (MST) between them is 100s ($MST_{s_1, s_2} = 100s$). As the time in which the aircraft 2 is delivered to the IAF is a result of the sum of the MST between it and aircraft 1 and the delivery time of aircraft 1, the delivery time of aircraft 2 to the IAF is 200s ($x_{s_2} = MST_{s_1, s_2} + x_{s_1} = 200s$). Finally, note that the challenge is to identify the sequence in which the last aircraft to be delivered (in this case, aircraft 2) is delivered as soon as possible, i.e., to reduce the time of the delivery of the last aircraft (x_{s_2}).

In this research, our focus is to deliver the set of aircraft from the entrance of the final sector to one of the IAFs available in this area in simple and complex situations, which

Figure 5: Delivery of aircraft to the IAF considering expected time duration..

Source: The author.

constitutes the Final Arrival Segments Optimization (FASO). Thus, arrival segments can be defined as a route that permits transition from the en-route phase to the approach phase, i.e., the phase in which the aircraft fly through the IAF, the Intermediate Fix (IF), also known as merge point, and the Final Approach Fix (FAF) (ICAO, 2006), whereas the final arrival segment can be defined as a route that permits transition from the final sector to the approach phase. Their difference is illustrated in Figure 6. Note that arrival segments may be standard, which are represented by the STARs, or defined in terms of vectoring points, which are considered in special situations (e.g. avoidance of cumulonimbus in bad weather conditions) (ICAO, 2006) and that the Figure 6 illustrates a direct path from the TMA entry to the IAF, which tends to be similar to the path taken when STARs are followed.

Figure 6: Difference of Arrival Segment, which is defined within the TMA, and the Final Arrival Segment, which is defined within the final sector and is the focus of this research.

Source: the author.

Furthermore, considering that this is a challenging and critical activity, metrics such

as response time must be taken into account. Finally, note that the safety constraints, such as minimum separation and CB avoidance, are considered as well as the impacts on ATCo workload in defining new paths (e.g. communication and surveillance).

3.4.2 Standard Instrument Arrival (STAR)

The Standard Instrument Arrival (STAR) is the “designated Instrument Flight Rule (IFR) arrival route linking a significant point, normally on an ATS route, with a point from which a published instrument approach procedure can be commenced” (ICAO, 2016). Basically, STARs leads the aircraft to the Initial Approach Fix (IAF) to start the actual Final Approach Procedure or Instrument Approach Procedure (IAP). One part of a STAR adopted in the TMA of Miami (KMIA), which is composed by a set of waypoints, is illustrated in Figure 7, whereas one of the IAPs adopted (which includes IAF, IF and FAF) is illustrated in Figure 8. Note that the IAF, IF and FAF are highlighted within green polygons.

Figure 7: One of the Standard Instrument Arrival (STAR) adopted in the TMA of Miami (KMIA).

Source: Adapted from (AIRNAV, 2016).

Although, in common situations, the arriving aircraft should normally be cleared to follow the appropriate STAR, some situations are more complex and demand different clearances. For instance, the presence of CB in the TMA may turn the STAR unfeasible to be followed. Furthermore, in critical cases in which the number of aircraft within the TMA is much higher than expected. The reader should note that, although in common operations STARs are followed, it is very reasonable considering that these critical events may happen (e.g. in cases of problems in the airspace flow management). In these cases, the ATCo must act in order to guide the aircraft to the IAF in a safe and efficient manner. Finally, the paths for the aircraft within the final sector are the final arrival segments.

Figure 8: One of the Instrument Approach Procedures (IAPs) adopted in Miami TMA.

Source: Adapted from (AIRNAV, 2016).

3.4.3 Instrument Approach Procedure (IAP)

According to ICAO (ICAO, 2005b), Instrument Approach Procedure (IAP) is "a series of predetermined manoeuvres by reference to flight instruments with specified protection from obstacles from the initial approach fix, or where applicable, from the beginning of a defined arrival route to a point from which a landing can be completed and thereafter, if a landing is not completed, to a position at which holding or en route obstacle clearance criteria apply".

In this context, an example of final approach route structure, in which the Initial Approach Fix (IAF) and the Final Approach Fix (FAF) are contained, is presented in Figure 9. According to this Figure, the aircraft may intercept the IAF and fly considering a merge point as the destination, the Intermediate Fix (IF). Although there are other paths the aircraft may follow in order to reach this merge point from the final sector, IAFs indicated standard paths. Note that the aircraft reduces its altitude during final approach procedures and the merge point can be reached from multiple paths, including the standard path (represented by the IAF). Finally, the IF connects all these paths to the FAF, where the actual landing procedure starts (BOURSIER et al., 2006).

Figure 9: Example of Final Approach Route structure.

Source: Adapted from (ICAO, 2006).

3.5 Aspects of Weather Conditions

Regarding airspace operation, severe weather is an important factor resulting flight delays (FROMM et al., 2005) (LIU et al., 2016). For instance, the estimation of the capacity of a set of sectors in a given airspace region during weather events is an important part of air traffic management (MITCHELL; POLISHCHUK; KROZEL, 2006). In this context, the definition of trajectories that avoid these adverse situations is desired. An important player in bad weather conditions is the CB.

CB (FAA, 2016) is an exceptionally dense and vertically developed cloud type that occurs as isolated clouds or as a line or wall of clouds in the shape of mountains or towers. The formation of this cloud may be spread out in the form of an anvil, as illustrated in Figure 10. Furthermore, CB is composed of water droplets and ice crystals and contains nearly the entire spectrum of flying hazards, including extreme turbulence, and are considered the ultimate manifestation of instability in terms of airworthiness and should be avoided at all times (FAA, 2016) (LUDLAM, 1956).

The size of these cloud formation may vary widely. However, according to specialists

Figure 10: Different cumulonimbus (CB) formations.

Source: (FAA, 2016)

of the safety analysis group (GAS) of the University of São Paulo, a reasonable shape to be considered, which is adopted in this research, is a circle in a 2D environment with a radius of 2 Nautical Miles (nm). Note that the cumulonimbus may move in different directions. Furthermore, in this research, we consider the clouds to be fixed in a specific position due to the fact that during the initial phase of the aircraft approach there are not great variations in their positions.

3.6 Concluding Remarks

The main goal of this chapter was to present all the relevant information related to the airspace operation that is needed in order to understand the contributions of this research. In fact, understanding the process of delivering aircraft from the final sector and the constraints that must be respected by the aircraft is essential.

Furthermore, the concepts of the airspace operation were highlighted. The fundamental roles played by the ATC and by the ATCo were discussed. After that, the ASS problem was defined. Finally, the aspects of the weather conditions and their impacts on the air transportation were presented.

In the following chapters, these concepts are used, especially in the Final Sector Simulation Tool (FSST) and in the Final Arrival Segment Optimization Model (FASOM) proposals, which are described in, respectively, chapters 7 and 8.

4 UNMANNED AIRCRAFT SYSTEMS (UAS)

This section describes the aspects of the UAS operation as well as challenges faced in their operation. Firstly, UAS is defined in terms of functionalists and sub-systems. Then, the UAS classifications are presented from both perspectives: piloting and size. Finally, a discussion on the challenges of integrating these autonomous aircraft into the non-segregated airspace is conducted.

4.1 UAS Definition

Unmanned Aircraft System (UAS), which is an important business considering its potential and applications (FASANO et al., 2016), is a system composed of sub-systems such as unmanned aircraft vehicle (UAV), its payloads, the control station and communications sub-systems (FASANO et al., 2016) (AUSTIN, 2011). The UAS has been employed in different scenarios and presents advantages in many applications, such as reducing the risks associated with pilots in applications (e.g. video surveillance) (GANTI; KIM, 2016). Furthermore, the sub-systems that compose the UAS have specific responsibilities that represent important aspects of the whole system operation, such as:

- **Control Station (CS):** represents the control center of the operation. This component enables the operator to operate the aircraft in an appropriate manner through specific interfaces (AUSTIN, 2011);
- **Payload:** is the extra mass the aircraft needs to carry and it is defined depending on the mission purpose. For instance, in sensing applications, equipment such as cameras, sensors and another payload may be required and the aircraft needs to operate in a manner that optimizes the process of gathering the desired data (LEASURE; NOLAN, 2015);
- **Aerial Vehicle:** represents the unmanned aircraft vehicle (UAV). This component is related to the performance of the aircraft, such as speed and altitude it operates.

The reader should note that the UAV performance may vary widely depending on the mission it has been designed for;

- **Navigation Systems:** this component plays the role of providing an understanding of the position of the UAV, at any moment in time, to the operator, during the flight, and to UAV, in emergency procedures such as "return to base" capability (AUSTIN, 2011);
- **The Launch, Recovery and Retrieval Equipment:** this component acts, with several available systems, in the most crucial phase in terms of safety in the aircraft operation: landing and take-off (DALAMAGKIDIS; VALAVANIS; PIEGL, 2011).
- **Communications:** is responsible for establishing the communication between the operator and the aircraft. This component is divided into two links: the uplink, which represents the communication from the operator to the aircraft, and the down-link, which deals with the communication from aircraft to the operator (AUSTIN, 2011);
- **Interfaces:** define the manner the components of UAS interact with each other. For instance, the protocol considered in the communication between the operator and the aircraft must be implemented in both systems in order to establish the data transference (AUSTIN, 2011); and
- **Interfacing with other Systems:** defines the manner the UAS interacts with the world, i.e., the manner it interacts with other systems (AUSTIN, 2011).

4.2 UAS Classifications

UAS can be divided into two main categories in terms of piloting: Remotely Piloted Aircraft Systems (RPAS) and Autonomous Aircraft (AA). The RPAS stands for a system with an operator, i.e., the aircraft is not fully autonomous. The International Civil Aviation Organization (ICAO) has been working to understand, to define and to integrate the RPAS aiming to provide an international regulatory framework (ICAO, 2015). An important aspect of RPAS is the Command and Control (C2) link, which connects the Remote Pilot Station (RPS) and the RPAS for controlling the flight (ICAO, 2015). However, this link may fail and, thus, the aircraft must become a fully autonomous system.

AA are aircraft piloted by software. Although there is much flexibility related to these aircraft, such as risk reduction and efficiency improvement, the software that pilots

Table 5: Categories of UASs in terms of weights.

Class	Weight
One	Less or equals to 149kg
Two	Between 150kg and 600kg
Three	Greater than 600kg

Source: Adapted from (ROMERO; GOMEZ, 2017).

the aircraft, and its interaction with other modules, may be a source of paths to unsafe states, especially into non-segregated airspace. Note that there is a concern towards the understanding of how these aircraft communicate and how precise they are in following instructions provided by the ATC.

In terms of size (weight), UASs can be classified into three categories in terms of weight (ROMERO; GOMEZ, 2017), as illustrated in Table 5. The Class One represents the small UASs, which has many applications in a smaller setting. Class Two represents aircraft with a medium size, varying its weight up to 600kg. Finally, aircraft heavier than 600 kg are classified in Class Three. In this research, a futuristic scenario, in which UASs are as large as commercial aircraft models, is considered an aircraft of Class Three are adopted.

4.3 Integration of UAS into Non-Segregated Airspace

In order to accomplish many missions, the UAS must operate in a non-segregated airspace¹. However, this integration may present issues such as impacts on safety levels.

According to ICAO (ICAO, 2005a), “the airspace will be organized and managed in a manner that will accommodate all current and potential new uses of airspace, for example, UAVs and that any restriction on the use of any particular volume of airspace will be considered transitory”. Furthermore, although rules for UAS flights are defined for segregated airspace (ICAO, 2015), the increasing interest in the usage of UAS for different applications (military and civilian) lead to a need for integrating them into non-segregated airspace. In order to accomplish this, the safety levels must not be compromised (ICAO, 2015). In (SESAR, 2017), 4 requirements to conduct the integration of Remotely Piloted Aircraft Systems (RPAS) in a safe manner, which can also be applied to other types of UAS (e.g. fully autonomous aircraft), are defined:

¹The non-segregated airspace does not consider specified dimensions, i.e., this airspace is used by the commercial aircraft and the rules of air must be respected in order to enable safe and efficient aircraft operations. Furthermore, it is used by many users (ICAO, 2011).

- “The integration of RPAS shall not imply a significant impact on the current users of the airspace”;
- “RPAS shall comply with existing and future regulations and procedures”;
- “RPAS integration shall not compromise existing aviation safety levels nor increase risk: the way RPAS operations are conducted shall be equivalent to that of manned aircraft, as much as possible”;
- “RPAS must be transparent (alike) to ATC and other airspace users”.

In this context, an effort to maintain acceptable ATCo workload levels is essential in terms of safety (NETO et al., 2017a). The workload of ATCo, which is defined and measured by the interaction of several factors (MOGFORD et al., 1995), is a metric that represents the difficulty of ATCo in understanding a particular situation (MECKIFF; CHONE; NICOLAON, 1998). Considering that airspace complexity is one of the main factors that impact ATCo workload in busy airspaces (MAJUMDAR; OCHIENG, 2002) and that this metric presents impacts on airspace capacity, raising it can lead the airspace to unsafe situations. Finally, several variables compose complexity, such as traffic density and mental factors (DERVIC; RANK, 2015) as illustrated in Figure 11.

Figure 11: Several variables that affect ATCo workload.

Source: Adapted from (DERVIC; RANK, 2015)

The workload itself is evaluated by the time spent by ATCo when controlling traffic in a given sector. In order to control, the ATCo performs a set of tasks that are divided into a set of activities. Each activity has a specific duration, generally expressed in seconds. Activities can be cognitive, which is related to the mental work of the ATCo to perform the air traffic control, and non-cognitive, which is related to, for instance, communications. Cognitive workload, or mental workload, represents all the mental activities that the ATCo performs in air traffic control. It can vary broadly depending on many factors

such as familiarity of the ATCo with the scenario (e.g. a scenario with UAS in early stages of its integration). Note that there is a lack of methods of measuring and quantifying the familiarity between a particular aircraft (e.g. UAS and MA) and the ATCo. Thus, according to (SUÁREZ et al., 2014), the complexity of a sector is related to ATCo mental workload, and assessing the ATCo mental workload inside a sector provides an estimation of the associated complexity. Finally, as UAS is considered a new technology into the non-segregated airspace that the ATCo may not be familiar with, it tends to increase mental ATCo workload due to the lack of familiarity (NETO et al., 2017a) (ZŁOTOWSKI; YOGEEESWARAN; BARTNECK, 2017), i.e., the duration of communication and surveillance tasks may be also increased. Furthermore, the familiarity between ATCo and UAS may increase in the future as the number of operations of these aircraft rises and, in a long-term future, the UAS may operate safely along with Manned Aircraft (MA).

4.4 Concluding Remarks

The main goal of this chapter was to present the aspects related to the Unmanned Aircraft Systems (UAS), which is a disruptive technology and offers many advantages to the airspace operation. As this research is focused on the integration of these aircraft into the non-segregated airspace, it is essential to present the considerations adopted.

Moreover, the definition of the UAS was presented, followed by its classifications. After that, a discussion on the integration of this aircraft into non-segregated airspace and their impact in the airspace in terms of ATCo workload were conducted. In the next chapters, the UAS presence is highlighted (e.g. in the FSST description, in Chapter 7).

5 COMBINATORIAL OPTIMIZATION

This Chapter presents an overview of combinatorial optimization methods, i.e., methods for finding optimal or near-optimal solutions considering a finite set of solutions. Firstly, combinatorial optimization is defined. Then, their classifications are presented. After that, a discussion on single-objective and multi-objective optimization is conducted. Finally, the meta-heuristic adopted in this research, the Particle Swarm Optimization (PSO), is presented as well as its implementation adopted, the Parallel Particle Swarm Optimization (PPSO).

5.1 Combinatorial Optimization Definition

According to (LAWLER, 1976), the combinatorial analysis is “the mathematical study of the arrangement, grouping, ordering or selection of discrete objects, usually finite in number”. In this context, combinatorial optimization is related to finding an optimal (or near-optimal) arrangement that may be one in one hundred or one in an effectively infinite number of possibilities. Examples of combinatorial optimization problems are (LAWLER, 1976):

- **Arc-covering problem:** Considering that an arc (i,j) covers the nodes i and j of a graph G , the problem is related to defining the minimum subset of arcs that covers all nodes in G ;
- **Min-cut problem:** Considering a flow network G , this problem is related to finding a subset of arcs that turns the graph disconnected if removed;
- **Spanning Tree problem:** This problem is related to the Min-cut problem. The main goal is to identify the subset of arcs that, if removed, the graph remains connected; and
- **Machine Sequencing problem:** Consists in the definition of a schedule of jobs

that must be processed, which consider specific processing time and deadline, by a set of machines.

The challenges of combinatorial optimization are related to the proposal of algorithms and techniques that are able to solve search problems quickly. Some approaches guarantee that the optimal solution is achieved. However, the time spent in finding this solution may be large (e.g. year of execution). It is also important to note that the main aspect of these proposals is related to the evolution of the algorithms, instead relying only on the advance of computer processing power evolution and that a combinatorial problem is not solved if the time spent in finding the solution is impracticable (LAWLER, 1976).

One should note that the problem faced in this research, i.e., the challenge of delivering a set of aircraft safely and efficiently considering the UAS integration into the non-segregated airspace to a set of objective points (i.e. to a set of IAFs), can be transformed into the problem of delivering a set of jobs to a set of machines (machine scheduling problem), which is a NP-hard (non-deterministic polynomial-hard) problem (SOTSKOV; SHAKHLEVICH, 1995), likewise the problem of arriving traffics (SAMÀ et al., 2017b) (MARINAKIS et al., 2017) (JI; FANG; YAN, 2014) (BIANCO; DELL'OLMO; GIOR-DANI, 1997). This transformation can be conducted by consireing the aircraft as the jobs and the objective points as the machines¹.

5.2 Optimization Methods Classification

Optimization methods can be classified, as illustrated in Figure 12 in three main categories: Enumerative, deterministic and stochastic (or heuristic) methods (COELLO et al., 2007). This Figure highlight different algorithms in each classification, although the enumerative approach is always the same.

5.2.1 Enumerative Method

The enumerative method, which is the simplest method, inspects every solution in the search space. This leads the search to guarantee the obtaining of true Pareto-optimal solution² (TANG et al., 2012). However, as inspecting a large number of solutions is re-

¹See Appendix A.

²As, in multi-objective optimization problems, a limited set of solutions is selected, a set of trade-off optimal solutions stands out. However, depending on the weight associated with each objective function and on the quality of each solution for each objective function, an optimal solution of this trade-off is selected, also known as Pareto-optimal solution (DEB, 2001).

Figure 12: Examples of optimization methods for each classification.

Source: Adapted from (COELLO et al., 2007)

quired in many real-world applications and the computation may be huge, the enumerative method is only suitable for problems with reduced search space.

5.2.2 Deterministic Methods

In order to deal with problems that consider a large number of solutions, shortcuts to best solutions regions are desired, i.e., reducing the search space tends to reduce the computation time. In this context, the deterministic methods, considered graph/tree search algorithms, aim to incorporate problem domain knowledge into the search (COELLO et al., 2007). As illustrated in Figure 12, approaches such as greedy and hill-climbing algorithms, branch and bound tree/graph search techniques, depth- and breadth-first search, and best-first search are deterministic methods that have successfully employed in different problems (COELLO et al., 2007). Furthermore, the performance largely rely on the implemented method and on the problem faced. Examples of deterministic methods are (COELLO et al., 2007):

- **Greedy algorithms:** make locally optimal choices. Although this may lead to optimal solutions in some cases, it may lead the search to local optima;
- **Hill-climbing algorithms:** search in the direction of steepest ascent from the current position. Note that the execution of this algorithm is irrevocable;

- **Depth-first algorithms:** employs a deeper search into a graph whenever is possible (CORMEN, 2009); and
- **Breath-first algorithms:** employs a strategy for exploring the edges out of the most recently discovered vertex (CORMEN, 2009).

5.2.3 Stochastic Methods

However, deterministic methods are unsuitable for many problems. Stochastic search and optimization approaches (e.g. Simulated Annealing, Tabu search, Particle Swarm Optimization, Ant Colony Optimization and Evolutionary Computing) were developed as alternative approaches for solving these irregular problems. They require a function assigning fitness values to possible solutions, i.e., a function that measures the quality of a given feasible solution, and a mapping mechanism between the problem and algorithm domains (COELLO et al., 2007). One should note that these algorithms are focused on finding good solutions in large search space, i.e., in most situations, the optimal solution is not founded and a near-optimal solution is provided. In fact, in the real-world, the near-optimal solutions are more appropriate than optimal ones. This is due to the fact that finding optimal solutions takes much more time than near-optimal solutions. Examples of stochastic methods are (COELLO et al., 2007):

- **Simulated Annealing:** is based on the analogy between the simulation of the annealing of solids and the problem of solving large combinatorial optimization problems, in which the annealing denotes a physical process of heating a solid followed by cooling through slowly lowering the temperature of the heat bath. Thus, all particles arrange themselves in the low energy ground state of a corresponding lattice, provided the maximum temperature is sufficiently high and the cooling is carried out sufficiently slowly (LAARHOVEN; AARTS, 1987). Note that the simulated annealing is a local search and requires the cooling schedule to be inversely proportional to the logarithmic function of time (SZU; HARTLEY, 1987).
- **Tabu search:** is a heuristic procedure for solving optimization problems, designed to be combined with other heuristics in order to escape from local optimality. This method employs flexible structures memory, conditions for strategically conduct the search process and memory functions for intensifying and diversifying the search (GLOVER, 1990);
- **Ant Colony Optimization:** Ant Colony Optimization (ACO) considers a rep-

resentation of the deposit of pheromone by ants on the ground in order to mark some favorable path. These marked paths should be followed by other members of the colony with a respective probability, i.e., this is a stochastic swarm-based optimization method. Finally, the ACO algorithm has presented good result in several problems (DORIGO; BIRATTARI; STUTZLE, 2006);

- **Evolutionary Computing:** given a population of individuals within some environment that has limited resources, this method exploits the competition for those resources causing natural selection (survival of the fittest), which tends to rise the fitness of the population. Based on the fitness values, some of the better candidates are chosen to seed the next generation by employs techniques such as recombination and/or mutation. There are many evolutionary methods present in the literature, such as the Genetic Algorithms (GA), Evolution Strategies (ES), Evolutionary Programming (EP) and Genetic Programming (GP) (EIBEN et al., 2003);
- **Particle Swarm Optimization:** is a swarm-based method that is inspired by the social action of searching for food by a flock of birds and has been successful in a wide variety of optimization tasks (TANG et al., 2012). In this method, bird work collaboratively in order to identify potential and optimal (or near-optimal) food sources.

5.3 Single-Objective and Multi-Objective Optimization

The number of objective functions of a given problem may change depending on the way the optimization problem is faced. Considering one objective function, which represents a single-objective optimization approach, the fitness evaluation depends on only one metric. Although many stages of filtering can be applied further to the results in order to achieve better solutions, single-objective optimization tends to be simpler. For instance, considering the problem of finding food sources, which inspired the creation of the Particle Swarm Optimization (PSO) meta-heuristic, the only variable to be maximized is the amount of food.

On the other hand, considering multiple objective functions, which constitutes a multi-objective optimization approach, may make things more difficult. The complexity comes due to the fact that, considering many objective functions, the solutions obtained may be balanced by the importance each variable has for the optimization problem. For example,

we can consider the optimization problem of buying a new car. Some cars are cheap but not comfortable, whereas others are very expensive and very comfortable. It is reasonable to consider that the cost of buying a car is a variable to be minimized where the comfort is a variable to be maximized. In this context, weights may be associated to each metric in order to select one solution into the region of the most appropriate solutions, also called the Pareto Optimal (DEB, 2001).

The process of a preference-based multi-objective optimization procedure is illustrated in Figure 13. Firstly, a multi-objective search is conducted into the search space and the non-dominated solutions³ are identified, which compose the Pareto front⁴. Then, considering additional high-level information (e.g. experience of ATCo is identifying which metric must be prioritized in a given airspace), the importance of each variable is defined. After that, a single-objective optimization function, that is composed of the weights of the variables, is applied to the set of feasible solutions that are present into the Pareto front. Finally, one solution is provided.

Figure 13: Schematic of a preference-based multi-objective optimization method.

Source: Adapted from (DEB, 2001)

5.4 Particle Swarm Optimization (PSO)

The Particle Swarm Optimization (PSO) is a method for optimization of continuous nonlinear functions related to artificial life (A-life), bird flocking, fish schooling, and swarming theory (KENNEDY, 1995) and is adopted in this research. This research adopts the PSO due to the fact that this method has become a candidate for many optimization applications due to its high-performance and flexibility and that it has been successfully applied in a wide variety of optimization tasks (TANG et al., 2012) (CHEN, 2009). The main advantages of PSO in comparison with other evolutionary algorithms are its few number of parameters and high computational efficiency (SHI et al., 2001)

³a solution s dominates a solution x if and only if s presents a greater or equal value in every variable compared to x and exists at least one variable in s that presents a greater value than x (VELDHUIZEN; LAMONT, 1998).

⁴The non-dominated vectors plotted in criterion space are known as the Pareto front (VELDHUIZEN; LAMONT, 1998).

(CHEN, 2009). Furthermore, PSO and Genetic Algorithms (GA) present similarities and differences considering a basic, binary version of GA (EBERHART; SHI, 1998).

However, in terms of performance, in many problems, while both obtain high quality solutions (with quality indices of 99% or more with a 99% confidence level), the computational effort required by PSO to achieve such quality solutions is less than the effort required by the GA (the computational efficiency of PSO over the GA is statically proven with 99% of confidence level in 7 out of 8 problems investigated) (HASSAN et al., 2005).

This meta-heuristic is based on the movement of particles within the search space, i.e., the particles are the agents that search for solutions. Each particle is a collection of float values which represents one solution (feasible or not), i.e., each decision variable of the problem composes the position of the particle. As presented in Equation 5.1, the position x_i of a particle p_i is a collection of the values that are assigned to each decision variable $x_{i1}, x_{i2}, \dots, x_{in}$.

$$x_i = \begin{bmatrix} x_{i1} \\ x_{i2} \\ \dots \\ x_{in} \end{bmatrix} \quad (5.1)$$

Furthermore, each particle moves in a direction within the search space in order to find new solutions. The movements are conducted for each particle based on its current velocity. Similarly to the position, the velocity is a collection of float values that represent the velocity in which the particle moves for each decision variable, as illustrated in Equation 5.2. The velocity v_i of a particle p_i is a collection of the velocities $v_{i1}, v_{i2}, \dots, v_{in}$ in which the particle moves in the search space for each decision variable $x_{i1}, x_{i2}, \dots, x_{in}$. In other words, the velocity represents how much the values assigned to the decision variable change. The velocity of each particle is essential in the process of updating the particles positions, which is based on the current velocity of the particles and the solutions found by the whole swarm, throughout the PSO execution.

$$v_i = \begin{bmatrix} v_{i1} \\ v_{i2} \\ \dots \\ v_{in} \end{bmatrix} \quad (5.2)$$

For instance, Figure 14 illustrates a swarm composed by 4 particles (p_1, p_2, p_3 and p_4)

Table 6: Positions and velocities of each particle in the situation presented in Figure 14

Particle	Position	Velocity
p1	[1.2, 2.8]	[0.5, 0.8]
p2	[2.6, 3.2]	[0.8, 0.5]
p3	[3.8, 2.1]	[0.4, 0]
p4	[4.5, 3.9]	[-0.5, -0.8]

Source: The author.

with different velocities (v_1, v_2, v_3, v_4) . Both the positions and the velocities are defined randomly. The positions and velocities of each particle are presented in Table 6. In this example, the decision variables are x_1 and x_2 , i.e., the position of each particle is composed of two elements. Likewise, the velocity of each particle, which measures how prone the particle is to change the decision variables in the next iterations, is also composed of two elements. In this context, note that the velocity of particles p_1 and p_2 are composed by positive values, which shows that there is a trend of increasing the decision variables (x_1, x_2) of these particles in the following iteration of the algorithm. On the other hand, the velocity of particle p_3 has one value equals to zero (x_2), which means that there is a trend of increasing only one of the decision variables in the following iteration. Finally, the velocity of particle p_4 is composed of two negative values, which shows that there is a trend of reducing the value of the two decision variables.

In fact, this movement of each particle considers its current velocity, the best solution found by the particle at that time (cognitive influence, i.e., the influence of the experience of the particle itself), and the best solution found by the swarm at that time (swarm influence, i.e., the influence of the experience of the whole set of particles) (CHEN, 2009). In this context, there are two attributes that drives the PSO operation: the *pbest* (particle best), which is an attribute of each particle and represents the best solution achieved by that particle, and the *gbest* (global best), which is an attribute of the PSO and represents the best global solution achieved, i.e., the best solution achieved by all particles. One should note that the PSO seems to lie between genetic algorithms and evolutionary programming due to the fact that it is highly dependent on stochastic processes, which is a characteristic of evolutionary programming, and the adjustment of *pbest* and *gbest* by each particle is conceptually similar to the crossover operation of genetic algorithms. Furthermore, the concept of fitness, employed in all evolutionary computation paradigms, is adopted (KENNEDY, 1995).

The PSO considers a set of parameters, which are described in Table 7. These parameters are used during the update of the velocities and the positions of the particles (c_1 ,

Figure 14: Example of swarm searching for solutions in terms of the decision variables (x_1, x_2) in the PSO execution composed by 4 particles (p_1, p_2, p_3 and p_4) with different velocities (v_1, v_2, v_3, v_4).

Source: The author.

c_2, w) as well as during the setup and execution phases of the PSO ($n, max_iteration$).

The process of updating the velocities and the positions of each particles are presented, respectively, in Equations 5.3 and 5.4 (SHI et al., 2001). In order to update the velocity for a given decision variable of a given particle p_i , three aspects are considered: the inertia ($w \times v_{id}$), the cognition ($c_1 \times rand() \times (pbest_{id} - x_{id})$) and the social aspect ($c_2 \times rand() \times (gbest_d - x_{id})$). In this sense, the parameter i identifies which particle is being considered, whereas the d represents the dimension of the particle considered⁵

$$v_{id} = \underbrace{w \times v_{id}}_{Inertia} + \underbrace{c_1 \times rand() \times (pbest_{id} - x_{id})}_{Cognitive} + \underbrace{c_2 \times rand() \times (gbest_d - x_{id})}_{Social} \quad (5.3)$$

$$x_{id} = x_{id} + v_{id} \quad (5.4)$$

⁵As the position of the particles is composed of a vector different values, the d represent which value is being considering in the updating process. For instance, if a particle is set in a three dimensional space, the vector that describes the position of a given particle is composed of three element and, consequently, the d varies from 1 to 3.

Table 7: Parameters of PSO

Parameter	Description
c_1	Cognitive parameter. This parameter quantifies the importance the experience, in terms of solution achievement, of a particle has in defining the particle direction in the next iteration.
c_2	Social parameter. This parameter quantifies the in terms of solution achievement, of the whole swarm represents in defining the direction of particles in the next iteration.
w	Inertia parameter. This parameter quantifies the difficulty faced by a particle in changing the direction, i.e., if the inertia weight w is much higher than the c_1 and c_2 parameters, the particle may change the direction very slightly in each iteration.
n	Number of particles in the swarm
$max_iteration$	Iterations limit

Source: (SHI et al., 2001).

The inertia factor (Equation 5.3) acts in order to apply the changes in the values accordingly to the current velocity. This means that in a situation in which the inertia is much higher than the c_1 and the c_2 (cognitive and social factors, respectively), the particle is strongly influenced by the current velocity in the movements adopted in the PSO operation.

Moreover, during the operation of the PSO, the temporary best solution found by each particle in the PSO iterations is stored and is called the *pbest* solution. Note that the *pbest* is composed of values that represent the decision variables, and may change throughout the PSO execution.

In this context, the cognitive factor (c_1) (Equation 5.3) multiplies a random continuous value, $rand()$, that varies from 0 to 1 and the subtraction of the value of the decision variable d (that can also be faced as dimension) of the *pbest* (at that time) by the same the decision variable d of the current position of the particle.

Similarly to the *pbest*, during the operation of the PSO, the temporary best solution found by the whole swarm in the PSO iterations is stored and is called the *gbest* solution. Note that the *gbest* is composed of values that represent the decision variables, and may change throughout the PSO execution. Figure 15 illustrates the difference between the *pbest* and the *gbest*. This Figure presents an example of the optimization problem in which

the execution of the PSO is not finished, two particles are employed and the objective is to maximize the value obtained by each solution. At that point, the *particle a* provided 4 feasible solutions and the *particle b* provided 3 feasible solutions. Thus, the *pbest* of the particle a and particle b are, respectively, the solutions s_{a2} and s_{b3} due to the fact that these solutions presented the best values at that point. However, the best global solution (*gbest*) is the solution s_{a2} , which presents the highest value. Note that as the execution is in the middle in this example, the *pbest* and the *gbest* may change if values with better quality are provided.

Figure 15: Example of PSO execution with two particles and a maximization objective function: difference between the *pbest* and the *gbest*.

<i>Particle a</i>	<i>Particle b</i>
<div>sa1 = 5.5</div> <div>sa2 = 7.3</div> <div>sa3 = 0.2</div> <div>sa4 = 2.1</div> <div>...</div>	<div>sb1 = 5.0</div> <div>sb2 = 6.2</div> <div>sb3 = 7.1</div> <div>...</div>
<i>pbest</i> = sa2 = 7.3	<i>pbest</i> = sb3 = 7.1
<i>gbest</i> = sa2 = 7.3	

Source: The author.

Finally, the swarm social factor (c_2) (Equation 5.3) multiplies a random continuous number that varies from 0 to 1 ($rand()$) and the subtraction of the best position of the decision variable d in the *gbest* by same decision variable d in the current position of the particle.

Furthermore, the position of the particle is, then, updated (Equation 5.4). Note that the current position x_i of the particle p_i is summed with the new velocity v_i ⁶, considering

⁶Note that, in the PSO, the velocity represents how a particle changes its position in a given iteration

all the components of this vector, i.e., this sum is conducted considering all decision variables d .

The Equations 5.3 and 5.4 can also be understood from the perspective presented in Figure 16. Considering that the three factors that drive the update process of the PSO (inertia, cognition and social aspect) are parameters and can be configured in different ways, this Figure illustrates that the new velocity, which defines the new position, is a result of a sum of different vectors represent by the inertia, the cognitive and the social weights. In other words, the updated position of the particle in the next iteration is a result of the the influences of the inertia, the social aspect and the cognitive aspect, which are regulated by the w , c_2 and c_1 , respectively.

Figure 16: Example of PSO execution with one particles and a maximization objective function: difference between the $pbest$ and the $gbest$.

Source: Adapted from (LI; HU, 2012).

Figure 17 shows the flow chart of the PSO with a brief description of each stage of the algorithm execution. Firstly, the required parameters are set, which are described in Table 7. Secondly, the initial positions and velocities of each particle are randomly generated and the iteration count (g) is set to 0.

Thirdly, considering that the iteration count (g) is different of the iteration limit ($max_iteration$), the quality of the solution for each particle is evaluated, i.e., the fitness evaluation is conducted. Note that, at this point, each particle represents a randomly-generated solution for the proposed problem, but an acceptable quality or even feasibility are not guaranteed. Furthermore, note that the traditional implementation of the PSO

and is an abstraction of the physical velocity, i.e., as this is a dimensionless value., it can be summed to the current position.

Figure 17: Flow chart of the Particle Swarm Optimization (PSO).

Source: Adapted from (TANG et al., 2012).

considers a maximum number of iterations. However, in this research, we adopt a time frame instead of the number of iterations, i.e., the execution of the PSO stops when the time is finished. It is worth-noting that the time frame considered must be set at a reasonable size in order to provide feasible solutions. Indeed, the algorithm may not be able to provide feasible solutions if the time frame is extremely short and the problem faced is complex.

After that, the feasible solutions founded are ranked based on Pareto dominance, i.e., the solutions are ordered depending on their achieved values (quality) in the considered objective function. Then, solution founded is compared to the best solution founded in all previous iterations by the particle, the Personal best (*pbest*), and, if the quality is higher than the *pbest*, the current solution becomes the actual *pbest*. Also, the current solution is compared to the best solution founded in all the previous iterations by the

whole swarm, the global best (*gbest*). If the quality of the current solution is higher than the quality of the *gbest*, the current solution becomes the actual *gbest*.

Furthermore, the positions and velocities of each particle are updated. The velocity update is conducted considering the Equation 5.3, whereas the position update is conducted considering the Equation 5.4 (SHI et al., 2001).

Then, if the current solution is non-dominated⁷ considering the objective function, this is added to the Pareto-optimal solutions set. Note that this step is optional and may vary widely depending on the objective function. For instance, one may consider all feasible solutions to be added in order to analyze the proposed solutions further. Finally, if the integration count (*g*) if equals to the iteration limit, the set of solutions founded is returned.

5.5 Parallel Particle Swarm Optimization (PPSO)

The Parallel Particle Swarm Optimization (PPSO), or Synchronous PPSO, is a method based on the traditional PSO but considers parallel processing for reducing the execution time (WEI; DU; YOUNAN, 2011). This manner of implementing the PSO is adopted in this research due to the need for shorter response times in the real-time problem faced. As it may take some time to process all characteristics of each particle, especially if the numbers of particles is large, parallel processing enables the search to be conducted quickly. Note that the achievement of the benefits provided by parallel execution depends on the processing power of the computer used, i.e., a computer that cannot process multiple threads may not present significant improvements on performance if executing a parallel application.

In order to implement parallel algorithms in the Java language, one should consider using the Java Threading Application Programming Interface (API) (OAKS; WONG, 1999). This API enables the user to build and process different threads, though the Thread class, in a parallel manner.

Figure 18 presents the PPSO flowchart. Indeed, the stages of its execution are very similar to those present in the traditional PSO implementation. However, the quality (or fitness) evaluation stage is conducted in parallel, i.e., all particles of the swarm calculate its quality in separated threads in order to reduce the total calculation time. Furthermore,

⁷A given solution x_i is non-dominated if there is not a solution x_k that (1) is better than x_i all objectives or (2) the solution x_i is not strictly better than x_k in at least one objective (NARZISI, 2008).

the process of updating their positions and velocities are also conducted in parallel. These two stages are bottlenecks of the PSO execution, and employing multiple threads in this critical region may reduce considerably the algorithm response time. Finally, there are other architectures that can be explored in future works, such as parallel processing islands.

Figure 18: Flow chart of the Parallel Particle Swarm Optimization (PPSO).

Source: Adapted from (WEI; DU; YOUNAN, 2011).

5.6 Concluding Remarks

The main goal of this chapter was to highlight the aspects of combinatorial optimization and how they can be applied to different problems. Thus, insights on how these concepts can be applied to the aircraft sequencing can be highlighted.

Furthermore, the definition of combinatorial optimization was presented as well as its classifications (enumerative, deterministic and stochastic). After that, a discussion on single-objective and multi-objective functions is conducted. Finally, the aspects of the Particles Swarm Optimization (PSO) and the Parallel Particle Swarm Optimization (PPSO) are presented.

The concepts contained in this Chapters are used in the Chapter 8, which presents the optimization model proposed in this research.

6 ASPECTS OF UAS INTEGRATION INTO NON-SEGREGATED AIRSPACE

This chapter aims to present a measurement system used nowadays in the development of new aircraft systems, called Technology Readiness Level (TRL), as well as a novel approach proposed in this research for measuring the impacts of UAS integration into non-segregated airspace, based on the TRL, called Technology Maturity Level (TML).

Both approaches highlight the evolution of aircraft level in terms of operation and one should note that the TML is not an alternative approach to the TRL, i.e., the TML is a complementary approach to the TRL to be considered for integration UAS into the non-segregated airspace.

6.1 Technology Readiness Level (TRL)

The Technology Readiness Levels (TRLs), which aims to measure how far a given technology is from its operation into airspace, are “a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology” and has been used in NASA Space Technology Planning and NASA Management Instruction (MANK-INS, 1995). This scale is useful in integrating new technologies smoothly by identifying precisely in which development level the technology is.

The levels of TRL are illustrated in Figure 19. The first level, “Basic principles observed and reported”, refers to an incipient development of a technology, i.e., the phase in which basic research begins to be translated into applied research. The second level, “Technology concept and/or application formulated”, illustrates the identification of practical applications of the technology. Although technologies may have several applications, key applications must be highlighted at this stage.

Figure 19: Technology Readiness Levels.

TRL9	Actual system 'flight proven' through successful mission operations
TRL8	Actual system completed and 'flight qualified' through test and demonstration (ground or space)
TRL7	System prototype demonstration in a space environment
TRL6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL5	Component and/or breadboard validation in relevant environment
TRL4	Component and/or breadboard validation in laboratory environment
TRL3	Analytical and experimental critical function and/or characteristic proof-of-concept
TRL2	Technology concept and/or application formulated
TRL1	Basic principles observed and reported

Source: Adapted from (MANKINS, 1995)

The third level, “Analytical and experimental critical function and/or characteristic proof-of-concept”, includes physical (or simulated) validation, which constitutes a proof-of-concept validation. The fourth level, “Component and/or breadboard validation in laboratory environment”, on the other hand, integrates the basic elements of the technology to prove the operation of a component.

TRL 5, “Component and/or breadboard validation in relevant environment”, represents a higher level of readiness of the technology. In this phase, a reasonably realistic application can be tested in a simulated or physical environment, in which one or more new technologies might be involved. In TRL 6, “System/subsystem model or prototype demonstration in a relevant environment (ground or space)”, a prototype is, finally, tested in a relevant environment, i.e., an environment with many of the challenges the technology is developed to face.

TRL 7, “System prototype demonstration in a space environment”, is a step beyond TRL 6 in which an actual system prototype demonstration is conducted into the airspace. In this phase, the prototype should be near or at the scale of the planned operating system and the demonstration must take place into the airspace.

TRL 8, “Actual system completed and 'flight qualified' through test and demonstra-

tion (ground or space)”, represents a more advanced phase of the technology and is the end of the system development. The reader should note that this stage may include the integration of new technologies into an existing system.

Finally, TRL 9, “Actual system ‘flight proven’ through successful mission operations”, represents the end of bug fixing aspects and refactoring of the developed technology.

6.2 Technology Maturity Level (TML)

Considering that a ATCo may control new types of aircraft that he/she is not used to deal with, it is reasonable to consider that an additional cognitive workload takes place. This increase is due to the uncertainty of the ATCo in how this aircraft performs the instruction, for instance, aircraft performance. In this context, the increase in cognitive activities duration may lead to the increase in the time spent in communication planning, i.e., the time spent in defining appropriate communication approaches. Furthermore, additional cognitive workload also may affect the time spent in surveillance, i.e., the ATCo acts in order to make sure the flight is evolving as expected.

Towards the UAS operation both remotely piloted and fully autonomous, there is a lack of operation into non-segregated airspace and, ultimately, a lack of familiarity in the relationship between this technology and the ATCo. In fact, the surveillance is clearly an impacted activity. This is due to the uncertainty of ATCo in how the aircraft understands and executes the instructions. On the other hand, the communication activities are also affected due to the time spent in defining proper manners to give a specific instruction.

In this sense, there is a lack of approaches that quantify the familiarity between the ATCo and a given aircraft. Considering two aircraft, one UAS and one MA, with the same performance, they still may present considerable differences in terms of workload. Thus, the aircraft that the ATCo are less familiar with tends to present significant quantitative impacts on workload. There is a need, furthermore, for a measurement system that considers this impact on workload levels and that is designed to be flexible for future changes.

For instance, since the beginning of the air traffic management, the aircraft that operate into the non-segregated airspace are Manned Aircraft (MA). This indicates that, throughout the year and with the advance of the air traffic transportation, the ATCo tends to rely on the performance of human pilots. In fact, this does not exclude the workload of the ATCo.

However, in the past few year, there has been a discussion on the integration of UAS into the non-segregated airspace. Apart from all the challenges that controlling an aircraft presents to the ATCo (e.g. defining proper heading angles, speed and altitude), these professionals may act more carefully due to the fact that a machine is piloting the aircraft. This relationship is very complex and measuring the impacts on the workload is hard due to the several factors involved (e.g. mental state, aircraft technology and weather condition).

Moreover, the relationship of ATCo and the UAS may evolve throughout the years. Considering the technological development and the gradual insertion of UAS into the non-segregated airspace, this relationship may be more mature, which tends to reduce the impacts on workload, i.e., the ATCo tends to act in order to control the aircraft with lower uncertainty levels in terms of the response of the autonomous aircraft. Finally, note that with the advent of UAS into the non-segregated airspace and as the ATCos get used to it, it is reasonable to consider that the level of familiarity of ATCo with Manned Aircraft (MA) tends to reduce, i.e., the ATCo workload tends to be impacted due to the fact that the trust on the UAS for executing instructions in optimized manner is higher than the trust on the MA.

In this context, the Technology Maturity Levels (TMLs), proposed in this research, are a systematic metric/measurement system that supports assessments of the familiarity of a particular aircraft with ATCOs and the consistent comparison of familiarity with the ATCo between different types of aircraft (NETO et al., 2017a). This scale, which varies from 0 up to 10, represents the level of familiarity, which may increase throughout the years of aircraft operation. Thus, the aircraft may be referred as its TML level in order to simplify the workload evaluation. However, although the TRL and the TML are independent measurement systems, it is reasonable to consider that the TML models the evolution of a given aircraft from the TRL 8 ("flight qualified") to TRL 9 ("flight proven") as illustrated in Figure 20.

Figure 20: Relationship between TRL and TML.

Source: The author

Table 8: Technology Maturity Levels (TMLs).

TML	Technology Description	Multiplication Factor
10	Mature	1
9	Common	1.1
8	Common	1.2
7	Common	1.3
6	Operational	1.4
5	Operational	1.5
4	Experienced	1.6
3	Experienced	1.7
2	Incipient	1.8
1	Incipient	1.9
0	Incipient	2

Source: The author.

The TML levels are illustrated in Table 8. The levels 0, 1 and 2 represent an “incipient” technology, which are considered as levels of aircraft that are in the early stage of their integration. Levels 3 and 4 represents aircraft with a higher maturity level, which is considered to be a “experienced” technology. After that, levels 5 and 6 refer to aircraft at an operational level. Finally, levels 7, 8 and 9 represent a level in which the workload impact is reduced and the technology is considered to be “common”, whereas the level 10 represents the mature level. The reader should note the level 10 represents the aircraft operation nowadays, i.e., in a long-term future aircraft may reach levels higher than 10 (considering that they may be more independent in terms of operation), which means that the aircraft may present a workload impact even lower than the workload impact presented by the MAs nowadays.

In terms of ATCo workload, the TML scale indicates the increase of this metric into ATCo workload. According to Table 8, the “multiplication factor”, i.e., the factor that multiplies the communication and surveillance activities, increases as long as the TML decreases. For instance, TML 10 represents a multiplication factor of 1¹, whereas TML 0 presents a multiplication factor of 2, i.e., controlling an aircraft with TML 0 is twice as costly in terms of communication and surveillance as controlling an aircraft with TML 10. Note that these values are linear² but, in the future, different distributions may be

¹The TML 10 is a mature level in which the ATCo spends as much time as the time which is spent in controlling MA nowadays in the non-segregated airspace. For this reason, the multiplication factor is equal to 1.

²This first step toward quantifying the impact on workload considers that the carefulness of ATCo with a given aircraft is directly related to the TML of it, i.e., it is reasonable to consider a gradual increase on the workload impact and to consider that an aircraft that the ATCo is not familiar with (TML 0)

used due to the complexity in measuring precisely the workload impact in each TML. The values adopted in this research as multiplication factors are not absolute values, i.e., this is a first and preliminary approach employed in order to measure the familiarity level that may be adjusted according to future investigations.

Furthermore, this approach of measuring the impact has been proposed by specialists of Safety Analysis Group (GAS), of the University of São Paulo. These specialists are actual Air Traffic Controllers and have more than 10 years of hands-on experience. Finally, this gradual increase on workload impact considers real-world experiences (e.g. controlling MA with different and not well-known performances, in which, considering complex scenarios, the time spent in certain activities such as communication as surveillance may be twice as much as the time spent in the same activities performed considering a well-known aircraft).

Moreover, in a long-term future, the TML may increase and be higher than 10, which tends to lead to a reduction of the multiplication factor and, ultimately, a reduction in the ATCo workload. This depends on the automation of aircraft and on its level of independence in terms of interaction with the ATCo.

Finally, an important aspect of the TML scale is that it is not related to UAS exclusively, i.e., this scale can be applied to any aircraft by means of the usage of the TML³. As, nowadays, UAS do not operate in non-segregated airspace, it is reasonable to consider that these aircraft have a low TML. On the other hand, considering a long-term future, it is reasonable to consider that the TML of UAS may increase (which reduces the ATCo workload impact of these aircraft) due to the operation of them throughout the years.

6.3 Concluding Remarks

The main goal of this chapter was to present one of the main contributions of this research, the TML. This novel approach to measure the impacts of the integration of UAS into non-segregated airspace is widely used in the following chapters.

Furthermore, the concepts of the Technology Readiness Level (TRL) are highlighted. A comprehensive description of each level is presented. Finally, note that although the TML and TRL are not correlated, i.e., they are independent measurement systems with different objectives, the descriptions of the different TRLs are used in order to illustrate

presents a higher workload impact in comparison with a mature aircraft (TML 10).

³The evolution of a given aircraft in terms of TML is given by the interaction of several factors, for instance, technology adoption time.

the characteristics of each TML.

The TML is used in all the next chapters and is essential for understanding the other contributions of this research, as well as the experiments conducted and their results.

7 FINAL SECTOR SIMULATION TOOL (FSST)

The air transportation is essential for society and it is increasing gradually (MARQUART et al., 2003). The number of flights annually in certain countries (e.g. United States of America) is huge, which leads to a high revenue. On the other hand, aviation is composed of critical systems, which demand a special effort from authorities in order to guarantee a minimum safety level, i.e., to reduce the probability of accidents. In fact, safety is a key metric in aviation and new procedures are adopted from the safety perspective. However, an important concept is the efficiency, which can be associated with the profitability of air traffic (FINAVIA, 2015). As these two metrics may oppose each other in many situations, i.e., a higher safety level may lead to a lower efficiency level (e.g. if the minimum separation is set at a large size, e.g. 15nm, the distance between the aircraft is larger and the collision probability is reduced, although the time spent in delivering a set of aircraft to the airport is increased), a challenge in airspace optimization is to balance them, aiming to find solutions with acceptable efficiency and safety. Optimal solutions, in terms of safety and efficiency, are not used in all situations, i.e., the solution employed must be feasible (from the safety perspective) and may not be optimal.

In the past few years, there has been a growth in Unmanned Aircraft Systems (UAS) numbers (GUERIN, 2015), and its relationship with the ATCo needs to be clear. The presence of UAS in a non-segregated airspace may represent a reduction in ATC capacity due to the lack of familiarity with this new technology. As the ATCo may be not sure about the behavior of the UAS, e.g., if the UAS will understand and execute specific instructions quickly and precisely, the workload tends to rise. In order to integrate this aircraft into a non-segregated airspace, challenges need to be addressed, such as: specific regulations, policies and procedures; enabling technologies and standards development for dealing with UAS; air traffic special services and infrastructure; social considerations (e.g. privacy, security, workload) (GRINDLE; HACKENBERG, 2016). Furthermore, complex events need to be taken into account if one considers the air traffic sequencing.

In this research, we also consider the cumulonimbus cloud formation as the bad

weather impacts. These clouds present a real impact on aviation (FROMM et al., 2005), and new routes may be assigned to air traffics in order to avoid them. Furthermore, this leads to a higher ATCo workload. As the integration of UAS will enable new applications and its usage will increase in a future (GUPTA; GHONGE; JAWANDHIYA, 2013), it is essential to develop ways to integrate it in a safe manner. Furthermore, there are some organizations investing in the development of such technology, such as The Boeing Company (BOEING, 2018) and NASA (NASA, 2018).

Firstly, this chapter presents a discussion on the definition of workload. After that, the Final Sector Simulation Tool (FSST), a simulation tool focused on the final arrival segment evaluation including the UAS presence, developed in this research, is shown. Finally, simulated experiments are conducted.

7.1 Responsibilities of ATCo

The Air Traffic Controller (ATCo) plays an important role in the airspace operation. This professional works in order to guarantee appropriate levels of safety and efficiency and to solve problems that show up in complex situations. More specifically, the Air Traffic Control (ATC) provides Air Traffic Services (ATS) to the flights. The main goals of these services, which are provided by the ATCo, shall be to: avoid collisions between aircraft; avoid conflicts (which may evolve to mid-air collisions) between aircraft in the manoeuvring area and obstructions in that area; optimize and maintain an orderly flow of air traffic; provide useful advice and information for the safe and efficient conduct of flights; and notify appropriate organizations regarding aircraft in need of search and rescue aid (IVAO, 2015). In order to avoid unsafe states, the ATCo must plan possible changes in the traffic routes. The process of sequencing aircraft can be defined as ordering the aircraft in a manner that safety and efficiency levels are respected while delivering the traffic to an objective point, i.e., the Initial Approach Fix (IAF).

The workload of ATCo can be defined and measured by the interaction of several factors, including the ATC complexity (MOGFORD et al., 1995), which is a metric that represents the difficulty of ATCo in understanding a particular situation (MECKIFF; CHONE; NICOLAON, 1998). There is an understanding by the research community and operational community that the airspace complexity is one of the main factors that impact ATCo workload (MAJUMDAR; OCHIENG, 2002), and, consequently, impact the airspace capacity. Several variables compose complexity, such as traffic density and mental factors (DERVIC; RANK, 2015). Each activity performed by the ATCo has a specific

duration, generally expressed in seconds. Activities can be cognitive, which is related to the mental work of the ATCo to perform the air traffic control, and non-cognitive, which is related to activities such as communications. Cognitive workload, or mental workload, represents all the mental activities that the ATCo performs in air traffic control. It can vary broadly depending on many factors such as human factor and familiarity of the ATCo with the scenario this professional is dealing with. In summary, the complexity of a sector is related to ATCo mental workload, and assessing the ATCo mental workload inside a sector will provide an estimation of the associated complexity (SUÁREZ et al., 2014). Finally, as UAS is a new technology into the non-segregated airspace, it tends to present a higher mental workload to the ATCos due to the lack of familiarity. Note that, in this research, additional activities are not performed by the ATCo in order to control the UAS, i.e., the impacts on the ATCo workload is given by its influence in the cognitive aspect of the ATCo.

According to the Technology Readiness Levels (TRL), proposed by NASA (MANKINS, 1995), levels 8 and 9 represent the “flight qualified” and “flight proven”, respectively. Considering that the insertion of UAS into shared airspace is a gradual process and that there is not historical data about UAS operation in this airspace (i.e. there is not familiarity with these aircraft in the non-segregated airspace), a possible way to consider its integration and this final stages of the TRL scale is using the Technology Maturity Level (TML), which is proposed in this research in Chapter 6.

7.2 Workload Evaluation Based on Vectoring Points

During the aircraft sequencing, performed by the ATCo, a very important resource is the radar vectoring, which can be defined as “the direction in which the longitudinal axis of an aircraft is pointed, usually expressed in degrees from North (true, magnetic, compass or grid)” (ICAO, 2016). In order to conduct the aircraft through these points, a set of activities must be performed. The reader should note that these activities and their duration (i.e., the time spent by the ATCo in performing this activity) are proposed by ATCos that compose the Safety Analysis Group of the Universidade de São Paulo, which have more than 10 years of hands-on experience. These activities are:

- Vectoring point definition (Activity 1): definition of the position that a single aircraft must fly to (mean duration: 5 seconds¹);

¹In order to define the vectoring point, the ATCo must: (1) understand the pilot’s intention, (2)

- Heading definition (Activity 2): definition of “the direction in which the longitudinal axis of an aircraft is pointed, usually expressed in degrees from North (true, magnetic, compass or grid)” (ICAO, 2016) (mean duration: 5 seconds²);
- Communication (Activity 3): act of communicating with the aircraft, considering message transmission and reception (mean duration: 15 seconds³)
- Surveillance (Activity 1): act of monitoring the aircraft in order to verify if the instructions are performed as expected (mean duration: 5 seconds⁴)

Furthermore, the workload associated with UAS operation is different. In fact, it is reasonable to consider that there is a higher cognitive workload in the UAS operation due to the lack of familiarity and operation of these aircraft into the non-segregated airspace, i.e., the ATCo may be not so sure on how precisely the autonomous machine understands and executes the instructions properly. In this research, we proposed the Technology Maturity Level (TML). This scale, which varies from 0 up to 10, aims to measure the level of familiarity the ATCo has considering a specific model of UAS. This familiarity increases throughout the years of experience⁵, and, considering the highest TML (level 10), the UAS is considered such as a Manned Aircraft (MA), i.e., there is not additional cognitive workload in the ATCo operation. However, it is important to note that every model of UAS inserted into the airspace starts with a low TML, which increases gradually.

Considering the TML, the duration of activities may be different in each level. The first activity, “Vectoring point definition”, is not considered to present additional workload due to the fact that the process does not involve interactions with the pilot (human or not). The second activity, “Heading definition”, also does not present great impact due to the fact that the process does not involve interaction with the pilot (human or not). Activities 1 and 2 can be faced with “physical” activities. However, activities 3 (“Communication”) and 4 (“Surveillance”) are the most impacted. Activity 3 (“Communication”) may take longer to be performed because the ATCo may not be sure if the UAS interprets and

observe the near traffics conditions, and (3) estimate, in a safe manner, future positions of the current aircraft.

²In order to define the heading, the ATCo must: (1) define the future position of the aircraft for accomplishing its specific needs, and (2) define the proper heading angle considering the objective point.

³In order to communicate with the pilot (human or not), the ATCo must: (1) instruct the aircraft, (2) receive the response from the pilot, and (3) provide additional information.

⁴In order to monitor the aircraft operation, the ATCo must: (1) observe if the aircraft is following the instructions in an appropriate manner, and (2) observe if the aircraft in the vicinity are following the instructions in an appropriate manner.

⁵Note that the focus of this research is to consider the different phases of UAS integration but not its evolution. Future directions of this research may include the precise measurement of the increase of the TML of a given aircraft throughout the years.

executes all the information given properly and, thus, more time tends to be spent. Finally, activity 4 (“Surveillance”) also presents a considerable increase on the workload levels due to the fact that the ATCo pays more attention on this new technology to ensure that it is operating as expected (i.e. executing the instructions quickly and precisely). Note that activities 3 and 4 involves the interaction between the ATCo and the pilot (human or not).

Table 9 illustrates the impacts of TML levels on these activities. Note that the base duration of the activities impacted, illustrated in the last row of this Table (activities 3 and 4, with, respectively, 15 and 5 seconds of duration), due to the cognitive aspect present in the interaction between the ATCo and pilot are multiplied by the multiplication factor associated to each TML. The total increases in comparison to the best scenario (TML 10), in seconds (s), on the workload due to the difference on TMLs are also illustrated in this Table (last column). Finally, note that the TML 10 is a reference in terms of workload because it represents the workload of a Manned Aircraft (MA) operating nowadays, i.e., it represents an aircraft that the ATCo is familiar with.

Table 9: Impacts of Technology Maturity Level (TML) on communication and surveillance.

TML	Multiplication Factor	Mean Time Spent in Communication (s)	Mean Time Spent in Surveillance (s)	Increase (s)
0	2	30	10	20
1	1.9	28.5	9.5	18
2	1.8	27	9	16
3	1.7	25.5	8.5	14
4	1.6	24	8	12
5	1.5	22.5	7.5	10
6	1.4	21	7	8
7	1.3	19.5	6.5	6
8	1.2	18	6	4
9	1.1	16.5	5.5	2
10	1	15	5	0

Source: The author.

7.3 The Challenge of Simulating the Final Sector

As the metrics considered in this research are safety, which is related to workload, and efficiency, the main goal of the simulation tool is to offer the possibility of simulate air traffic sequencing in an appropriate manner considering the workload during the vectoring process and duration of the sequencing, i.e., the time spent in the process of delivering all traffics to the IAF.

The simulation tool proposed in this research, the Final Sector Simulation Tool (FSST), is developed using the Java language and aims to represent the vectoring during final approach procedures to be used in further applications, such as optimization. The simulations are focused on ATCo workload and air traffic efficiency evaluation.

7.3.1 Scenario Building

This research is focused on the final sector (illustrated in Figures 4 and 6), in which the aircraft are conducted to the airport. In this critical area of the airspace the aircraft have a set of objective points, also called Initial Approach Fixes (IAFs), as illustrated in Figure 21. All aircraft must be delivered to that point to arrive at the airport. Note that the aircraft may enter into this sector from many different sectors. However, in a realistic scenario for ATC, which considers the aircraft sequencing, the aircraft may enter the final sector going to the same objective point. It is the ATCo's duty to order the flow appropriately.

Figure 21: Set of objective points, also called Initial Approach Fixes (IAFs), of the aircraft within the final sector.

Source: The author.

Furthermore, this can become complex and difficult as specific factors appear, such as the increase in the traffics numbers. This makes the sequencing more complex and finding a near-optimal solution may not be simple. Other actors also make it more complex: the UAS and the cumulonimbus. The UAS represents a challenge in terms of sequencing due to the ATCo's lack of familiarity with this new technology. The cumulonimbus represents a problem in sequencing because the aircraft cannot fly through them, i.e., the routes during the vectoring process in the sequencing can be completely different depending on where these clouds appear.

The reader should note that this simulation tool considers situations in which standard procedures, such as Standard Terminal Arrival Route (STAR), cannot be followed due to the traffic restrictions, i.e., vectoring is needed in order to maintain the safety levels (e.g. avoiding conflicts). The conflict detection module of the proposed simulation tool is also considered and the separation is set at compile-time, i.e., in future works, the separation can be changed by the ATCo (e.g. in emergency situations), which can be represented by the end user or a automated ATCo. Also, if the aircraft goes through cumulonimbus, which is not suitable, or if the heading of the aircraft is inappropriate when it reaches the IAF, an incident is detected by the incident detection module of the method proposed. The final sector is considered as airspace, which has a specific size and formats that can be checked in public charts (e.g. SIDs, STARs). Finally, the workload computation is also a duty of the airspace model, which considers the list of activities performed by the ATCo in this evaluation. This model contains instances of the aircraft, which can be Manned Aircraft (MA) or Unmanned Aircraft Systems (UAS). They differ from the workload perspective but their performance is considered the same (e.g. size and speed) due to the fact that we are considering a futuristic scenario and that the focus is to evaluate solutions in terms of ATCo workload and efficiency. Aircraft with different performances presents impacts on workload, even considering only manned aircraft. In this case, considering the same performance enables the workload evaluation to consider the familiarity between the ATCo and an aircraft more effectively.

7.3.2 Aircraft Operation

In this simulation tool, as illustrated in Figure 22, the aircraft's state is represented by three metrics: heading, speed and position. The heading, which can be defined as "provision of navigational guidance to aircraft in the form of specific headings, based on the use of radar," is the angle in which the aircraft is operating and can be changed by 3 degrees per second according to the standard rate of turn (ICAO, 2006). The speed

represents how long the aircraft flies per hour and, consequently, per second. Finally, the position of the aircraft is a tuple (x,y) that represents a point in the Cartesian plane, i.e., the simulation tool considers a 2D scenario in order to simplify the representation and focus on the vectoring process itself. This simplification can be adopted due to the fact that the height of the aircraft is similar within the final sector and that there is a longitudinal separation that is considered, regardless the height difference, in order to elevate the safety level. Thus, we intend to explore the z-axis in future works considering areas in which the aircraft change their height considerably.

Figure 22: Example of aircraft state.

Source: The author.

The simulations are driven by ticks⁶, which represents a duration of 1 second. For instance, considering that 1 knot (kt)⁷ is equivalent to 1 Nautical Mile (nm)⁸ per hour (h) and that 1kt is equivalent to 0.000278nm per second (s), if the aircraft is performing a speed of 180kts (or 180nm/3600s), in 1 second (1 tick or 1 loop execution) it flies 0.05nm (180×0.000278). In order to simulate a realistic scenario in terms of specific metrics, some aspects of the airspace are abstracted. Firstly, in order to simplify these characteristics, the speed of aircraft is fixed (180kts), which represents a realistic speed during final approach procedures. Note that although this speed may change in future directions of this research considering a limited range of allowed speed for final sector operations, the proposed model considers it to be constant in order to simplify the simulation process and show the applicability of the simulator to represent several problems.

In order to accomplish what is expected from the aircraft, a function implemented performs the following process: given a position indicated by the ATCo in the airspace,

⁶One tick represents one step in the simulation process. In this research, one tick represents the time interval of one second. This means that, in one tick, the distance traveled by aircraft is the same distance traveled in one second.

⁷1kt = 1,852 kilometers/hour

⁸1nm = 1,852 kilometers

the aircraft changes its heading in order to fly in the right direction. This process of changing the heading according to the position indicated by the ATCo is illustrated in Figure 23. Note that the change of the aircraft heading must respect the standard rate of turn, which is 3 degrees per second (ICAO, 2006). Finally, the aircraft exits the final sector if it reaches the IAF, i.e., the objective point in that sector (Figure 6). The approach sequencing finishes when all aircraft are delivered to this point. Note that although the final approach involves the Initial Approach Fix (IAF), the Intermediate Fix (IF) and the Final Approach Fix (FAF), this simulation tool is focused on the final phase of the arrival segment definition, which involves the delivery of aircraft from the final sector to the IAF. More specifically, it defines strategies for the sequencing of arriving flights at an airport during the final phase of the flight (CAPRI; IGNACCOLO, 2004).

Figure 23: Changes applied to heading in order to reach the objective points.

Source: The author.

7.3.3 ATCo Operation

In the simulator developed in this research, an interface is proposed to control the aircraft, i.e., vectoring points can be defined. These vectoring points represent points of airspace (i.e., a tuple (x,y) of the Cartesian plane associated with an aircraft v) that the ATCo wants to lead the aircraft to. Note that in a realistic scenario, changing the heading of the aircraft is equivalent to defining vectoring points. Also, note that this interface is a simplification of the interface used by ATCos while controlling air traffic and that it can also be used by applications to control aircraft automatically, which enables the controlling process for, e.g., optimization applications. The UAS is considered as a Manned Aircraft (MA), but presents higher levels of workload for the ATCo. The gradual inclusion of this technology in the airspace is also modeled in this simulation tool considering the Technology Maturity Level (TML), proposed in this research. Finally, considering the TML, the cost in terms of the workload of each vectoring point in MA is 30s and it is increased by 2s considering each TML level as illustrated in Table 9. For example, the workload of vectoring point definition of a UAS with TML 10, which presents the same

workload than MA, is 30s. The vectoring workload of a UAS with TML 9 is 32s, of TML 8 is 34s, etc. Finally, the workload associated to TML 0, which presents the highest cost in terms of workload and model UAS at the very early stage of its integration, is 50s. Note that, in order to define each vectoring point, the ATCo must perform four activities (vectoring points definition, heading definition, communication and surveillance) and that the duration of each activity is illustrated in Section 7.2 and the TML impacts on these activities (communication and surveillance) are illustrated in Table 9.

7.3.4 Outputs

The outputs of the simulations are based on two metrics: safety and efficiency. The safety is expressed in terms of ATCo workload, which is a measure of seconds spent in the activities performed by the ATCo in order to define vectoring points. Furthermore, the efficiency is expressed in terms of sequencing duration, which is the time spent in the process of delivering all aircraft to the objective point (in our case, the IAF). Basically, the efficiency is expressed in terms of the number of ticks the simulation took to be finished. It may be short or long, depending on the situation presented. Furthermore, note that the number of Vectoring Points (VP) defined may not be directly related to the efficiency level, i.e., in some cases, a higher number of VPs (at a certain limit) may represent a higher efficiency whereas, in others, a higher number of VPs may represent a lower efficiency level. This depends on the situation faced by the ATCo. The workload is also related to the complexity, i.e., a more complex scenario tends to present a higher workload to the ATCo due to the fact that the workload is computed based on the number of vectoring positions defined by the ATCo and the type of aircraft controlled (e.g. UAS).

7.3.5 Graphical User Interface (GUI)

In order to visualize the sequencing solutions for the final approach, a Graphical User Interface (GUI) is proposed. This GUI considers an animation of the aircraft following their respective vectoring points and, finally, the IAF. A screenshot of this GUI is illustrated in Figure 24.

In this Figure, the black points represent the aircraft. Note that each black point is followed by a label, which describes the aircraft type and its TML. Furthermore, each aircraft is set in the center of a blue circle, which illustrates the minimum separation required for each aircraft. In this research, we consider 5nm as minimum separation, which is an acceptable distance to maintain the safety levels (XIAOTIAN; ZHANG, 2017).

Figure 24: Graphical User Interface (GUI) of the Final Approach Simulation Tool (FSST) and the airspace elements plotted in the chart (nm x nm).

Source: The author.

Thus, the red circles represent the cumulonimbus (CB), i.e., the aircraft cannot fly through a red circle considering feasible solutions. Finally, the green squares represent vectoring points established for each aircraft. Note that in order to achieve the IAF, the aircraft follows a pseudo-vectoring point set at the IAF position and represented by a red square.

Moreover, reaching the IAF with inappropriate headings, disrespecting the minimum separation or flying through CBs lead the GUI to present an alert of “unfeasible solution detected” and the simulation stops due to the facts that the provided solution does not respect the safety constraints, as illustrated in Figure 25. In the end of a successful simulation, an alert is presented highlighting the duration of the sequencing and the ATCo workload of this operation, as illustrated in Figure 26.

Figure 25: Alert presented in the end of the simulation in case of incident detection.

Source: The author.

During the begging of the GUI execution, input of data is conducted by selecting a JavaScript Object Notation (JSON) file, which is a universal file extension focused on interoperability, that presents the position of each aircraft, initial heading, type, minimum separation, set of vectoring points to be followed (path) and the IAF position. Thus, the information of CBs positions is also provided. An example of a valid JSON object and its result in the GUI is presented in Figure 27.

7.4 Simulation Experiments

In this section, the simulation experiments are conducted. The main goal is to show the applicability of the proposed simulation tool considering different sequencing solutions. In the following experiments, the red square represents the IAF, i.e., the point all aircraft

Figure 26: Alert presented in the end of the simulation in case of success.

Source: The author.

must come to, whereas the green squares represent additional VPs assign to the aircraft. The aircraft and their position in the x- and y-axis are also illustrated. These positions refer to a Cartesian plane that abstracts the airspace, i.e., the x value represents, in Nautical Miles (nm), the position of the aircraft in the x-axis of the Cartesian plane, whereas the y value represents the position in the y-axis. Finally, the reader should note that the distances and positions consider Nautical Miles (nm) as measure unit.

7.4.1 Experiment I

In the first experiment, only Manned Aircraft (MA) are considered. Firstly, we consider the simplest scenario, in which a single aircraft, aligned to the IAF, is flying. This scenario is illustrated in Figure 28. The start position of aircraft is (0,15), and the IAF

Figure 27: Building of the airspace considering the json file data.

Source: The author.

is set at (15,15) (both coordinates are defined in terms of Nautical Miles). Considering that the aircraft goes directly to the IAF, the total workload computed is 30s. Finally, it takes 298 ticks to deliver the aircraft to the IAF, which means 298 seconds of duration.

Figure 28: Manned Aircraft (MA) in a simple scenario.

Source: The author.

Secondly, we consider a scenario considering two aircraft operating simultaneously, as illustrated in Figure 29. The two aircraft start at (0,20) and (-5, 10), respectively, and fly to (15,15), which is the position of the IAF. This is a simple case study that shows the operation of two aircraft and, thus, an increase in the workload, which is 60s. Furthermore, the whole sequencing, which does not presented conflicts, takes 411s.

Thirdly, a scenario in which two aircraft are conducted to the same IAF but considering one additional Vectoring Point (VP) for one aircraft is considered (Figure 30). The two aircraft are set at (-5,17) and (-7,10), respectively. The second aircraft is conducted to a vectoring point at (-3,16) whereas the first aircraft is conducted directly to the IAF at

Figure 29: Two manned aircraft operating simultaneously.

Source: The author.

$(15,15)$. This shows a more realistic situation in traffic sequencing, in which two aircraft use the same path. Finally, the workload achieved was 90s, and this experiment takes 505s to be executed.

Figure 30: Sequencing of two manned aircraft with one additional Vectoring Point (VP).

Source: The author.

Finally, a scenario in which aircraft are conducted through different vectoring points is considered (Figure 31). The two aircraft are set at $(-4,20)$ and $(0,10)$, respectively. The first aircraft is conducted to $(7,23)$ before going to the IAF at $(15,15)$. The second aircraft is conducted to $(7,8)$ before going to the IAF. Note that the aircraft avoid the

cumulonimbus centered⁹ at (7.5,15.5). Finally, the duration of this sequencing is 456s, with 120s of total workload.

Figure 31: Additional Vectoring Points (VPs) employed for cumulonimbus (CB) avoidance.

Source: The author.

7.4.2 Experiment II

In experiment II, problems that may happen during aircraft sequencing are considered. Firstly, we consider a scenario in which cumulonimbus impact the sequencing, illustrated in Figure 32. The initial positions of the two aircraft are (-4,20) and (0,10). Note that this scenario is very similar to that presented in Figure 31, but, in this case, there is a cumulonimbus with center at (12,12). Also, the vectoring points of the first aircraft are at (8,22) and (15,15) and the vectoring points of the second aircraft are at (7,8) and (15,15). Finally, at (11.1,11.3), the aircraft reaches the area of turbulence of the cumulonimbus. This represents an unsafe state, i.e., this is not considered a feasible solution in terms of sequencing and may not be used in order to maintain the safety levels of the airspace. Thus, the FSST stops the simulation.

Secondly, we also consider a scenario in which conflicts impact the sequencing, illustrated in Figure 33. The initial positions of the two aircraft are (0,20) and (0,10). The vectoring points of the first aircraft are at (7,23) and (15,15) and the vectoring points of the second aircraft are at (7,8) and (15,15). However, when the first aircraft reaches

⁹A reasonable shape to be considered to represent a CB in a 2D environment is a circle, as presented in Section 3.5. In this research the radius of the CB is 2 Nautical Miles (nm), but the authors intend to explore different CB sizes in future works.

Figure 32: Aircraft collides with cumulonimbus (CB).

Source: The author.

$(12.5, 17.6)$ and the second aircraft reaches $(13.1, 13.1)$, there is a conflict, i.e., the distance between these two aircraft is less than the minimum separation (5nm). This also illustrates an unfeasible solution because it leads to unsafe states and, thus, the FSST stops the simulation.

7.4.3 Experiment III

In the third experiment, we include the UAS in sequencing. All experiments conducted are similar to those presented in experiment I, but considering the UAS presence. Firstly, we consider a scenario similar to that presented in Figure 28, but considering only one UAS. This UAS is classified as TML 0, i.e., it is in early stages of integration into shared airspace, whereas the MA is classified as TML 10. Thus, it takes 298s to be delivered to the IAF and produces 50s of ATCo workload. Considering the situation in which the aircraft is MA, the total ATCo workload is 30s.

Secondly, we present a scenario, similar to that presented in Figure 29 (for MAs), considering two UAS classified as TML 4 and 7 operating simultaneously. The two aircraft start at $(0, 20)$ and $(-5, 10)$ and fly to $(15, 15)$, which is the position of the IAF. The workload evaluated is 78s whereas the whole sequencing takes 411s. In comparison, the total workload evaluated in the scenario with two MA was 60s.

Figure 33: Conflict detected when distance is lower than minimum separation (5nm).

Source: The author.

Thirdly, a scenario in which UASs, set at $(-5,17)$ and $(-7,10)$ and classified as TML 5, are conducted through the same path is considered (similarly to the Figure 30, but considering only UAS). The second UAS is conducted to a vectoring point at $(-3,16)$ whereas the first UAS is conducted directly to the IAF, at $(15,15)$. Finally, the workload achieved was 120s, and this experiment takes 505s to be executed. The total workload evaluated considering only MAs was 90s.

Finally, a scenario in which UAS are conducted through different vectoring points is considered (similar to the scenario presented in Figure 31, but considering only UAS). The UAS, set at $(-4,20)$ and $(0,10)$, are classified as TML 3 and 8. The first UAS (TML 3) is conducted to $(7,23)$ before going to the IAF at $(15,15)$. The second UAS (TML 8) is conducted to $(7,8)$ before going to the IAF. Finally, the duration of this sequencing is 456s, with 154s of workload (considering only MAs, this value is equal to 120s).

7.4.4 Experiment IV

In this experiment, we consider the operation of UAS along with an MA, which is set at $(-5,20)$ whereas the UAS (TML 0) is set at $(-9,10)$ as illustrated in Figure 34. In order to deliver both aircraft to IAF without conflicts, additional vectoring points are needed. As the MA is closer to the IAF than the UAS, it may fly directly to the destination. The UAS is, then, vectored to $(-5,15)$ before going to $(15,15)$, i.e., IAF. The workload achieved

was 130s whereas the time of sequencing was 527s.

Figure 34: Using additional Vectoring Points (VPs) on UAS for minimizing sequencing duration.

Source: The author.

However, although this solution presents good results in terms of sequencing duration, it presents a high workload. An alternative solution is to vector the MA due to the fact of the ATCo is used to deal with these aircraft. Although the sequencing process takes longer, the workload tends to be lower. Thus, Figure 35 illustrates this scenario: considering the same initial position of both aircraft, the MA is sent to $(-6,12)$ whereas the UAS goes directly to the IAF. Finally, it presents a higher sequencing duration (613s), but also presents a considerable decrease in workload levels (110s). Note that the trade-off between efficiency and ATCo workload depends on the priorities of the FSST users, i.e., the solutions present different results in both metrics and a prioritization may be considered in order to identify appropriate solutions.

Figure 35: Using additional Vectoring Point (VP) on UAS for minimizing ATCo workload.

Source: The author.

7.5 FSST Validation

In order to ensure that the FSST is operating as expected, i.e., the results of FSST are similar to those obtained in the real world or in validated simulation tools, a validation process is conducted. In this process, we consider two key aspects: the Total Airspace and Airport Modeler (TAAM) and the consultancy of actual Air Traffic Controllers (ATCo).

TAAM, which is widely used for air traffic simulation, is a fast-time gate-to-gate simulator (SOOD; WIELAND, 2003) that presents key features for supporting airspace analysis such as variation of scenarios, 3D multi-colour models, ground functionality (e.g. terminals, runways and taxiways), airside functionality (e.g. terminal airspace, SIDs/STARs and flow management) and direct output to database tools (JEPPESEN, 2015). This simulator has been used for aviation analysis and regional studies, i.e., small subsets of airports and airspace, although there is a growing interest in using TAAM for much larger scenarios (BODOH; WIELAND, 2003). Also, it can help airlines to optimize their operation by, for instance, planning operations in terms of cost efficiency and aircraft substitutions, optimizing schedule design, managing the introduction of regional jets and proposing manners to reduce delays and increase efficiency (JEPPESEN, 2018). Furthermore, the specialists of Safety Analysis Group (GAS), of the University of São Paulo are actual Air Traffic Controllers and have more than 10 years of hands-on experience, i.e., this validation also comes from a practical background.

The validation process is conducted from three different perspectives. In this section, firstly, we employ the Total Airspace and Airport Modeler (TAAM) in order to validate the aircraft movements. Secondly, we consider TAAM as well as the consultancy of actual Air Traffic Controllers (ATCo) in order to validate the heading change. Finally, a validation of the workload evaluation is also conducted.

7.5.1 Movements Duration Validation

In order to validate the movements duration into TAAM, a simple scenario was considered: one aircraft flying from one waypoint to another, at 180kts (ground speed), that are placed 10nm from each other¹⁰. The simulations using the TAAM and the FSST are illustrated in Figure 36. In this Figure, the aircraft (which is illustrated by a black circle

¹⁰Note that in the experiment conducted in TAAM, which uses the coordinate system, the route in which the aircraft flies has a length of 10nm and is defined by one meridian. This means that the distance traveled is equivalent to the distance between two coordinates with 10 minutes of difference. Thus, note due to the fact that 1 degree of difference in any place except the Equator line represents a distance different to 10nm.

and a white square in FSST and in TAAM, respectively) is set in direction of an objective point. In FSST, it is represented as a red square, whereas in TAAM it is represented by a yellow square.

Figure 36: Validation of FSST (a) using TAAM (b).

Source: Adapted from (JEPPESEN, 2015).

The simulation conducted in the TAAM achieved the duration of 3 minutes and 15 seconds, whereas the FSST achieved 3 minutes and 17 seconds, which is a very close result. As illustrated in the same Figure, the speed of the aircraft displayed in TAAM is 155kts, which seems to be different to the speed performed in FSST (180kts). However, there is a difference in these simulators: the FSST works with True Airspeed (TAS)¹¹, whereas the TAAM works with Indicated Airspeed (IAS)¹². In order to translate the speeds to a common pattern, considering the International Standard Atmosphere (ISA) (AIRBUS, 2002), it is reasonable to consider that given that the aircraft's altitude is 10000ft, the altimeter setting is 1013.2 hectopascal (hPa) and the temperature is equal to -5 degrees (Celcius). In this context, 155kts of IAS is equivalent to 180kts of TAS according to Equation 7.1¹³. In this equation, TAS and IAS represent, respectively, the true airspeed and the indicated airspeed. Thus, σ represents the relative density (present in the ISA) and K represents the compressibility correction (which is related to volume changes), whereas the K_i represents the instrumental correction or antenna error (AIRBUS, 2002)

¹¹True Airspeed (TAS) is the true airspeed of the airplane relative to undisturbed air (OFR, 1962).

¹²Indicated Airspeed (IAS) is "the pilot static airspeed indicator reading as installed in the airplane without correction"(OFR, 1962).

¹³Note that this equation is only used for demonstrating that the speed performed in TAAM is equivalent to the speed performed in the FSST, i.e., this equation is not applied in other parts of this research.

(INDOAVIS, 2017). Finally, as the effects of wind are not considered in the TAAM simulation nor in the FSST and as the difference between GS and TAS are defined in terms of the wind component, the GS is equivalent to the TAS as illustrated in Equation 7.2 (AIRBUS, 2002). The difference between the TAS and the GS is illustrated in Figure 37.

$$TAS = \sigma \times K \times (IAS + K_i) \quad (7.1)$$

$$GS = TAS + windComponent \quad (7.2)$$

Figure 37: Difference between Ground Speed (GS) and True Airspeed (TAS) considering the wind influence.

Source: Adapted from (AIRBUS, 2002).

7.5.2 Headings Validation

In order to validate the heading changes, simulation in TAAM were considered. Considering traditional operations, for instance, when aircraft assigns to a STAR, and even in situations in which usual vectoring points are established, the FSST and TAAM presented similar heading changes.

Furthermore, a randomly-generated testbed composed of 25 different situations were performed and validated by the specialist of the Safety Analysis Group of the University of São Paulo based on their experiment in real-world situations, in which the aircraft change their headings in order to follow Vectoring Points (VPs). These situations considered one aircraft with a specific heading and one vectoring point set at a random position. The FSST conducted the aircraft as expected, varying the heading in the right direction and at an appropriate rate. An example of randomly-generated situation is presented in Figure 38.

Figure 38: Example of (a) randomly-generated situation and (b) the proposed solution.

Source: The author.

7.5.3 Workload Evaluation Validation

The validation of the workload evaluated method is conducted in terms of the internal functions of computing the ATCo workload. Note that instead of comparing the actual time spent by the ATCo in FSST and in TAAM, this validation aims to compare the manner in which both tools compute this metric. This is due to the fact that the value presented in this research for each activity are proposed by specialists, but it may be adjusted in future researches. Thus, the values present in TAAM are not absolute and may be changed in future implementations.

The workload evaluation in TAAM is performed considering different events. For instance, the aircraft entry in a sector, the changes in flight levels, changes in speed and the application of flow control. However, the main goal of FSST is to simulate the final sector focusing on the aircraft sequencing by the usage of vectoring points.

In this context, TAAM performs the workload evaluation similarly to FSST, i.e., for each vectoring point defined for each aircraft, a set of activities that must be performed by the ATCo are computed in TAAM. Likewise, FSST presents this approach for evaluating the actual ATCo workload. Furthermore, as an extension, the FSST presents a novel approach to evaluate the workload of UAS operations in this context, i.e., the workload computed may be different depending on the type of the aircraft and its TML. Note that the efficiency, on the other hand, is evaluated considering the traditional manner (aircraft sequencing duration).

7.6 Concluding Remarks

The main goal of this chapter was to present a simulation tool, called Final Sector Simulation Tool (FSST), for evaluating safety (from workload perspective) and efficiency in aircraft sequencing in final sector considering the UAS presence.

Furthermore, discussions on the role played by the ATCo as well as the process of defining vectoring points were conducted. After that, a description of the tool was presented and the experiments showed the effectiveness of this approach. Finally, the validation process was conducted, which highlighted that the FSST presents similar results compared with real-world situations and validated simulation tools.

The FSST is used in the further steps of this research in order to evaluate the quality of the solutions proposed by the optimization method proposed from the safety and efficiency perspectives.

8 FINAL ARRIVAL SEGMENT OPTIMIZATION MODEL (FASOM)

In this chapter, the Final Arrival Segment Optimization Method (FASOM) is presented. This is a novel method, proposed in this research, for optimizing aircraft sequencing in the final sector considering the UAS presence and, consequently, different Technology Maturity Levels (TMLs). The literature review showed that there are gaps in the integration of UAS into this critical phase considering the airspace constraints (e.g. minimum separation).

Firstly, considerations on the Final Arrival Segment Optimization (FASO) are presented. Secondly, the architecture of the FASOM is shown. Then, the airspace building module is explained. After that, the optimization module, which is used for constructing the airspace based on the data of the input files, is presented. Finally, a discussion on topics related to the solution selection module is conducted.

8.1 Considerations on the Final Arrival Segment Optimization (FASO)

In this section, we present the considerations that must be highlighted regarding the optimization process. Firstly, we presented the problems that may occur into airspace and, consequently, should be avoided in the solutions provided in the optimization process. Then, the definitions of feasible and unfeasible solutions are provided. Finally, examples of feasible solutions for selected situations are provided.

8.1.1 The Process of Optimizing the Aircraft Sequencing

The main goal of the optimization process is to provide safe and efficient solutions for given situations in the airspace. In this sense, airspace constraints must be respected. Figure 39 shows the characteristics of the problem faced. The aircraft reach the final

sector from multiple entry points. After that, all aircraft have objective positions to reach (IAF) at a time interval (deadline). Note that the final sector may have more than one IAF and that, although the final approach¹ itself is not in the scope of our research, it is important to highlight that the aircraft fly through the IAF and, further, through the IF and FAF, in order to land in the respectively assigned runway.

Figure 39: Characteristics of the problem faced in the optimization process within the final sector.

Source: The authors.

In this context, the situations faced may be simple or difficult. Figure 40 depicts the difference between two given scenarios. The first is composed of four aircraft that share the same IAF. Note that this situation is simpler than the next one, but it does not necessarily constitute a simple operation into the airspace. In the second situation, complex events are included. The number of aircraft is increased to seven and a CB is considered nearby the IAF. One should note that the scenarios become difficult because the aircraft must be delivered as fast as possible, i.e., minimize the time interval in which the aircraft are delivered (deadline) is a challenge.

Considering that the minimum separation must be respected and that the aircraft are not allowed to fly through CBs, there are many possible manners to solve the sequencing problem. Figure 41 present two different solutions for the situation proposed in Figure 40 (a). Although the solutions tend to be similar in terms of sequencing duration, they may present different levels of ATCo workload depending on the Technology Maturity Level (TML) of each aircraft. In the first solution, the third aircraft presented flies directly to

¹The final approach can be faced as the final phase of the approach manoeuvre for landing (ICAO, 2006).

Figure 40: Comparison between simpler (a) and harder (b) situations.

Source: The author.

the IAF and the orders follow it in a sequence, whereas in the second solution provided the second aircraft flies directly to the IAF.

Figure 41: Different solutions for the situation proposed in Figure 40 (a).

Source: The author.

In fact, the priority of each aircraft presents a considerable impact in sequencing solutions. Note that, in terms of ATCo workload, the TML of each aircraft also indicates which of them must be prioritized. For instance, if an aircraft presents a lower TML (e.g. UAS operating nowadays into the non-segregated airspace) and the situation presents other aircraft with higher TML (e.g. Manned Aircraft operating nowadays), the best solutions in terms of workload is assigning a direct final arrival segment to the aircraft with

lower TML and establish vectoring points for the others, which present a higher TML. In fact, establishing additional VPs for aircraft with higher TMLs tends to present a lower ATCo workload rate than establishing additional VPs to aircraft with lower TMLs. Note that this observation is taken from the workload perspective, i.e., the balance between sequencing duration and workload level may change the most appropriate solution depending on the priority assigned to the workload and to the efficiency (respecting the safety constraints, such as minimum separation).

8.1.2 Solution Definition

In order to build feasible solutions, the respect to airspace constraints is essential. Despite the challenges these restrictions bring to the final arrival segment design, vectoring points must be assigned to the aircraft in order to define the paths, i.e., the final arrival segments are defined in terms of vectoring points.

Moreover, the representation of solutions in these environments can be expressed as in Equations 8.1, 8.2 and 8.3.

$$S = [segment_1, segment_2, ..., segment_m], \quad (8.1)$$

$$Segment_k = [vp_1^k, vp_2^k, ..., vp_{n_k}^k], \quad k \geq 1, k \leq m, n_k > 0, vp_{n_k}^k = IAF_k \quad (8.2)$$

$$state = [n_1, n_2, ..., n_m] \quad (8.3)$$

The sequencing solution, i.e., the set of final arrival segments, is presented in Equation 8.1. A final arrival segment for a given aircraft can be defined as a collection of Vectoring Points (VPs) that guides the aircraft from the entry of the final sector to the IAF. Examples of segments are illustrated in Figure 42. In this Figure, the segments (a) and (b) proposed for the aircraft are composed by three additional VPs (VP 1, 2 and 3), whereas the segment (c) is composed by one additional VP (VP 1). The segments are defined in terms of the number of aircraft into the situation, i.e., m represents the index of the last aircraft and, consequently, the number of aircraft. The segments are presented in Equation 8.2. The segment of a given aircraft k , which varies from 1 up to the total number of aircraft m , is composed of a list of vectoring points. Note that each vectoring

point is expressed as a tuple (x,y) into the Cartesian plan and that the last vectoring point assigned to each aircraft ($vp_{n_k}^k$) represents the IAF assigned to it. Finally, Equation 8.3 represents the state of a given solution, i.e., the number of vectoring points assigned to each aircraft. Note that each aircraft receives, at least, one vectoring point, which guides it to the IAF.

Figure 42: Examples of possible final arrival segments for a given situation.

Source: The author.

One should note that an effective manner for representing the number of VPs assigned to all aircraft is by using states, which can be defined as a collection of the number of VPs (including the IAF) that composes the aircraft segment in a given situation. Each element of the state refers to the number of VPs assigned to each aircraft. Note that, in this context and from the perspective of workload evaluation, it is reasonable to consider IAF as VP since the ATCo must act, communicate with and monitor the aircraft that are

conducted to the IAF. In fact, in the process of vectoring, the ATCo must conduct the aircraft to this point using an additional VP. For instance, in Figure 42, there is only one aircraft in the three examples presented, which leads the state of it to be composed of one element. In the examples (a) and (b), the state value of the solution provided is [4]. This is due to the fact that the aircraft, in both cases, is instructed to followed four presented in (three additional VPs and the IAF), whereas, in example (c), the state of the solution provided is [2] due to the number of VPs (one additional VP and the IAF). In situations in which the aircraft is higher than one, the number of elements of a state is higher than one, i.e., the number of elements in a state is equivalent to the number of aircraft in the situation. Furthermore, the state is a manner to describe a given solution in terms of VPs assigned to the aircraft and it is widely used during the optimization process.

Finally, the problem faced in this research considers that: (1) pilots (human or not) are capable to execute the instructions provided by the ATCo; (2) one important metric apart from ATCo workload is the sequence duration; (3) the airspace constraints are respected. This problem, thus, can be faced as a machine schedule problem, which has been proved to be NP-hard in (SOTSKOV; SHAKHLEVICH, 1995). Furthermore, it is reasonable to consider that our proposal deal with an NP-hard problem (SAMÀ et al., 2017b) (MARINAKIS et al., 2017) (JI; FANG; YAN, 2014). A discussion on this aspect is presented in Appendix A.

8.1.3 Application Example

Figure 43 shows an example of situation and its respective sequencing solution. In that case, there are two aircraft placed at (1, 17) and (1, 11), and their IAF are placed at (15, 15). The hypothetical solution proposed conducts the aircraft 1 to the vectoring points 1 (5, 18.5) and 2 (10, 20) before delivering it to the IAF, whereas the aircraft 2 is conducted to the vectoring points 3 (5, 9) and 4 (10, 8.5). Equations 8.4, 8.5, 8.6 and 8.7 present this sequencing solution expressed in a formal manner.

$$S = [segment_1, segment_2] \quad (8.4)$$

$$Segment_1 = [VP_1, VP_2, IAF] = [(5, 18.4), (10, 20), (15, 15)] \quad (8.5)$$

$$Segment_2 = [VP_3, VP_4, IAF] = [(5, 9), (10, 8.5), (15, 15)] \quad (8.6)$$

$$state = [3, 3] \quad (8.7)$$

Equation 8.4 presents the actual solution provided. The $segment_1$ refers to the aircraft 1, whereas the $segment_2$ refers to the aircraft 2. Both segments are expressed in Equations 8.5 ($segment_1$) and 8.6 ($segment_2$). Note that the vectoring points assigned to each aircraft compose the segments and that the last element is the IAF. Equation 8.7 presents the state of the solution. As each aircraft received three vectors (considering that the aircraft receive vectors to reach the IAF), the state is defined as a list of two elements due to the fact that there are two aircraft in the scenario illustrated. Note that the elements of this state are 3 (number of VPs, including the IAF, assigned to the aircraft 1) and 3 (number of VPs, including the IAF, assigned to the aircraft 2). Finally, note that the feasibility of this simulation must be evaluated by the Final Sector Simulation Tool (FSST), which is presented in Chapter 7, and that the main goal of the optimization process is to build optimization solutions that minimize the time interval in which the aircraft are delivered (deadline) and the ATCo workload.

Figure 43: Example of situation and its respective sequencing solution.

Source: The author.

8.2 FASOM Architecture

To order to achieve the desired results in the optimization process in an appropriate manner, different responsibilities should be assigned to different modules. For instance, the optimization process itself is different to the process of input reading and should be conducted in different parts of the system. In order to accomplish this, Figure 44 depicts the FASOM architecture.

Figure 44: Architecture of the Final Arrival Segment Optimization Model (FASOM).

Source: The author.

The first module of the FASOM is the Airspace Building Module. The main goal of it is to receive external data and transform it into a format that the Optimization Module is able to understand, i.e., this module acts as an interface. Firstly, a JSON file is provided with the data needed in order to build the airspace, considering the positions of aircraft, CBs and IAFs. Finally, this data is converted into a Java object (airspace) that is, further, accessed and manipulated by the Optimization Module.

The second and intermediate module is the Optimization Module, which is the most important module. In this module the actual optimization process is conducted. It aims to, considering the input data provided in suitable ways, offer a set of feasible solutions in terms of aircraft sequencing. The optimization method adopted in this research, the

Parallel Particle Swarm Optimization (PPSO), is, then, employed in order to achieve this set of feasible solutions considering parameters variation. This method is adopted due to its high-performance in several applications (optimization tasks) and due to its advantages in comparison to other techniques such as Evolutionary Algorithms (EA) and Genetic Algorithms (GA) (TANG et al., 2012) (CHEN, 2009) (SHI et al., 2001) (CHEN, 2009) (EBERHART; SHI, 1998). One should note that the PSO has presented good results, but this depends on the characteristics of the problem and on the configuration of the parameters. In some problems, EA and GA may outperform the PSO in terms of quality of the solution and search efficiency.

The feasibility and the fitness evaluation, i.e., the quality of evaluation in terms of efficiency (sequencing duration) of each solution provided is conducted by the FSST, simulation tool proposed in this research. For each solution provided, a verification of its quality and feasibility is, then, verified. Note that, in Figure 44, the PPSO is within an orange square. This indicates that the PPSO could be substituted by other methods (e.g. ACO and genetic algorithms), i.e., the author intends to extend this research in future works considering different techniques. Finally, a set of feasible solutions is provided in appropriate data structures to the next module.

The third module is the Solution Selection Module. The main goal of it is to select the most appropriate solution based on weights established for each metric². Thus, this solution can be built in a JSON file that can be, further, simulated in the FSST. Firstly, the set of feasible solutions is provided by the optimization module and, then, the filtering process, which orders and selects a solution by the importance (weight) of safety (ATCo workload) and efficiency (sequencing duration). Finally, the file built (JSON) is compatible with the FSST.

The following three sections present, respectively, the Airspace Building Module, the Optimization Module and the Solution Selection Module. Each module is discussed in a in-depth approach, considering the implementation of the functions.

8.3 Airspace Building Module

This section presents the aspects related to the airspace building module. Firstly, we present the expected structure of the JSON file. Then, the parsing methods are shown.

²Note that the weights assigned to each metric are defined by the application user, i.e., the application allows the user to prioritize the reduction of the ATCo workload or the reduction of the aircraft delivery duration. Finally, the weight may also be equal.

Finally, the actual airspace building is illustrated.

8.3.1 JSON Structure

In order to provide data to the FASOM, an appropriate format must be followed. This format allows the process to be uniform and simpler. Listings 1 and 2 show, respectively, an example of the JSON file that is formatted in an appropriate manner to be understood by the FASOM and the set of IAFs that can be assigned to the aircraft.

```

1  {
2    "aircraftList": [
3      {
4        "x": "15",
5        "y": "0",
6        "id": "0",
7        "type": "UAS",
8        "TML": "10",
9        "separation": "5",
10       "heading": "90",
11       "path": []
12     }
13   ],
14   "CBList": [
15     {
16       "x": "7.5",
17       "y": "7.5",
18       "radius": "2"
19     }
20   ]
21 }

```

Listing 1: Example with line numbers enabled

The fields of the Listing 1 are defined as follows:

- **“aircraftList”**: the list of aircraft present in the situation;
 - **“x”**: The position in the x-axis of the aircraft;
 - **“y”**: The position in the y-axis of the aircraft;
 - **“id”**: The identification number of the aircraft;
 - **“type”**: The type of the aircraft. It can be Manned Aircraft (MA), Remotely Piloted Aircraft System (RPAS) or Autonomous Aircraft (AA). This attribute

```

1  {
2      "IAFlist":[
3          {
4              "x":"20",
5              "y":"15",
6              "min_final_heading": "45",
7              "max_final_heading": "135"
8          },
9          {
10             "x":"10",
11             "y":"15",
12             "min_final_heading": "0",
13             "max_final_heading": "90"
14         }
15     ]
16 }

```

Listing 2: Example of set of IAFs that can be assigned to the aircraft

is not used in the optimization process, i.e., this is an illustrative attribute that is employed in order to facilitate the understanding of different scenarios;

- **“TML”**: The Technology Maturity Level (TML) of the aircraft;
 - **“separation”**: The minimum separation to be applied in the aircraft operation. Note that we only consider 5nm of separation due to the fact that this is a reasonable separation applied in the airspace nowadays. Furthermore, the author intends to extend it in future works;
 - **“heading”**: The heading (degrees) of the aircraft in the beginning of the aircraft sequencing;
 - **“path”**: The set of vectoring points the aircraft must follow. This must be an empty list due to the fact that the optimization process will fill this blank list with optimized vectoring points.
- **“CBLlist”**: The list of cumulonimbus (CB) present in the airspace configuration;
 - **“x”**: The position in the x-axis of the CB;
 - **“y”**: The position in the y-axis of the CB;
 - **“radius”**: The radius of the CB. Note that, in this research, we are considering CBs in a circular shape and with radius of 2nm due to the fact that this is a reasonable CB size present in the airspace. However, the author intends to extend it in future works.

The fields of the Listing 2 are defined as follows:

- **“IAFlist”**: The list of Initial Approach Fix (IAF) available;
 - **“x”**: The position in the x-axis of the IAF;
 - **“y”**: The position in the y-axis of the IAF;
 - **“min_final_heading”**: As there is an expected angle (in the plane) range for the aircraft heading when reaching the IAF, this attribute describes the lower bound of this range;
 - **“max_final_heading”**: As there is an expected angle (in the plane) range for the aircraft heading when reaching the IAF, this attribute describes the upper bound of this range.

The processing of extracting the data from the JSON files is conducted by using the Java language as well as the json-simple library (v.1.1). All the data is converted into actual java objects in order to be, further, delivered to the optimization process.

8.3.2 Airspace Building

After the process of extracting data from the JSON files, the next step is to fetch this data into Java objects. In order to accomplish this, the class JSONUtil is provided. This class manages all aspects related to the data extraction and objects building. Listing 3 presents one of the methods of this class, which is responsible for building the airspace from a JSON file.

Firstly, the aircraft list is extracted and stored in the *aircraftList* variable (line 6), which contracts the List interface of the Java language being an *ArrayList* object. Note that the aircraft information is provided as well as the IAF list. Secondly, the *cumulonimbusList*, which is an *ArrayList* object, is initialized and receives the list of CBs present into the JSON file (line 10). Finally, the airspace is built considering the aircraft and CB lists (line 14).

Listings 4, 5 and 6 show, respectively, the *getAircraftList*, the *getCumulonimbusList* methods and the *Airspace* constructor. In the *getAircraftList* method, the *aircraftList-Description* (line 5) variable holds the information of all aircraft into the airspace. The *aircraftList* variable is, then built (line 3) and filled with all aircraft (line 12), which are get from the JSON data (line 8).

```

1  public static Airspace buildAirspace(String RawAirspaceInputFile,
2  String RawIafInputFile) {
3      JSONObject parsedIAF = (JSONObject) new JSONParser().parse(iafInputFile);
4
5      // parsing aircraftList
6      ArrayList<Aircraft> aircraftList =
7          getAircraftList(parsedAirspace, parsedIAF);
8
9      // parsing CBs
10     ArrayList<Cumulonimbus> cumulonimbusList =
11         getCumulonimbusList(parsedAirspace);
12
13     // building the airspace
14     Airspace airspace = new Airspace(aircraftList, cumulonimbusList);
15 }

```

Listing 3: Method for building the airspace from a valid JSON file.

In the *getCumulonimbusList* method (Listing 5), the process is very similar to the *getAircraftList* method although this is applied for building the *cumulonimbusList* variable. Finally, the *Airspace* (Listing 6) constructor builds the airspace itself from the aircraft and CBs lists.

8.4 Optimization Module

In this section, we present the actual optimization process. All parameters and decisions taken in its development are presented, as well as its functionality. In order to accomplish this, a discussion on the application of the Parallel Particle Swarm Optimization (PPSO) method in the final arrival segment design problem is conducted.

In order to apply this technique to the problem faced in this research, a set of step must be taken. Firstly, we present the fundamental concepts on the application of this method into the final arrival segment design problem. Finally, the aspects of the implementation of it are also shown.

8.4.1 Fundamental Concepts

In order to apply the PPSO into the Final Arrival Segment Optimization (FASO) problem, adjustments and abstractions must be considered. Firstly, we include additional parameters that are described in Table 10.

```

1  private static ArrayList<Aircraft> getAircraftList(JSONObject parsedAirspace,
2  JSONObject parsedIAF) {
3      ArrayList<Aircraft> aircraftList = new ArrayList<Aircraft>();
4
5      ArrayList<Object> aircraftListDescription =
6          (ArrayList<Object>) parsedAirspace.get("aircraftList");
7
8      for (int i = 0; i < aircraftListDescription.size(); i++) {
9          // building aircraft
10         Aircraft a = aircraftParser(aircraftListDescription, i, parsedIAF);
11         // adding it to aircraftList
12         aircraftList.add(a);
13     }
14     return aircraftList;
15 }

```

Listing 4: Method for extracting the aircraft list from a valid JSON file.

One suitable manner to conduct the optimization process is by using states, which are collections of the number of VPs that composes the aircraft segments in a given situation, as presented in Section 8.1.2. Regarding a state-driven optimization process, the search must consider a different state at time, i.e., the number of VPs assign to each aircraft must remain the same during part of the PSO execution. For instance, considering the state $[1, 2]$ for a situation with two aircraft, many solutions (feasible or not) can be provided. In this sense, we conduct the search of solutions maintaining the state according to a time interval. If, at least, one feasible solution is provided in the search considering a given state, the search process stops after the time interval. However, if there are not solutions provided by the method, other states are considered in the search. In fact, there is a need for a short response search to explore different states in order to find feasible solutions. Note that, apart from the time spent in the processing of each state, there is a need for a short response time in the problem faced in this research, i.e., there is a need for defining a specific deadline in order to make sure unsafe states are not reached due to latency in the solution provision.

Thus, the first additional parameter is the duration of search in a given state, limits the duration execution in milliseconds of the search within a state. Note that this parameter is considered for all states explored.

The second parameter is the iteration slice, which represents the number of iterations of the PSO for shuffling the positions and velocities of all particles.

```

1 private static ArrayList<Cumulonimbus> getCumulonimbusList(JSONObject parsedJson) {
2     ArrayList<Cumulonimbus> cumulonimbusList = new ArrayList<Cumulonimbus>();
3
4     ArrayList<Object> CBLISTDescription =
5         (ArrayList<Object>) parsedJson.get("CBLIST");
6     for (int i = 0; i < CBLISTDescription.size(); i++) {
7         // building aircraft
8         Cumulonimbus cb = cbParser(CBLISTDescription, i);
9         // adding it to aircraftList
10        cumulonimbusList.add(cb);
11    }
12    return cumulonimbusList;
13 }

```

Listing 5: Method for extracting the CB list from a valid JSON file.

```

1 public Airspace(ArrayList<Aircraft> aircraftArray, ArrayList<Cumulonimbus> CBArry) {
2     this.aircraftArray = aircraftArray;
3     this.CBArry = CBArry;
4 }

```

Listing 6: Constructor of the Airspace class.

The traditional PSO and PPSO do not include this shuffling process, thus we are including this process in order to avoid local optima. In fact, sometimes, good solutions may retain particles around a specific region into the search space. However, better solutions may also be found in other regions. For instance, if all particles are located around an area distant from 0 in all axis which has a set good solutions, even if much better solutions are located around the beginning of all axis (i.e. an area near to 0 in all axis), the cognitive factor, the inertia and the social factors tend to act in a manner to retain the particles within that area. The shuffling process avoids the particles to be moving around a limited region in the search space and facilitate the exploration of different areas (that may present better solutions than those already discovered). This process consists in change the position and velocities of the particles considering random values. Thus, the particle tends to search in different regions of the search space.

Furthermore, note that the search space is limited to be conducted inside the final sector, i.e., the PPSO aims to suggest VPs inside a geographically limited area. Thus, the shuffling method considered is stochastic, i.e., inside the search space, the particle positions and velocities are random.

Table 10: Additional parameters considered for solving the FASO problem

Additional Parameter	Description
Duration of search	Limits the duration execution in milliseconds of the search within a state. This enables the particles to move around different areas into the search space. Note that this parameter represents the stopping criteria of the search process.
Iteration Slice	Number of iterations for particle shuffling.
Maximum number of Vectoring Points per aircraft	Limit for the path building in terms of VPs.

Source: the author.

Regarding the number of decision variables³ considering in the optimization process, this is related to the number of VPs assigned to the aircraft. This relationship is illustrated in Equation 8.8. As we are considering the conduction of the aircraft to the IAF to be applied considering a VP definition, the total number of vectoring points to be defined is the number of VP (nVP_i) assigned to each aircraft i subtracted by 1, which represents the instruction to lead the aircraft the IAF (which is necessary for all aircraft), varying from 1 to the number of aircraft (m) present in the situation, and, considering that each VP is defined in terms of two values (x- and y-axis), the result is the multiplication of all actual VPs by 2, i.e., each VP represent two decision variables for the PPSO operation (illustrated in Figure 45). In summary, each additional VP definition represents a search for two decision variables, the x and the y values for that VP, i.e., the collection x_k that represents the position of the particle p_k in the search space is composed by two elements per additional VP.

$$number_{decision_variables} = 2 \times \sum_{i=1}^m (nVP_i - 1) \quad (8.8)$$

On the other hand, as the states of the solutions provided, which are lists containing the number of VPs assigned to each aircraft as presented in Section 8.1.2, there is a relationship of the number of decision variables and the states illustrated in Equation 8.9. In the sum, the index of an element in the state s , which varies from 1 to the size of the state $len(state)$, is considered in the subtraction of the value of the element $state[i]$ by the size of the state, i.e., the number of decision variables is defined as the sum of VPs

³A decision variable represents a value that the optimization method must provide during the search process. The number of decision variables (or dimensions) is equal to 2 for each additional Vectoring Point (VP) since 2 coordinates, x and y , must be provided.

Figure 45: Example of the particles search (within the search region) for better solutions in terms x and y for defining only one VP (x- and y-axis).

Source: The author.

without those related to the IAF. Furthermore, as the number of decision variables is defined based on the state, it is reasonable to consider the search process to be driven by states. Finally, the result is multiplied by 2 due to the fact that each VP considers one values for the x-axis and other for the y-axis.

$$number_{decision_variables} = [(\sum_{s=1}^{len(state)} state[s]) - len(state)] \times 2 \quad (8.9)$$

In this context, the solution search is conducted considering different states. For instance, consider the situation illustrated in Figure 46, in which three aircraft are present, i.e., the final arrival segments must be built. The solutions exploration is illustrated in Figure 47.

The first state to be explored is the state in which all aircraft fly directly to the IAF. This state composes the generation 1, presented in Figure 47. A generation is a set of states that, in total, are composed by the same number of decision variables. The number of decision variables in this generation during the PPSO operation is equal to zero due to the fact that there are not additional VPs to be defined. If this is a feasible solution in terms of airspace constraints (minimum separation and CBs), the PPSO execution finishes with an optimal solution. Note that the feasibility and quality of all solution are

evaluated by the FSST as illustrated in Figure 44.

Figure 46: Example of situation considering bad weather conditions and the presence of three aircraft.

Source: The author.

As the position of the CB present in the situation forces the aircraft to consider an alternative route, a new generation of states is needed. This new generation (generation 2) is composed by three elements, i.e., it is composed by the variation of each element in the initial state (which is composed by three elements). In order to generate new elements, the number of vectoring points of each aircraft is incremented. Note that all states of the generation 2 present 2 decision variables to be considered in the PPSO operation according to Equation 8.9. Along with the parallel processing of critical steps within the PPSO execution, the evaluation of each state is also conducted in separated threads, i.e., the search for solutions into child vertices in the same generation is conducted in parallel. Finally, if feasible solutions are not found in this generation, a new generation must be created. Hence, the algorithm creates new states generations considering the limit of the VPs and the search execution within each state must respect a time limit, i.e., if the deadline for a given state is reached, the search process stops and starts again considering a different state (see Table 10).

8.4.2 Implementation

The initialization of the PPSO execution is illustrated in Listing 7. Firstly, the parameters of the PPSO are defined (*numberOfParticlesPerDimension*, *iterSlice*, *maxIter*, *maxDurationEachState*, *maxVPperAircraft*) in lines 2 to 6. Finally, the actual optimiza-

Figure 47: State generations and their decision variables into the PPSO execution.

Source: The author.

tion process is started in line 10.

Secondly, Listing 8 presents the *PPSOoptimizer* method, which starts the actual optimization process. Firstly, the bounds of the search are defined in order to limit the search into the x- and y-axis in lines 1 to 4. Then, considering the search to be conducted in a state-driven manner and that it starts with the initial state (direct flights to the IAF), the search is conducted until a solution is found or until the limit of VPs is reached.

Thirdly, Listing 9 presents the *executeParallelOptimization* method. The main goal of this method is to build all the threads (line 2), execute them in parallel (lines 5 to 7) and wait for each one according to the *maxDurationEachState* parameter (lines 10 to 17).

Then, Listing 10 presents the *run* method of the *ParallelPSO* class. This method, which is execute in parallel considering multiple states, aims to find solutions according to the state (lines 6 for initial state and line 9 for the others).

After that, the *optimize* method (Listing 11) presents the parallel steps illustrated in Figure 18. While the iteration count i is smaller than the maximum iteration input *maxIter*, the particles of the swarm are evaluated (line 7) and their velocities and positions updated (line 10). In order to avoid local optima, the particles are randomly shuffled (lines

```

1  // parameters
2  int numberOfParticlesPerDimension = 5;
3  int iterSlice = 30;
4  int maxIter = 5000;
5  int maxDurationEachState = 10000;
6  int maxVPperAircraft = 3;
7
8  // results
9  ArrayList<Vector<Map<String, Object>>> result =
10 Optimizer.PSOoptimize(airspace, outputJson, outputRawData,
11                        iterSlice, maxIter,
12                        maxDurationEachState, maxVPperAircraft,
13                        numberOfParticlesPerDimension);

```

Listing 7: Initialization of the PPSO execution.

```

1  ArrayList<Double> bounds = new ArrayList<Double>();
2  bounds.add(-35.0);
3  bounds.add(60.0);
4  listOfStates = getInitialListOfStates();
5
6  while (!(listOfStates.size() == 0)) {
7      executeParallelOptimization(listOfStates, airspace, bounds, iterSlice,
8                                  maxIter, outputFile, solutions, bestSolutions, maxDurationEachState,
9                                  numberOfParticlesPerDimension);
10     listOfStates =
11         getNewListOfStates(listOfStates, maxVPperAircraft); // VPlimit
12 }

```

Listing 8: The *PPSOoptimize* method.

14 to 17) whether the iteration count i is greater than the iteration slice input (see Table 10) *sliceLimit*.

Finally, Listings 12 and 13 presents, respectively, the *evaluateSwarm* and the *updateVelocityAndPosition* methods. Note that these two methods are executed in parallel. The *evaluateSwarm* method evaluates the quality of each particle (line 5) considering a parallel execution of threads previously built (line 2), where as the *updateVelocityAndPosition* method builds threads considering the *ParticleUpdater* class (lines 3 to 9), which subscribes the *Runnable* interface, and execute them in parallel (line 12).

```

1  // Building threads
2  ArrayList<Thread> listOfPSOThreads = buildThreads(airspace, listOfStates);
3
4  // Executing Threads
5  for (Thread t : listOfPSOThreads) {
6      t.start();
7  }
8
9  // waiting for threads
10 for (Thread t : listOfPSOThreads) {
11     try {
12         t.join(maxDurationEachState);
13         t.interrupt();
14     } catch (InterruptedException e) {
15         continue;
16     }
17 }

```

Listing 9: The *executeParallelOptimization* method.

8.5 Solution Selection Module

This section presents the aspects of the solution selection. Firstly, the set of feasible solutions is described. Secondly, a discussion on the objective functions considered in this research is conducted. Finally, the aspects of the preparation of the JSON file are presented.

8.5.1 Attributes of Feasible Solutions

The PPSO execution provides a set of feasible solutions as result. The attributes of the solutions provided in this set are defined as follows:

- **Status:** The status of the simulation. The value of this attribute is equal to 1 in case of success, i.e., if all aircraft are delivered respecting the airspace constraints, and 0 otherwise;
- **Duration:** The time spent in delivering all aircraft to the IAF. This attribute is related to airspace efficiency;
- **Issue:** Identifies the issues that the given solution presents. The issues can be related to CBs or conflicts, i.e., loss of minimum separation. Note that feasible

```

1  public void run() {
2      Airspace currentAirspace =
3      (Airspace) SerializationUtils.clone((Serializable) airspace);
4      if (this.stateIsInitialState()) {
5          this.simpleRun(currentAirspace);
6      } else {
7          if(isStateFeasible(currentAirspace)){
8              this.optimize(currentAirspace);
9          }
10     }
11 }

```

Listing 10: The *run* method of the *ParallelPSO* class, which subscribes to the *Runnable* interface.

solutions present *null* as issue value if the solution respected the airspace constraints, i.e., if it is a feasible solution;

- **Aircraft List:** The list of aircraft involved in the issue. If the issue is related to a CB, this list presents only one aircraft. In case of conflict, two aircraft are considered. Furthermore, if there is not issue, this list is empty. This attribute is very important in order to detect when a specific aircraft must be assigned to a additional VP. For example, if the aircraft is not able to fly directaly to the IAF since there a CB in the path, at least one additional VP is need;
- **State:** The state of the solution, i.e., a list that quantifies the number of vectoring points assigned to each aircraft;
- **Solution:** the actual final arrival segments, i.e., set of vectoring points assigned to the set of aircraft. Note that this attribute is related to the state attribute. This is due to the fact that the solution is a list of continuous values that represent the positions into the x- and y-axis of the VPs;
- **Workload:** the ATCo workload evaluated according to the total number of VPs assigned to the set of aircraft. Note that the workload of VPs may change according to the type and TML of the aircraft.

Finally, Table 11 shows the attributes of the solution illustrated in Figure 48. In this example, the additional vectoring point 1 (VP1) is assigned to the aircraft 1, whereas the additional vectoring point 2 (VP2) is assigned to the aircraft 2. The duration of this operation is 465s, whereas the workload evaluated is 120s. As it is a feasible solution,

```

1  private void optimize(Airspace currentAirspace) {
2      int i = 0;
3      int sliceLimit = 0;
4      while (i < this.maxIter) {
5
6          // Evaluating quality of particle in the swarm
7          evaluateSwarm(currentAirspace);
8
9          // updates velocity and position
10         updateVelocityAndSpeed();
11
12         i++;
13         // checking slice limit and swarm shuffling
14         if (i > sliceLimit) {
15             this.shuffleSwarm();
16             sliceLimit += this.iterSlice;
17         }
18     }
19 }

```

Listing 11: The *optimize* method.

the status is 1, the issue is null and the aircraft list (the aircraft that are involved in the issue) is empty. Note that as each aircraft needs one extra VP, the state of the solution is equal to [2,2]. Thus, the solution is composed of four numbers, which represent two VP (x and y values). According to the state ([2,2]), the first aircraft receives one extra VP, i.e., the two first values of the solution attribute are the x and y coordinates of the VP1. Finally, the two other values represent the x and y coordinates of the VP2.

Table 11: Attributes of solution presented in Figure 48.

Attribute	Value
Status	1
Duration	465 (s)
Issue	null
Aircraft List	[]
State	[2,2]
Solution	[-1.164093545170906, 15.749382510962144, 11.028901699780988, 8.759289753473794]
Workload	120 (s)

Source: the author.

```

1  private void evaluateSwarm(Airspace currentAirspace) {
2      ArrayList<Thread> particleThreadsList = buildParticleThreadsList(currentAirspace);
3      // cycle through particles in swarm and evaluate fitness
4      for (Thread t : particleThreadsList) {
5          t.start();
6      }
7      // waiting for all threads
8      for (Thread t : particleThreadsList) {
9          try {
10             t.join(this.maxDurationEachState);
11         } catch (InterruptedException e) {
12             continue;
13         }
14     }
15     // evaluating fitness (gbest)
16     for(ParallelParticle p:this.swarm){
17         this.evaluateParticleFitness(p, p.getExecutionResult());
18     }
19 }

```

Listing 12: The *evaluateSwarm* method.

8.5.2 Objective Functions

In order to select one solution within a set, an order must be defined. Indeed, an important metric in this definition is the sequencing duration, which is related to efficiency. However, including the UAS into the non-segregated airspace may lead the controlling process more difficult, which impacts the workload and, ultimately, the safety levels. Thereupon, safety (represented by the ATCo workload) and efficiency (represented by the sequencing duration) are the metrics considered in order to measure the quality of different solutions.

In this context, Equations 8.10 and 8.11 shows the objective functions (f_1 and f_2) adopted in this research. The first one indicates the minimization of the ATCo workload as a goal. The index i of the aircraft varies from 1 to the total number of aircraft m . The function f_1 , thus, is defined in terms of the numbers of VPs nVP_i assigned to an aircraft i and the workload associated with the VP definition for a particular aircraft W_{TML_i} , which varies according to the TML of the aircraft i .

$$\text{Min } f_1 = \sum_{i=1}^m nVP_i \times W_{TML_i} \quad (8.10)$$

```

1  private void updateVelocityAndPosition() {
2      // building thread list
3      ArrayList<Thread> updaterThreadList = new ArrayList<Thread>();
4      for(ParallelParticle p : this.swarm){
5          ParticleUpdater particleUpdater =
6              new ParticleUpdater(p, swarm, gbest, bounds);
7          Thread t = new Thread(particleUpdater);
8          updaterThreadList.add(t);
9      }
10     // updating particles
11     for(Thread t : updaterThreadList){
12         t.start();
13     }
14     // waiting for all threads
15     for(Thread t : updaterThreadList){
16         try {
17             t.join(maxDurationEachState);
18             t.interrupt();
19         } catch (InterruptedException e) {
20             continue;
21         }
22     }
23 }

```

Listing 13: The *updateVelocityAndPosition* method.

On the other hand, the second equation is related to the sequencing duration. The function f_2 is defined in terms of the distance d_l traveled by the last aircraft delivered l . Thus, the computation of the total duration is conducted in terms of the distance traveled by the last aircraft in the direction of the IAF. Furthermore, this value is divided by the speed performed. Note, as in this research we are considering the speed as 180 kts, the distance traveled is divided by 180.

$$\text{Min } f_2 = \frac{d_l}{180\text{kts}} \quad (8.11)$$

Finally, the process of ordering the solution into the solutions set and, further, picking the most appropriate solution, are conducted considering the Equation 8.12. In this equation, the α and β variable represent, respectively, the weight associated to the minimization of f_1 (workload) and the weight associated to the minimization of f_2 (duration). Note that these values vary from 0 to 1, $\alpha + \beta = 1$, and that these values are defined by the user of the optimization tool, i.e., the end user may prioritize workload or efficiency

Figure 48: Example of a feasible solution for a specific situation.

Source: The author.

in the solution selection. Finally, the f_3 enables the choice of one solution into a Pareto optima. Note that in order to be used in the same equation, the value of f_1 and f_2 of a given solution instance k as independent variables are normalized using the Min-Max normalization method (MITSA, 2010), which is a simple normalization method for combining independent variables. In this method, the value of an instance is subtracted from the minimum value of all instances. Then, this subtraction is divided by the subtraction of the maximum value of instances by the minimum value of the instances. Note that the weights α and β are assigned by the user of our proposal, i.e., this method is adaptable to situations in which safety is prioritized, to situations in which efficiency is prioritized and, finally, in situations in which both have the same priority (in the case in which $\alpha = \beta = 0.5$) and an adaptation of the Min-Max normalization method (which is characterized by the sum of 1 to the denominator) in order to avoid the result to be infinite in cases that the maximum value is equal to the minimum value.

$$\text{Min } f_3 = \alpha \frac{f_1^k - \min(f_1)}{1 + (\max(f_1) - \min(f_1))} + \beta \frac{f_2^k - \min(f_2)}{1 + (\max(f_2) - \min(f_2))} \quad (8.12)$$

8.5.3 JSON Preparation for the FSST

Listing 14 shows the process for building the JSON file according to the result achieved in the optimization process. Firstly, it is important to note that the building process is also driven by the states, as highlighted in line 8. In lines 9 to 16, the x and y coordinates

present in the solution (line 7) are transformed into actual VPs and the final arrival segment of the aircraft, including the IAF position, is built.

Finally, a String variable *jsonResult* receives the data of aircraft and CBs (lines 18 to 21) to be, further, written in an actual JSON file (line 22). Note that the output file of the whole process is very similar to the input file, i.e., the position of CB and aircraft as well as their headings. However, this step of the FASOM fills the blank space with the solution, i.e., fill the path list with the appropriate arrival segment.

```

1  public static void buildJSONFromResult(Map<String, Object> result, Airspace airspace,
2  String outputPath) {
3      Airspace outputAirspace = airspace.clone();
4
5      // including bestSolution path into the airspace
6      ArrayList<Integer> state = (ArrayList<Integer>) result.get("state");
7      ArrayList<Double> solution = result.get("solution");
8      for (int i = 0; i < state.size(); i++) {
9          int numberOfAdditionalVPs = (state.get(i) - 1);
10         ArrayList<Position> path = getPath(solution);
11
12         Position iafPosition = airspace.getAircraftArray().get(i)
13             .getPath().get(airspace.getAircraftArray()
14                 .get(i).getPath().size() - 1);
15         path.add(iafPosition);
16         outputAirspace.getAircraftArray().get(i).setPath(path);
17     }
18     String jsonResult =
19     buildAircraftJson(outputAirspace.getAircraftArray())
20     jsonResult +=
21     buildCBJson(outputAirspace.getCBArray())
22     write(outputFilePath, jsonResult)
23 }
```

Listing 14: The *buildJSONFromResult* method.

8.6 Concluding Remarks

The main goal of this chapter is to present all the optimization model proposed in this research and highlight its applications as well as how to apply it. The Parallel Particle Swarm Optimization (PPSO) is adopted as meta-heuristic due to its advantages and high-performance, but the optimization module can be adapted, in future works, for employing other techniques by simply switching the PPSO implementation by any other

meta-heuristic. Note that this adaptation is simple, which makes the FASOM suitable for testing and evaluating the performance of other meta-heuristics.

Furthermore, considerations on the Final Arrival Segment Optimization (FASO) are highlighted. After that, the architecture of our proposal was presented. Finally, a description of each module (airspace building, optimization and solution selection) is shown.

The following Chapters (9 and 10) aims to show the applicability of this proposal in challenging situations, in which the UAS is present.

9 EVALUATION METHOD

This Chapter presents the aspect to be considered in order to apply our optimization approach in different situations. Note that this method offers a guide to the evaluation and proposition of feasible solutions for different given situations. Firstly, we present the steps considered in order to apply our proposal to a given situation. After that, we present a discussion on the parameters adopted in the experiments conducted.

9.1 Application Method

The situations considered are those related to the design of final arrival segment for a set of aircraft and may consider bad weather conditions, i.e., the situations faced by this method may be simpler or harder.

The method adopted in this research is illustrated in Figure 49.

Figure 49: Methodology adopted in this research

Source: The author.

Firstly, in the Input Data phase, all the data needed for the simulation process is collected, such as aircraft positioning data, set of schedules considered during the simulations and TML of all aircraft. The aircraft type (MA, RPAS or AA) must be set in order to be properly illustrated during the solution demonstration (which is conducted by the FSST), as well as the position of the IAFs and the cumulonimbus.

Secondly, in the Scenario Construction (JSON) phase, all the collected data is fed into the FASOM. In this phase, the airspace is built and the characteristics of the sector studied must be highlighted. Finally, the position of all airspace actors must be included.

Thirdly, the Adjustment of the input file is conducted in a manner that unexpected fields are avoided. In this phase, the aircraft attributes, such as position and heading, as well as the CBs and IAFs attributes are checked. A initial verification of all fields is conducted in order to make all the data is presented and formatted as expected.

After that, the Verification process is conducted in order to evaluate the considered inputs (e.g. TML). In the case of the values are not valid, a new adjustment is needed. Otherwise, the Optimization process can be executed. In order to accomplish this, the input files are provided to FASOM and all fields are checked in order to make sure there is not unexpected data, i.e., different types of data or even blank data.

The simulation phase consists of the fast-time simulation execution, in which all events are logged. This information is, further, used to calculate the workload.

Then, the Output Filtering stage is responsible for selecting the solutions that are feasible and, ultimately, highlight the most appropriate solution considering the objective functions. Finally, the Evaluation stage is responsible for evaluating the results in order to verify the impact of MA, RPAS and AA insertion into the final arrival segments design considering non-segregated airspace in terms of workload.

9.2 Execution Method

In the experiments that can be faced, the sets of aircraft may vary. The situations faced in this context may consider a mix of Manned Aircraft (MA), Remotely Piloted Aircraft Systems (RPAS) and Autonomous Aircraft (AA) or even homogeneous scenarios with only one type. Furthermore, some situations present bad weather conditions, which makes the airspace more complex. The ability of FASOM of dealing with different weather conditions highlights its applicability in several situations.

Moreover, the evolution of TML throughout ages considered in the case studies of this research are presented in Table 12. Each age represents a specific era in the terms of UAS acceptance, i.e., this does not represent one single year, but a period of time reasonably superior to one year. Note that the values present in this Table are parameter to our method validated with specialists, i.e., in future works these values may be precisely adjusted (e.g. by regulatory authorities), that the main goal of this Table is to show the

Table 12: Ages (in terms of TML evolution) considered in this research.

Age	MA	RPAS	AA
1	7 - 10	3 - 6	0
2	7 - 10	7 - 10	3 - 6
3	3 - 6	3 - 6	7 - 10

Source: The author.

evolution of UAS (RPAS and AA) acceptance throughout the years and that the main goal of this research is to propose the method instead of identifying precisely the TML of each type of aircraft throughout the years (which is intended to be developed in future works).

The first age considers scenarios in which MA is more common in the airspace. In this age, RPAS and AA have been included lately but still, the RPAS is considered to be a more mature technology than the AA. At age two, AA and RPAS evolve in terms of TML. Note that, in this age, RPAS achieved the same TML as MA. Finally, age three represents a considerable reduction in MA and RPAS numbers, which decreases their TML. This decrease is due to the consideration that AAs may offer advantages in terms of efficiency and safety throughout the years. During the simulation process, specific ages are chosen in order to demonstrate the impacts on the workload related to each fleet.

Regarding the TML assignment, the superior limit of the TML intervals (10) are employed due to the fact that we aim to evaluate the safety and efficiency aspects of the aircraft in their maximum achievable performance, considering the TML age. Thus, this approach enables us to evaluate aircraft that the ATCo is considerably familiar with, considering the TML age. This, although, is intended to be extended in future works to be applied in different situations (e.g. considering pessimistic scenarios from the TML perspective). For instance, the TML of MA at age 1 is 10, whereas the TMLs of RPAS and AA are, respectively, 6 and 0. Furthermore, the TML of RPAS at age 2 is 6. Likewise, the TML of AA at age 3 is 10, whereas the TML of MA and RPAS at the same age is 6.

In the experiments, the parameters considered are the situation faced problem, the TML age and parameters related to the PPSO operation. Note that this parameter, presented in Chapter 5, is the number of particles in the swarm¹, the number of iterations considered for the shuffling process, the maximum number of iterations of the algorithm itself and the time spent in the search for each state².

¹The number of particles that search for solutions in the search space, which have positions and velocities. These represent, respectively, the decision variables and how they change in the PPSO iterations.

²As presented in Section 8.1.2 and illustrated in Figure 47, a state is a collection of the number of

Each case study considers a different situation in terms of aircraft positioning. Some may be more difficult than others and the TML and type of aircraft vary throughout the different case studies.

The weather condition is also an impacting factor into the optimization process. Each case study considers different weather conditions that may be simple or hard from the final arrival segment design perspective. These scenarios may not present CBs into the airspace in some cases. However, in other cases, the presence of CBs in the airspace may represent a considerable or even substantial impact on the arrival segment design.

Figure 50 illustrates possible weather conditions in a given situation, which provides an understanding on possible situation that may occur in specific scenarios. The first Scenario (a) presents the best weather condition within those three. The second one (b), considers the presence of one CB, which may change considerably the sequencing. Finally, the third situation (c) includes three CBs that present a substantial impact in the airspace, i.e., the solutions provided vary considerably from those that may be provided for the scenario (a).

Figure 50: Impacts of different weather conditions.

Source: The author.

One should note that some variables in this research are fixed. For instance, the maximum number of vectoring points are fixed to 9 per aircraft³, once this value is not reached if any other solution is found in previous states. Thus, the number of iterations is also maintained at a huge level due to the fact that the constraint of this optimization process is the response time.

VPs that composes all aircraft segments in a given situation.

³Establishing 9 Vectoring Points (VPs) per aircraft for conducting the fleet to the IAF in the final sector is virtually impracticable due to the high number of VPs. Thus, adopting this superior limit leads to an effective search starting from the initial state and exploring the different generations.

9.3 Concluding Remarks

This Chapter presented the evaluation method that can be adopted in order to apply our optimization approach in different scenarios. In fact, the identifications of the steps needed in order to enable the FASOM to deal with a specific problem is essential.

Firstly, the steps of the evaluation method are presented and discussed. After that the manner in which the execution is intended to be performed is presented. In the following Chapter, the FASOM is applied to specific problem according to the steps presented herein.

10 CASE STUDIES

This Chapter presents the experiments conducted in this research. The case studies show the applicability of our approach in different situations, which may include a considerably high number of aircraft and bad weather conditions.

The proposal presented in this research is capable of solving several situations in the final sector considering the airspace constraints. For all case studies, the objective function illustrated in the Equation 10.1, which has been presented in Section 8.5.2, is employed.

$$\text{Min } f_3 = 0.5 \times \frac{f_1^t}{\max(f_1)} + 0.5 \times \frac{f_2^t}{\max(f_2)} \quad (10.1)$$

This objective function is used for selecting solutions in the Pareto front. The main goal is to conduct the optimization process in a balanced manner, in which α and β are equal to 0.5, i.e., they have the same priority for the solution selection¹. This approach is considered for achieving solutions with good results in both objectives, but these values can be adjusted according to the preferences of the user entity (e.g. regulatory authorities). Note that f_1 is a function related to the ATCo workload, whereas the f_2 is related to the sequencing duration. For instance, two solutions are proposed and both present the same workload, the solution with the lowest duration is selected. Similarly, considering that two solutions are proposed and both present the same duration, the solution with the lowest workload is selected.

Furthermore, considering that in this research our focus is to propose the method and as future directions we intend to measure precisely the performance based on the variation of the parameters, in order to obtain the feasible solutions, the parameters c_1 ², c_2 ³ and

¹This approach aims to show the applicability of our method in a balanced scenario, in which efficiency and safety present the same priorities. The analysis of the differences in the solutions provided considering variations in the α and β parameters is a future direction of this research.

²Cognitive aspects (see Section 5.4).

³Social aspects (see Section 5.4).

w^4 of the PSO are all set to 1. This highlights that all aspects have the same priority in the particles' position and velocity update, but we intend to verify the influence of each of these parameter in future works.

Moreover, the number of particles within the swarm increases by 50 for each additional decision variable. As each particle needs to be updated (position and velocity) and it takes some time, reducing the number of particles leads to broader movements into the search space. Thus, each additional variable increases the search space considerably.

In this context, adding 50 particles for each additional decision variable, in the experiments conducted, demonstrated to be an effective and balanced approach of searching for solutions in the search space with a acceptable performance in terms of movements. However, note that this research aims to present a novel method for dealing with the challenge of integrating the UAS into complex scenarios (e.g. the Final Sector), i.e., a in-depth analysis on how the changes in each parameter affect the results precisely is intended to be conducted in future works.

In order to illustrate it, Figure 51 shows a scenario in which the aircraft needs to be assigned to an additional VP (a) and the search for the VP definition using 100 particles (b). The search for an additional VP consists in searching for the x and y values of its position. Hence, as we are considering 50 particles for each decision variable present in the optimization problem, this example considers 100 particles.

Finally, 800ms is the time limit of the search for each state, which seems to be a reasonable response time due to the fact that the aircraft in this time interval change their position slightly from the perspective of the whole final sector. Note that this is a reduced value due to the need of the ATCo for real-time solutions. The experiments conducted in this research are performed in a High Performance Computer (32 virtual CPUs 2.2Ghz, 128GB RAM) of the University of São Paulo.

The first case study presents a simpler scenario in which there are not the presence of bad weather conditions and considers 3 aircraft. The second case study aims to show the applicability of our proposal in a more challenging situation, in which the number of aircraft increases in comparison to the first case study (4) and the weather presents bad conditions. Finally, the third case study is focused on showing the applicability of our method in a complex environment, which is composed by 5 aircraft and CBs are present in important areas of the Final Sector.

⁴Inertia (see Section 5.4).

Figure 51: A scenario in which the aircraft needs to be assigned to an additional VP (a) and the random disposition of 100 particles in the search space (b).

Source: The author.

10.1 Case Study I

The first case study of this research considers a simpler scenario illustrated in Figure 52. In this scenario, three aircraft are considered (MA, RPAS and AA). The RPAS is set at position (5, 25), whereas the MA and the AA are set, respectively, at the positions (15, 15) and (5, 5). Finally, the Initial Approach Fix (IAF) is set at (5, 15). Note that the aircraft trajectories of all solutions presented in this case study, considering all ages, are illustrated in Appendix B⁵.

Figure 52: Scenario adopted in case study I.

Source: The author.

⁵The Figures that describe the aircraft trajectories are composed by four images (a, b, c and d) that illustrated the different position of each aircraft throughout the time. Furthermore, there are grey lines that describe the trajectory of each aircraft, i.e., the path in which the aircraft fly is marked by this grey line. In the last image of each Figure, the grey lines show the full trajectory traveled by each aircraft, i.e., the final arrival segment of each aircraft.

Table 13: Description of the solution provided by FASOM in Case Study I (Age 1).

Aircraft	Type	TML	Additional VPs
1	MA	10	(9.19, 20.7)
2	RPAS	6	(11.08, 28.5)
3	AA	0	—

Source: The author.

Table 14: Description of the solution provided by FASOM in Case Study I (Age 2).

Aircraft	Type	TML	Additional VPs
1	MA	10	(6.5, 19.79)
2	RPAS	10	(6.5, 29.11)
3	AA	6	—

Source: The author.

10.1.1 Experiments

In order to build the final arrival segments for these aircraft, FASOM is employed. Considering the age 1, the feasible solution provided by this optimization method is illustrated in Table 13. In this solution, the MA (aircraft 1, TML10) is assigned to an additional VP, which is set at (9.19, 20.7), as well as the RPAS (aircraft 2, TML6), which is assigned to an additional VP at position (11.8, 28.5). Finally, the aircraft with the lowest TML (aircraft 3, which is an AA with TML 0) is not assigned to an additional VP, i.e., this aircraft flies directly to the IAF (see Figure 58, in Appendix B).

Considering the age 2, the solution, which is described in Table 14 is similar to that proposed considering the age 1, i.e., the aircraft 1 (MA, TML 10) and aircraft 2 (RPAS, TML 10) are assigned to an additional VPs ((6.5, 19.79) and (6.5, 29.11), respectively), whereas the aircraft 3 (AA), which still presents the lowest TML (6), flies directly to the IAF (see Figure 59, in Appendix B).

The solution provided in the age 3, illustrated in Table 15, for this scenario is different. The aircraft 3 (AA) achieved the highest TML (10) and is assigned to an additional VP set a position (11.2, 10.2), whereas the aircraft 2 (RPAS) presents a reduction in its TML (6) and is assigned to an additional VP set at (7.61, 27.75). On the other hand, the aircraft 1 (MA), which also presented a reduction in the TML (6), is not assigned to an addition VP, i.e., this aircraft flies directly to the IAF (see Figure 60, in Appendix B).

The solutions presented for all ages, illustrated in Tables 13, 14 and 15, presented the results, in terms of duration (of delivering all aircraft to the IAF), workload and elapsed time (of processing time) presented in Table 16. Note that the results achieved results

Table 15: Description of the solution provided by FASOM in Case Study I (Age 3).

Aircraft	Type	TML	Additional VPs
1	MA	6	—
2	RPAS	6	(7.61, 27.75)
3	AA	10	(11.2, 10.2)

Source: The author.

Table 16: Results achieved in Case Study I.

Age	Duration (s)	Workload (s)	Elapsed Time (s)
1	503	186	4.523
2	474	158	3.015
3	429	174	4.616

Source: The author.

are similar in terms of processing time, whereas the duration varies slightly.

10.1.2 Results

The solution adopted in the experiment conducted in the case study 1 considering the TML age 1 delivered the aircraft with the lowest TML (AA, TML 0) first, to the IAF. However, the second aircraft to be delivered (MA) presents a higher TML (10) in comparison to the third aircraft to be delivered (6). This is due to the fact that the optimization process is not conducted in terms of the sequence in which the aircraft is going to be delivered. Instead, the optimization process considers the number of additional VPs each aircraft is assigned to. In this case, regardless the sequence in which the aircraft are delivered, the solutions are focused on the reduction of the number of VPs assigned to each aircraft (prioritizing the aircraft with lower TMLs).

Note that the experiment conducted considering the TML age 2 is similar to the first one, considering the same sequencing even with the difference of TMLs between these two ages.

Finally, the solution provided for the TML age 3 considered a different sequence due to the changes in the TML of each aircraft. The MA (TML 6) is the first to be delivered, followed by the AA (TML 10) and the RPAS (TML 6).

In terms of the results achieved in the case study I, presented in Table 16, note that the workload levels are similar in all ages. This illustrates that, regardless the TML age (i.e. regardless the TML variation of the aircraft), the solutions provided maintained the workload level stable. Finally, note that the elapsed processing time is considerably short

for real-time applications due to the fact that the highest time presented (4.6s) represents a short distance to be traveled by the aircraft, i.e., the aircraft do not move dramatically, from the Final Sector perspective, in 4.6s.

10.2 Case Study II

The second case study of this research considers a more challenging scenario illustrated in Figure 53. In this scenario, four aircraft are considered (MA, RPAS and two AA). The two AA are set at positions (23.9, 35.34) and (20.5, 29.95), respectively. The RPAS is set at position (19.6, 1.2) and the MA is set at the position (24.55, 4.7). The IAF is present at the position (4.6, 14.9). This scenario also considers the presence of two cumulonimbus (CBs) with centers at positions (14.95, 21.3) and (14.8, 8.15). Note that the aircraft trajectories of all solutions presented in this case study, considering all ages, are also illustrated in Appendix B.

Figure 53: Scenario adopted in case study II.

Source: The author.

10.2.1 Experiments

The solution provided by FASOM for this scenario, considering the TML age 1, is described in Table 17. In this feasible solution, the aircraft 2 (AA with TML 0) flies directly to the IAF, whereas the others three are assigned to one extra VP each. Aircraft 1 (AA, TML 0), 3 (RPAS, TML6) and 4 (MA, TML 10) are assigned to VPs set, respectively, at position (23.0, 35.3), (14.7, 16.9) and (23.0, 18.5) before going to the IAF (see Figure 61, in Appendix B).

The solution presented in age 2, similar to the provided considering the age 1, is detailed in Table 18. The aircraft 2 (AA, TML 6) goes directly to the IAF. However, the aircraft 1 (AA, TML 6) is assigned to one additional VP set at (15.5, 12.0). Similarly, the aircraft 3 (RPAS) and 4 (MA) present the highest TML (10) and are assigned to one additional VP each, set, respectively, at positions (20.0, 13.7) and (26.1, 19.4) (see Figure

Table 17: Description of the solution provided by FASOM in Case Study II (Age 1).

Aircraft	Type	TML	Additional VPs
1	AA	0	(23.9, 35.3)
2	AA	0	—
3	RPAS	6	(14.7, 16.9)
4	MA	10	(23.0, 18.5)

Source: The author.

Table 18: Description of the solution provided by FASOM in Case Study II (Age 2).

Aircraft	Type	TML	Additional VPs
1	AA	6	(15.5, 12.0)
2	AA	6	—
3	RPAS	10	(30.0, 13.7)
4	MA	10	(26.1, 19.4)

Source: The author.

62, in Appendix B).

Considering the TML age 3, the solution provided is considerably different. In this solution, described in Table 19, both AA (TML 10) are assigned to additional VPs before going to the IAF, set at positions (26.6, 14.4) and (6.28, 37.9), as well as the MA (TML 6) with the additional VP set at (19.0, 0.8). Finally, the RPAS (TML 6) is conducted directly to the IAF (see Figure 63, in Appendix B).

The results achieved by the solutions provided in this case study, considering the TML ages 1, 2 and 3, are illustrated in Table 20. Note that all metrics are similar considering the different ages, i.e., the optimization method proposed in this research is able to adapt the search for finding solutions with reduced ATCo workload regardless the age considered (which changes the ATCo workload related to each aircraft).

Table 19: Description of the solution provided by FASOM in Case Study II (Age 3).

Aircraft	Type	TML	Additional VPs
1	AA	10	(26.6, 14.4)
2	AA	10	(6.28, 37.9)
3	RPAS	6	—
4	MA	6	(19.0, 0.8)

Source: The author.

Table 20: Results achieved in Case Study II.

Age	Duration (s)	Workload (s)	Elapsed Time (s)
1	844	286	9.687
2	887	234	10.014
3	803	234	9.454

Source: The author.

10.2.2 Results

Toward the Case study II, the solutions change considerably in terms of the TML age variation. In fact, in this scenario, there is the possibility of delivering only one aircraft without additional VPs⁶: the RPAS or one of the AA. In this sense, considering the TML ages 1 and 2, one AA is delivered without additional VPs due to its low TML (0 and 6 for the respective ages) and the other aircraft are delivered considering additional VPs. However, in the TML age 3, the TMLs of AAs (10) are higher than the TML of the RPAS (6). This leads the RPAS to fly to the IAF without any additional VPs, differently to the other aircraft.

The results of the experiments conducted in case study II (Table 20) illustrate the similarity in terms of workload levels that the solutions present considering the TML age variation. This shows that the FASOM provided feasible solutions maintaining the workload levels and considering, furthermore, similar solutions duration. Finally, the processing time is a bit higher, achieving up to 10.014s, because this scenario is more challenging if compared to the scenario presented in case study I.

10.3 Case Study III

The last case study of this research consider a complex scenario, illustrated in Figure 54, in which there is the presence of five aircraft (two MA, two RPAS and one AA). The two RPAS are set at positions (27.5, 27.95) and (17.45, 29.95), whereas the two MA are set at (16.2, 0.6) and (16.5, 15.05), respectively. The only AA present in this scenario is set at position (27.35, 2.25). Furthermore, the IAF is set at (1.55, 14.95), whereas there are CBs at the positions (8.9, 14.2), (14.95, 21.8) and (24.6, 13.95). Note that the aircraft trajectories of all solutions presented in this case study, considering all ages, are illustrated in Appendix B.

⁶Note that if both aircraft are delivered without one additional VP, the solution is not feasible due to the fact that the separation of these two aircraft in the region near to the IAF is lower than 5nm.

10.3.1 Experiments

Figure 54: Scenario adopted in case study III.

Source: The author.

In order to deliver the set of aircraft presented in this scenario, considering the TML age 1, FASOM proposed the solution that is described in Table 21. In this feasible solution, the aircraft 2 (AA, TML 0) and 4 (RPAS, TML 6) go directly to the IAF. The aircraft 1 (RPAS, TML 6) is assigned to the position (16.5, 1.4) before going to the IAF. Similarly, the aircraft 3 and 5 are assigned, respectively, to the positions (12.9, 21.8) and (7.4, 19.9) before reaching the objective point (IAF) (see Figure 64, in Appendix B).

The solution provided considering the TML age 2, illustrated in Table 22, selected the aircraft 2 (AA) and 3 (MA) to fly directly to the IAF. The two RPAS present in this scenario, aircraft 1 and 4, fly, respectively, to the positions (35.5, 24.0) and (33.5, 27.1) before going to the IAF. Finally, the aircraft 5, which is a MA, is directed to the additional VP located at the position (21.3, 28.1) (see Figure 65, in Appendix B).

Table 21: Description of the solution provided by FASOM in Case Study III (Age 1).

Aircraft	Type	TML	Additional VPs
1	RPAS	6	(16.5, 1.4)
2	AA	0	—
3	MA	10	(12.9, 21.8)
4	RPAS	6	—
5	MA	10	(7.4, 19.9)

Source: The author.

Table 22: Description of the solution provided by FASOM in Case Study III (Age 2).

Aircraft	Type	TML	Additional VPs
1	RPAS	10	(35.5, 24.0)
2	AA	6	—
3	MA	10	—
4	RPAS	10	(33.5, 27.1)
5	MA	10	(21.3, 28.1)

Source: The author.

Finally, the last experiment, which considers the TML age 3, is conducted employing the solution described in Table 23. In this solution, the AA (aircraft 2) and one of the MA (aircraft 3) are conducted to the IAF directly. In this context, both RPAS (aircraft 1 and 4) are conducted indirectly, i.e., are conducted to additional VPs located at positions (13.7, 38.0) and (20.7, 2.7). Thus, the other MA (aircraft 5) is conducted to the position (6.2, 31.2) before going to the IAF (see Figure 66, in Appendix B).

The quality of the solutions proposed by FASOM for this case study, considering the TML age variation, is illustrated in Table 24. Similarly to the case studies I and II, the results of each metric (duration, workload and elapsed time) are similar considering all ages.

Table 23: Description of the solution provided by FASOM in Case Study III (Age 3).

Aircraft	Type	TML	Additional VPs
1	RPAS	6	(13.7, 38.0)
2	AA	10	—
3	MA	6	—
4	RPAS	6	(20.7, 2.7)
5	MA	6	(6.2, 31.2)

Source: The author.

Table 24: Results achieved in Case Study III.

Age	Duration (s)	Workload (s)	Elapsed Time (s)
1	991	284	10.406
2	1107	248	10.074
3	1039	296	9.954

Source: The author.

10.3.2 Results

The last case study (III) provided different solutions throughout the TML ages variation. In this scenario, the solution can conduct two out of three aircraft (one of the RPAS, one of the MA and or AA) to the IAF without additional VPs. In the TML age 1, the AA (TML 0) and one of the RPAS (TML 6) are conducted directly to the IAF, whereas the others are assigned to one additional VP. However, considering the TML ages 2 and 3, the AA (TMLs 6 and 10) and one of the MA (TMLs 10 and 6) are chosen to be conducted directly. Finally, the other aircraft are assigned to additional VPs.

In terms of the results achieved in the case study III, although the workload is similar throughout the TAML ages, one can note a certain level of instability in comparison to the results of the other case studies (i.e., differences regarding the workload level). This is due to the fact that this is a more complex scenario in which changes in the TML of the aircraft may change the sequence considerably. Finally, the elapsed time reached up to 10.4s, which is similar to the elapsed time achieved in case study II.

10.4 Discussion

The duration of the solution, considering the TML ages variation, for each case study, is illustrated in Figure 55. This chart shows that the results achieved in the different case studies are considerably different but considering the age variation, each case study presented slight differences in each experiment.

Figure 55: Comparison of the sequencing duration achieved in case studies I, II and III considering the TML age variation.

Source: The author.

On the other hand, the workload of case study II and III are similar, as illustrated in Figure 56. Note that, at TML age 1, the workload of both case studies is very similar and they start to spread out throughout the TML age variation. Furthermore, the case study I present a lower workload level. Note that the variations of the experiments within the same case study are slight, i.e., the optimization method proposed is able to adapt the search for finding solutions with reduced ATCo workload regardless the age considered (which changes the ATCo workload related to each aircraft).

Figure 56: Comparison of the ATCo workload achieved in case studies I, II and III considering the TML age variation.

Source: The author.

Finally, Figure 57 shows a comparison of the elapsed time achieved in each case study considering the TML age variation. This chart shows that the elapsed time of case studies

II and III are very similar due to the complexity faced in both scenarios, which is different from the elapsed time achieved in the case study I (i.e case study I represents a simpler scenario).

Figure 57: Comparison of the elapsed time achieved in case studies I, II and III considering the TML age variation.

Source: The author.

In summary, the results achieved showed that the FASOM provided feasible and good solutions, which are adapted according to the TML of each aircraft in order to maintain the workload and duration levels stable. This stability is also illustrated in the comparison of the results achieved in each case study.

11 CONCLUSION

Since the air transportation is essential for society and it is increasing gradually and new technologies (e.g. UAS) are being proposed and integrated into the airspace, methods for optimizing their operation and enabling a smooth integration are import. In this context, in order conduct the UAS into challenging scenarios (e.g. those which consider bad weather conditions), it is reasonable to consider that the ATCo may be not familiar with this technology and may be careful, which tends to increase the workload level and, ultimately, impact the safety levels of the airspace.

In fact, conducting aircraft in the TMA considering bad weather conditions and UAS is a complex task. In order to support this successfully, supporting tools must consider airspace restrictions, the different aspects of each aircraft and the role of the ATCo in this context. The work proposes a parallel swarm-based method for optimizing final aircraft arrival segments design considering the UAS presence, which is conducted from the ATCo workload and sequencing duration perspectives. Finally, the solutions consider airspace restrictions such as minimum separation between aircraft and bad weather conditions, i.e., the presence of cumulonimbus (CB).

The following sections describe the main contributions of this dissertations and provide possible future directions of this research. Firstly, the contributions are reviewed. Then, the future works presented. Finally, a discussion on the final remarks is conducted.

11.1 Contributions

The contributions of this research, which are presented throughout this dissertation, are a novel approach to measuring the integration of UAS into non-segregated airspace, a formal model to represent the final sector of the Terminal Maneuvering Area (TMA) and, furthermore, a swarm-based optimization method for aircraft sequencing considering the UAS presence. In summary, the main contributions of this research can be detailed as follows:

1. **A novel approach for measuring the impact of the integration of UAS into the non-segregated airspace:** We introduce the Technology Maturity Level (TML), which models the familiarity of ATCo with a particular aircraft. Thus, impacts on ATCo workload of any aircraft (e.g. MA, and UAS), which is related to airspace safety, can be measured accordingly to the TML. This method is inspired by the Technology Readiness Level (TRL), which is a measurement system related to the technological maturity of a given aircraft. The TML can be faced as an important metric (given further analysis on its impacts) regarding the relationship between the UAS and the ATCo and there are many aspects to be developed in future efforts (e.g. the evolution of TML throughout the years);
2. **A simulation model for representing airspace operations into the final sector:** the Final Sector Simulation Tool (FSST), which aims evaluate safety (from workload perspective) and efficiency in aircraft sequencing in final sector considering the UAS presence and considers bad weather conditions and the Technology Maturity Level (TML) of the aircraft, is presented. The FSST is a validated tool that achieved realistic results, for instance, in terms of sequencing duration and considers many aspects of this area of the airspace, such as the presence of bad weather conditions and rules defined for the aircraft landing, e.g., the presence of the Initial Fix Approach (IAF), in which the initial approach procedure starts (further, in the Final Approach Fix, the final approach starts);
3. **A stochastic model for building safe and efficient final arrival segments:** the optimization is achieved by the usage of the sequencing duration, which is related to efficiency, and ATCo workload, which is related to safety, and employing an adaptation of the Particle Swarm Optimization (PSO) meta-heuristic. The parallel structure leads to a better performance in terms of search region exploration due to the fact that the position and velocity of each particle are evaluated and updated in parallel.

11.2 Future Works

Although this work aims to address specific topics toward the UAS operation, there are many possibilities of extension of this effort. Some future directions are:

- **Measuring the impacts of parameters changes in the results of the FA-SOM:** As the focus of this research is to propose the method for optimizing the

operation of UAS into the Final Sector, one future direction is to analyze the parameter variation in order to find out the best parameter combination for each scenario. This variation considers the parameter of the PPSO, such as number of particles and values of the c_1 , c_2 and w ;

- **Measuring the evolution of the TML of different types of aircraft throughout the years:** In this research, ages of TML are considering in the experiments. Although the ages are clearly different from each other, one challenge and future direction is on how to measure the evolution of the TML throughout the year from many perspectives (e.g. operational and regulatory);
- **Employing different architectures of optimization in the FASOM:** As the FASOM supports the implementation of different meta-heuristics (e.g. Ant Colony Optimization and variations of Genetic Algorithms), other architectures may be employed in future work, such as the combination of meta-heuristics (e.g. an implementation of different meta-heuristics that act in parallel);
- **Applying variations in airspace constraints and parameters:** Another future direction is the development of flexible structures, such as: variable CB sizes and shapes; CB movements; and changes minimum separation of the aircraft depending on their types as well as on the characteristics of airspace (e.g. complexity);
- **Arrival Segment Design Considering Failures in C2 Link:** This research considers the RPAS presence but does not include failures in the C2 link, which are failures in the communication between the remote pilot and the aircraft. According to the contingency operations proposed by ICAO, considering a failure in the communication within the final sector, conducting all aircraft considering the presence of an independent aircraft (i.e. an aircraft that cannot be controlled) is a challenge. Thus, one of the future directions of this research is on how the set of aircraft can be conducted to the IAF considering this issue. the optimization of arrival segments considering a problematic aircraft into the final sector is a challenging task;
- **Priority Establishment of UAS sequencing into non-segregated Airspace:** Our optimization approach, in the safety context, is driven by the number of VPs assigned to each aircraft. However, an alternative approach may be considered, such as conducting the aircraft to the IAF with different prioritization rules. Instead of controlling aircraft from the level of familiarity (TML), one alternative approach is to consider the priority level. One example of prioritized aircraft, nowadays, is the emergency aircraft. Furthermore, a challenge is to identify the priority of the

UAS in the context of the list of priorities assigned to the aircraft types employed nowadays;

- **Optimization of the UAS operation into the TMA:** Although our proposal is developed to be applied into the final sector, which is part of the TMA, there are many situations faced in larger scenarios that may be considered in future works. For instance, as the area is considerably larger, it is reasonable to consider a larger number of aircraft. Examples of applications are airspace resilience (e.g. in case of problems in airports) and impacts of weather conditions in a long period of time (e.g. decades). The main idea is to extend the research conducted in the final sector to a larger and more complex area, the TMA;
- **Automation of the Air Traffic Control (ATC):** One of the challenges of the future directions of this research is the automation of the ATC and ATCo. For instance, approaches such as ATC Maturity Level (AML), that represents the level of maturity and autonomy of a system in terms of acting in controlling manned and unmanned aircraft (e.g. different approach for modeling the relationship between the autonomous ATC with UAS and between the autonomous ATC and MA can be developed).

11.3 Final Remarks

This research deals with the integration of UAS into non-segregated airspace. As this is a challenging task, a set of contributions are proposed to address this problem. The optimization method proposed incorporates the aspects of UAS operation identified, as well as the airspace constraints.

The results show that our strategy present feasible solutions with acceptable workload and duration levels considering the weather conditions and the UAS presence. As future directions, many aspects can be identified, for instance, swarm-based airspace resilience optimization.

REFERENCES

- AHMED, M. S.; ALAM, S.; BARLOW, M. An evolutionary optimization approach for path planning of arrival aircraft for optimal sequencing. In: INTELLIGENT AND EVOLUTIONARY SYSTEMS: ASIA PACIFIC SYMPOSIUM, IES 2016, 20. November 2016, **Proceedings...** [S.l.: s.n.], 2017. p. 1–16.
- AIRBUS. *Getting to grips with aircraft performance*. 2002. Available in: <https://www.skybrary.aero/bookshelf/books/2263.pdf>. Accessed in: February 2018.
- AIRNAV. Miami International Airport Area Chart (ARC). Available in: <https://www.airnav.com/airport/KMIA>. Accessed: February 2018. 2016.
- ALAM, S.; ABBASS, H. A.; BARLOW, M. Atoms: Air traffic operations and management simulator. *IEEE Transactions on intelligent transportation systems*, IEEE, v. 9, n. 2, p. 209–225, 2008.
- ALLIGNOL, C. et al. Integration of uas in terminal control area. In: IEEE. DIGITAL AVIONICS SYSTEMS CONFERENCE (DASC), 2016 IEEE/AIAA, 35. **Proceedings...** [S.l.], 2016. p. 1–7.
- ALONSO-AYUSO, A. et al. Multiobjective optimization for aircraft conflict resolution. a metaheuristic approach. *European Journal of Operational Research*, Elsevier, v. 248, n. 2, p. 691–702, 2016.
- ARANTES, J. S. et al. Heuristic and genetic algorithm approaches for uav path planning under critical situation. *International Journal on Artificial Intelligence Tools*, World Scientific, v. 26, n. 01, p. 1760008, 2017.
- AUSTIN, R. *Unmanned aircraft systems: UAVS design, development and deployment*. New York: John Wiley & Sons, 2011. v. 54.
- BENNELL, J. A. et al. Dynamic scheduling of aircraft landings. *European Journal of Operational Research*, Elsevier, v. 258, n. 1, p. 315–327, 2017.
- BIANCO, L.; DELL'OLMO, P.; GIORDANI, S. Scheduling models and algorithms for tma traffic management. *Modelling and simulation in air traffic management*, Springer, p. 139–167, 1997.
- BODOH, D. J.; WIELAND, F. Performance experiments with the high level architecture and the total airport and airspace model (TAAM). In: WORKSHOP ON PARALLEL AND DISTRIBUTED SIMULATION, 2003, PADS 2003, 17. **Proceedings...** [S.l.: s.n.], 2003. p. 31–39.
- BOEING. *Boeing: Autonomous Systems*. 2018. Available in: <http://www.boeing.com/defense/autonomous-systems/index.page>. Accessed in: February 2018.

- BORENER, S. S. et al. Modeling emergent risks in complex airspace: UAS operations in a metroplex environment. In: IEEE. DIGITAL AVIONICS SYSTEMS CONFERENCE (DASC), 2015 IEEE/AIAA, 34. **Proceedings...** [S.l.], 2015. p. 5B3–1.
- BOURSIER, L. et al. Airborne spacing in the terminal area: A study of non-nominal situations. In: AIAA AVIATION TECHNOLOGY, INTEGRATION AND OPERATIONS CONFERENCE, 2006, 5. **Proceedings...** [S.l.: s.n.], 2006.
- BRANCH, A. et al. A design study for the safe integration of unmanned aerial systems into the national airspace system. In: IEEE. PERFORMANCE SYSTEMS AND INFORMATION ENGINEERING DESIGN SYMPOSIUM (SIEDS), 2016 IEEE. **Proceedings...** [S.l.], 2016. p. 170–175.
- BUCCERONI, M. A. et al. a multi-perspective virtual reality visualization of unmanned aerial systems in the us national airspace. In: IEEE. SENSORS APPLICATIONS SYMPOSIUM (SAS), 2016 IEEE. **Proceedings...** [S.l.], 2016. p. 1–4.
- CAPRÌ, S.; IGNACCOLO, M. Genetic algorithms for solving the aircraft-sequencing problem: the introduction of departures into the dynamic model. *Journal of Air Transport Management*, v. 10, n. 5, p. 345 – 351, 2004. ISSN 0969-6997.
- CHEN, P.-H. Particle swarm optimization for power dispatch with pumped hydro. In: *Particle Swarm Optimization*. [S.l.]: InTech, 2009.
- CLOTHIER, R.; DENNEY, E.; PAI, G. Making a risk informed safety case for small unmanned aircraft system operations. *Safety (TLOS)*, v. 3, p. 4, 2017.
- COELLO, C. A. C. et al. *Evolutionary algorithms for solving multi-objective problems*. [S.l.]: Springer, 2007. v. 5.
- CORMEN, T. H. *Introduction to algorithms*. [S.l.]: MIT, 2009.
- DALAMAGKIDIS, K.; VALAVANIS, K.; PIEGL, L. *On Integrating Unmanned Aircraft Systems into the National Airspace System: Issues, Challenges, Operational Restrictions, Certification, and Recommendations*. [S.l.]: Springer Netherlands, 2011.
- DEB, K. *Multi-objective optimization using evolutionary algorithms*. New York: John Wiley & Sons, 2001. v. 16.
- DECEA. *Area Chart (ARC) - SP*. 2017. Available in: <https://www.aisweb.aer.mil.br/download/?arquivo=612a2b51-b1cb-4826-a094d266e3df7049>. Accessed: February 2018.
- DERVIC, A.; RANK, A. *ATC complexity measures: Formulas measuring workload and complexity at Stockholm TMA*. 2015. Available in: <http://www.diva-portal.org/smash/get/diva2:790857/FULLTEXT01.pdf>. Accessed in: February 2018.
- DORIGO, M.; BIRATTARI, M.; STUTZLE, T. Ant colony optimization. *IEEE Computational Intelligence Magazine*, IEEE, v. 1, n. 4, p. 28–39, 2006.
- EBERHART, R. C.; SHI, Y. Comparison between genetic algorithms and particle swarm optimization. In: INTERNATIONAL CONFERENCE ON EVOLUTIONARY PROGRAMMING. **Proceedings...** [S.l.: s.n.], 1998. p. 611–616.

EIBEN, A. et al. *Introduction to evolutionary computing*. [S.l.]: Springer, 2003. v. 53.

FAA. *Advisory Circular - Aviation Weather*. 2016. Available in:
https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_00-6B.pdf.
 Accessed in: February 2018.

FARLIK, J. Conceptual operational architecture of the air force simulator: Simulation of air defense operations. In: IEEE. MILITARY TECHNOLOGIES (ICMT), 2015 INTERNATIONAL CONFERENCE. **Proceedings...** [S.l.], 2015. p. 1–5.

FASANO, G. et al. Sense and avoid for unmanned aircraft systems. *IEEE Aerospace and Electronic Systems Magazine*, v. 31, n. 11, p. 82–110, November 2016. ISSN 0885-8985.

FINAVIA. *Efficiency is backbone of airport competitiveness*. 2015.

FORTES, J. L. C.; FRAGA, R.; MARTIN, K. An approach for safety assessment in UAS operations applying stochastic fast-time simulation with parameter variation. In: IEEE. PROCEEDINGS OF THE 2016 WINTER SIMULATION CONFERENCE. **Proceedings...** [S.l.], 2016. p. 1860–1871.

FROMM, M. et al. Pyro-cumulonimbus injection of smoke to the stratosphere: Observations and impact of a super blowup in northwestern canada on 3–4 august 1998. *Journal of Geophysical Research: Atmospheres*, Wiley Online Library, v. 110, n. D8, 2005.

FRONTERA, G. et al. Approximate 3d euclidean shortest paths for unmanned aircraft in urban environments. *Journal of Intelligent & Robotic Systems*, Springer, v. 85, n. 2, p. 353–368, 2017.

GANTI, S. R.; KIM, Y. Implementation of detection and tracking mechanism for small uas. In: 2016 INTERNATIONAL CONFERENCE ON UNMANNED AIRCRAFT SYSTEMS (ICUAS). **Proceedings...** [S.l.: s.n.], 2016. p. 1254–1260.

GAO, Y.; ZHANG, X.; GUAN, X. Cooperative multi-aircraft conflict resolution based on co-evolution. In: IEEE. INSTRUMENTATION & MEASUREMENT, SENSOR NETWORK AND AUTOMATION (IMSNA), 2012 INTERNATIONAL SYMPOSIUM. **Proceedings...** [S.l.], 2012. v. 1, p. 310–313.

GIMENES, R. et al. Guidelines for the integration of autonomous uas into the global atm. *Journal of Intelligent & Robotic Systems*, Springer Science & Business Media, v. 74, n. 1-2, p. 465, 2014.

GIRDNER, N. An integrated system safety model of the national airspace system. In: IEEE. RELIABILITY AND MAINTAINABILITY SYMPOSIUM (RAMS), 2016 ANNUAL. **Proceedings...** [S.l.], 2016. p. 1–6.

GIRISH, B. An efficient hybrid particle swarm optimization algorithm in a rolling horizon framework for the aircraft landing problem. *Applied Soft Computing*, Elsevier, v. 44, p. 200–221, 2016.

GLOVER, F. Tabu search: A tutorial. *Interfaces*, INFORMS, v. 20, n. 4, p. 74–94, 1990.

- GRIMACCIA, F. et al. Risk analysis of the future implementation of a safety management system for multiple rpas based on first demonstration flights. *Electronics*, v. 6, n. 3, p. 50, 2017.
- GRINDLE, L.; HACKENBERG, D. L. Unmanned aircraft systems (UAS) integration in the national airspace system (NAS) project: Kdp-a for phase 2 minimum operational performance standards. 2016. Available in: <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160013707.pdf>. Accessed in: February 2018.
- GUERIN, D. Consideration of wake turbulence during the integration of remotely piloted aircraft into the air traffic management system. In: IEEE. INTERNATIONAL CONFERENCE ON UNMANNED AIRCRAFT SYSTEMS (ICUAS), 2015. **Proceedings...** [S.l.], 2015. p. 926–935.
- GUPTA, S. G.; GHONGE, M. M.; JAWANDHIYA, P. Review of unmanned aircraft system (uas). *International Journal of Advanced Research in Computer Engineering & Technology (IJARCET)*, v. 2, n. 4, p. pp–1646, 2013.
- HASSAN, R. et al. A comparison of particle swarm optimization and the genetic algorithm. In: AIAA MULTIDISCIPLINARY DESIGN OPTIMIZATION SPECIALIST CONFERENCE, 1. **Proceedings...** [S.l.: s.n.], 2005. v. 18, p. e21.
- HEISEY, C. W. et al. A reference software architecture to support unmanned aircraft integration in the national airspace system. *Journal of Intelligent & Robotic Systems*, Springer, p. 1–15, 2013.
- HOEKSTRA, J. M.; ELLERBROEK, J. Bluesky ATC simulator project: an open data and open source approach. In: INTERNATIONAL CONFERENCE ON RESEARCH IN AIR TRANSPORTATION, 7. **Proceedings...** [S.l.: s.n.], 2016.
- HOMOLA, J. et al. UAS traffic management (UTM) simulation capabilities and laboratory environment. In: IEEE. DIGITAL AVIONICS SYSTEMS CONFERENCE (DASC), 2016 IEEE/AIAA, 35. **Proceedings...** [S.l.], 2016. p. 1–7.
- HONG, Y. et al. Conflict management considering a smooth transition of aircraft into adjacent airspace. *IEEE Transactions on Intelligent Transportation Systems*, IEEE, v. 17, n. 9, p. 2490–2501, 2016.
- HONG, Y. et al. Nonlinear conflict resolution and flow management using particle swarm optimization. *IEEE Transactions on Intelligent Transportation Systems*, IEEE, v. 18, n. 12, p. 3378–3387, 2017.
- HORIO, B. et al. Safety risk assessment case study using airspace conflict analysis simulation. In: INTEGRATED COMMUNICATIONS, NAVIGATION AND SURVEILLANCE CONFERENCE (ICNS), 2012. **Proceedings...** [S.l.: s.n.], 2012. p. D2–1.
- HU, X.-B.; LIAO, J.-Q.; PAOLO, E. D. A simulation study on air traffic control strategies. In: IEEE. WORLD CONGRESS INTELLIGENT CONTROL AND AUTOMATION (WCICA), 2016, 12. **Proceedings...** [S.l.], 2016. p. 1577–1583.

- ICAO. *Air Traffic Services - Annex 11*. 2001. Available in: <https://www.theairlinepilots.com/forumarchive/quickref/icao/annex11.pdf>. Accessed in: February 2018.
- ICAO. *Global ATM Operational Concept - Doc 9854-AN/458*. 2005. Available in: [https://www.icao.int/Meetings/anconf12/Document%20Archive/9854_cons_en\[1\].pdf](https://www.icao.int/Meetings/anconf12/Document%20Archive/9854_cons_en[1].pdf). Accessed in: February 2018.
- ICAO. *Rules of Air - Annex 2*. 2005. Available in: https://www.icao.int/Meetings/anconf12/Document%20Archive/an02_cons%5B1%5D.pdf. Accessed in: February 2018.
- ICAO. *Aircraft Operations - DOC 8168*. 2006. Available in: http://www.chcheli.com/sites/default/files/icao_doc_8168_vol_1.pdf. Accessed in: February 2018.
- ICAO. *Cir 328 AN/190 Unmanned Aircraft Systems Operations (UAS)*. 2011. Available in: https://www.icao.int/Meetings/UAS/Documents/Circular%20328_en.pdf. Accessed in: February 2018.
- ICAO. *Manual on Remotely Piloted Aircraft Systems (RPAS) - Doc 10019 AN/507*. 2015. Available in: http://servicos.decea.gov.br/arquivos/drone/Doc_10019_Manual_on_RPAS_English_.pdf. Accessed in: February 2018.
- ICAO. *Air Traffic Management - DOC 4444*. 2016. Available in: <http://www.navcanada.ca/EN/media/Publications/ICAO-Doc-4444-EN.pdf>. Accessed in: February 2018.
- INDOAVIS, I. A. S. *True Airspeed (TAS) calculator*. Available in: <http://indoavis.co.id/main/tas.html>. Accessed in: February 2018. 2017.
- IVAO. *Air Traffic Services*. 2015. Available in: https://www.ivaio.aero/training/documentation/books/PP_ADC_Air_traffic_services.pdf. Accessed in: February 2018.
- JEPPESEN. *Total Airspace and Airport Modeller (TAAM) Product Profile*. Available in: <http://ww1.jepesen.com/documents/aviation/government/TAAM-product-profile.pdf>. Accessed: February 2018. 2015.
- JEPPESEN. *Total Airspace and Airport Modeller (TAAM) Brochure*. Available in: <http://ww1.jepesen.com/documents/aviation/government/TAAM-FactSheet.pdf>. Accessed: February 2018. 2018.
- JI, X.; FANG, J.; YAN, R. An online method for the real-time aircraft arrival sequencing and scheduling problem. In: WORLD CONGRESS ON INTELLIGENT CONTROL AND AUTOMATION (WCICA), 2014, 11. **Proceedings...** [S.l.: s.n.], 2014. p. 1067–1070.
- JIANG, X.; ZHOU, Q.; YE, Y. Method of task assignment for uav based on particle swarm optimization in logistics. In: ACM. PROCEEDINGS OF THE 2017 INTERNATIONAL CONFERENCE ON INTELLIGENT SYSTEMS, METAHEURISTICS & SWARM INTELLIGENCE. **Proceedings...** [S.l.], 2017. p. 113–117.

KAMIENSKI, J.; SEMANEK, J. Atc perspectives of uas integration in controlled airspace. *Procedia Manufacturing*, Elsevier, v. 3, p. 1046–1051, 2015.

KENNEDY, J. Particle swarm optimization. In: *Encyclopedia of machine learning*. [S.l.]: Springer, 1995. p. 760–766.

KHADILKAR, H.; BALAKRISHNAN, H. Integrated control of airport and terminal airspace operations. *IEEE Transactions on Control Systems Technology*, IEEE, v. 24, n. 1, p. 216–225, 2016.

KOPARDEKAR, P. H. et al. Airspace complexity measurement: An air traffic control simulation analysis. *International Journal of Industrial Engineering: Theory, Applications and Practice*, v. 16, n. 1, p. 61–70, 2009.

KORN, B.; TITTEL, S.; EDINGER, C. Stepwise integration of uas in non-segregated airspace-the potential of tailored uas atm procedures. In: IEEE. INTEGRATED COMMUNICATIONS, NAVIGATION AND SURVEILLANCE CONFERENCE (ICNS), 2012. **Proceedings...** [S.l.], 2012. p. P1–1.

LAARHOVEN, P. J. V.; AARTS, E. H. Simulated annealing. In: *Simulated annealing: Theory and applications*. [S.l.]: Springer, 1987. p. 7–15.

LAWLER, E. L. *Combinatorial optimization: networks and matroids*. [S.l.]: Courier Corporation, 1976.

LEASURE, M.; NOLAN, M. *Unmanned Aviation Systems: The Definitive Guide*. [S.l.]: eAcademicBooks LLC, 2015.

LEE, W. S. et al. Fault tree analysis, methods, and applications 2013; a review. *IEEE Transactions on Reliability*, R-34, n. 3, p. 194–203, Aug 1985. ISSN 0018-9529.

LI, C.; HU, J.-W. A new ARIMA-based neuro-fuzzy approach and swarm intelligence for time series forecasting. *Engineering Applications of Artificial Intelligence*, v. 25, n. 2, p. 295 – 308, 2012. ISSN 0952-1976. (Special Section: Local Search Algorithms for Real-World Scheduling and Planning).

LI, X. et al. Utilization pattern of closely spaced parallel runways and simulation of operational efficiency. In: IEEE INTERNATIONAL CONFERENCE ON PROGRESS IN INFORMATICS AND COMPUTING (PIC), 2015. **Proceedings...** [S.l.: s.n.], 2015. p. 158–162.

LIU, Y. et al. Aircraft rerouting decision-making model under severe weather. In: INTERNATIONAL CONFERENCE ON INFORMATION SCIENCE AND CONTROL ENGINEERING (ICISCE), 2016, 3. **Proceedings...** [S.l.: s.n.], 2016. p. 814–818.

LUDLAM, F. Cumulonimbus. *OSTIV Publications*, v. 4, p. 145–148, 1956.

MA, W. et al. An efficient approximation algorithm for aircraft arrival sequencing and scheduling problem. *Mathematical Problems in Engineering*, Hindawi Publishing Co., v. 2014, 2014.

- MAJUMDAR, A.; OCHIENG, W. Factors affecting air traffic controller workload: Multivariate analysis based on simulation modelling of controller workload. *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies (TRBNA), n. 1788, p. 58–69, 2002.
- MAJUMDAR, A. et al. En-route sector capacity estimation methodologies: An international survey. *Journal of Air Transport Management*, v. 11, n. 6, p. 375 – 387, 2005. ISSN 0969-6997.
- MAJUMDAR, A.; POLAK, J. Estimating capacity of europe’s airspace using a simulation model of air traffic controller workload. *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies (TRBNA), n. 1744, p. 30–43, 2001.
- MANKINS, J. C. Technology readiness levels. *White Paper, April*, v. 6, 1995.
- MARINAKIS, Y. et al. A hybrid particle swarm optimization–variable neighborhood search algorithm for constrained shortest path problems. *European Journal of Operational Research*, Elsevier, v. 261, n. 3, p. 819–834, 2017.
- MARQUART, S. et al. Future development of contrail cover, optical depth, and radiative forcing: Impacts of increasing air traffic and climate change. *Journal of Climate*, v. 16, n. 17, p. 2890–2904, 2003.
- MCFADYEN, A.; MARTIN, T. Terminal airspace modelling for unmanned aircraft systems integration. In: IEEE INTERNATIONAL CONFERENCE ON UNMANNED AIRCRAFT SYSTEMS (ICUAS), 2016. **Proceedings...** [S.l.: s.n.], 2016. p. 789–794.
- MCFADYEN, A. et al. Simulation and modelling tools for quantitative safety assessments of unmanned aircraft systems and operations. In: IEEE. AEROSPACE CONFERENCE, 2016 IEEE. **Proceedings...** [S.l.], 2016. p. 1–12.
- MCGOVERN, S. M.; KALISH, A. Stochastic airspace simulation tool development. In: IEEE. IEEE/AIAA DIGITAL AVIONICS SYSTEMS CONFERENCE (DASC), 2009, 28. **Proceedings...** [S.l.], 2009. p. 2–D.
- MECKIFF, C.; CHONE, R.; NICOLAON, J.-P. The tactical load smoother for multi-sector planning. In: USA/EUROPE AIR TRAFFIC MANAGEMENT RESEARCH AND DEVELOPMENT SEMINAR, 1998, 2. **Proceedings...** [S.l.: s.n.], 1998.
- MEHLITZ, P. et al. Race: Building airspace simulations faster and better with actors. In: IEEE. IEEE/AIAA DIGITAL AVIONICS SYSTEMS CONFERENCE (DASC), 2016, 35. **Proceedings...** [S.l.], 2016. p. 1–9.
- MITCHELL, J. S.; POLISHCHUK, V.; KROZEL, J. Airspace throughput analysis considering stochastic weather. In: AIAA GUIDANCE, NAVIGATION, AND CONTROL CONFERENCE, 2006. **Proceedings...** [S.l.: s.n.], 2006. v. 19.
- MITSA, T. *Temporal Data Mining*. Available in: https://books.google.com.br/books?id=4P_7ydvW7cAC. Accessed in: February 2018. [S.l.]: CRC, 2010. (Chapman & Hall/CRC Data Mining and Knowledge Discovery Series). ISBN 9781420089776.

MOGFORD, R. H. et al. *The Complexity Construct in Air Traffic Control: A Review and Synthesis of the Literature*. [S.l.], 1995.

MURATA, A. et al. Optimization of aircraft landing route and order: An approach of hierarchical evolutionary computation. In: EAI INTERNATIONAL CONFERENCE ON BIO-INSPIRED INFORMATION AND COMMUNICATIONS TECHNOLOGIES (FORMERLY BIONETICS), 2016, 9. **Proceedings...** [S.l.: s.n.], 2016. p. 340–347.

NARAYAN, P. et al. Computationally adaptive multi-objective trajectory optimization for uas with variable planning deadlines. In: IEEE AEROSPACE CONFERENCE, 2009. **Proceedings...** [S.l.: s.n.], 2009. p. 1–8.

NARZISI, G. Multi-objective optimization. *A quick introduction, New York University lectures*, 2008.

NASA. *Armstrong Flight Research Center*. 2018. Available in: https://www.nasa.gov/centers/armstrong/programs_projects/UAS_in_the_NAS/index.html. Accessed in: February 2018.

NETO, E. C. P. et al. Evaluating safety and efficiency in aircraft sequencing in final approach considering the uas presence. In: CONGRESSO DE PESQUISA E ENSINO EM TRANSPORTES, 2017, 31. **Proceedings...** [S.l.: s.n.], 2017.

NETO, E. P. et al. An airspace capacity-based safety assessment model considering uas integration. In: IEEE. INTERNATIONAL CONFERENCE ON UNMANNED AIRCRAFT SYSTEMS (ICUAS), 2017. **Proceedings...** [S.l.], 2017. p. 961–970.

NOSKIEVIČ, T.; KRAUS, J. Air traffic control tools assessment. *MAD-Magazine of Aviation Development*, v. 5, n. 2, p. 6–10, 2017.

OAKS, S.; WONG, H. *Java threads*. New York: O'Reilly Media, 1999.

OFR, United States. Office of the Federal Register. *Code of Federal Regulations: 1949-1984*. [S.l.]: U.S. General Services Administration, National Archives and Records Service, Office of the Federal Register, 1962. Available in: <https://books.google.com.br/books?id=4kQdBVc1eUoC>. Accessed in: February 2018.

OZTEKIN, A.; FLASS, C.; LEE, X. Development of a framework to determine a mandatory safety baseline for unmanned aircraft systems. *Journal of Intelligent & Robotic Systems*, Springer, v. 65, n. 1, p. 3–26, 2012.

PASTOR, E. et al. Real-time simulations to evaluate the rpas integration in shared airspace. In: SESAR INNOVATION DAYS (SIDS2014), 2014, 4. **Proceedings...** Madrid, Spain: [s.n.], 2014. p. 1–10.

PAVLINOVIĆ, M. et al. Air traffic controllers' practical part of basic training on computer based simulation device. In: JUBILARNI MEĐUNARODNI SKUP ZA INFORMACIJSKU I KOMUNIKACIJSKU TEHNOLOGIJU, ELEKTRONIKU I MIKROELEKTRONIKU, 2017, 40. **Proceedings...** [S.l.: s.n.], 2017.

PERROTTET, J. Enabling unrestricted uas airspace access: Performance based navigation. In: INTEGRATED COMMUNICATIONS, NAVIGATION AND SURVEILLANCE CONFERENCE (ICNS), 2017. **Proceedings...** [S.l.: s.n.], 2017. p. 6D1–1–6D1–5.

RAMALINGAM, K.; KALAWSKY, R.; NOONAN, C. Integration of unmanned aircraft system (uas) in non-segregated airspace: A complex system of systems problem. In: IEEE INTERNATIONAL SYSTEMS CONFERENCE (SYSCON), 2011. **Proceedings...** [S.l.: s.n.], 2011. p. 448–455.

RIBEIRO, V. F. et al. Modeling the swarm optimization to build effective continuous descent arrival sequences. In: IEEE INTERNATIONAL CONFERENCE ON INTELLIGENT TRANSPORTATION SYSTEMS (ITSC), 2016, 19. **Proceedings...** [S.l.: s.n.], 2016. p. 760–765.

ROMERO, J.; GOMEZ, L. Proposal for rpas integration into non-segregated airspaces. In: IEEE INTEGRATED COMMUNICATIONS, NAVIGATION AND SURVEILLANCE CONFERENCE (ICNS), 2017. **Proceedings...** [S.l.: s.n.], 2017. p. 6C2–1.

SAMÀ, M. et al. Optimal aircraft scheduling and flight trajectory in terminal control areas. In: IEEE. IEEE INTERNATIONAL CONFERENCE ON MODELS AND TECHNOLOGIES FOR INTELLIGENT TRANSPORTATION SYSTEMS (MT-ITS), 2017, 5. **Proceedings...** [S.l.], 2017. p. 285–290.

SAMÀ, M. et al. Metaheuristics for efficient aircraft scheduling and re-routing at busy terminal control areas. *Transportation Research Part C: Emerging Technologies*, Elsevier, v. 80, p. 485–511, 2017.

SAMÀ, M. et al. Scheduling models for optimal aircraft traffic control at busy airports: tardiness, priorities, equity and violations considerations. *Omega*, Elsevier, v. 67, p. 81–98, 2017.

SCALA, P.; MOTA, M. M.; DELAHAYE, D. Optimization and simulation based approach for an arrival and departure manager tool. In: IEEE. WINTER SIMULATION CONFERENCE, 2016. **Proceedings...** [S.l.], 2016. p. 3718–3719.

SESAR. *RPAS ATM CONOPS*. 2017. Available in: <https://www.eurocontrol.int/sites/default/files/publication/files/Brochure%20RPAS%20CONOPS.pdf>. Accessed in: February 2018.

SESSO, D. B. et al. An approach to assess the safety of ads-b-based unmanned aerial systems: Data integrity as a safety issue. *Journal of Intelligent & Robotic Systems*, Springer, v. 84, n. 1-4, p. 621–638, 2016.

SHAKHATREH, H. et al. Efficient 3d placement of a uav using particle swarm optimization. In: IEEE INTERNATIONAL CONFERENCE ON INFORMATION AND COMMUNICATION SYSTEMS (ICICS), 2017, 8. **Proceedings...** [S.l.: s.n.], 2017. p. 258–263.

SHI, Y. et al. Particle swarm optimization: developments, applications and resources. In: IEEE. CONGRESS ON EVOLUTIONARY COMPUTATION, 2001. **Proceedings...** [S.l.], 2001. p. 81–86.

SHMELOVA, T.; BONDAREV, D.; ZNAKOVSKA, Y. Modeling of the decision making by uav's operator in emergency situations. In: INTERNATIONAL CONFERENCE ON METHODS AND SYSTEMS OF NAVIGATION AND MOTION CONTROL (MSNMC), 2016, 4. **Proceedings...** [S.l.: s.n.], 2016. p. 31–34.

- SOOD, N.; WIELAND, F. Total airport and airspace model (taam) parallelization combining sequential and parallel algorithms for performance enhancement. In: WINTER SIMULATION CONFERENCE, 2003. **Proceedings...** [S.l.: s.n.], 2003. v. 2, p. 1650–1655 vol.2.
- SOTSKOV, Y. N.; SHAKHLEVICH, N. V. Np-hardness of shop-scheduling problems with three jobs. *Discrete Applied Mathematics*, Elsevier, v. 59, n. 3, p. 237–266, 1995.
- SUÁREZ, N. et al. Quantifying air traffic controller mental workload. In: FOURTH SESAR INNOVATION DAYS, 2014. **Proceedings...** [S.l.: s.n.], 2014.
- SUN, K.; ZHANG, X.; CAI, K. A new method of 4d trajectory generation in the airspace simulation system. In: IEEE. INTERNATIONAL CONFERENCE ON ELECTRONIC MEASUREMENT & INSTRUMENTS (ICEMI), 2009, 9. **Proceedings...** [S.l.], 2009. p. 4–472.
- SUNDAR, K. et al. Path planning for multiple heterogeneous unmanned vehicles with uncertain service times. *arXiv preprint arXiv:1702.07647*, 2017.
- SZU, H.; HARTLEY, R. Fast simulated annealing. *Physics letters A*, Elsevier, v. 122, n. 3-4, p. 157–162, 1987.
- TANG, K. et al. *Multiobjective optimization methodology: a jumping gene approach*. New York: CRC, 2012.
- TOY, J. *Complexity Metric Comparison Study for Controller Workload Prediction in 4D Trajectory Management Environments*. 2015. Available in: <https://repository.tudelft.nl/islandora/object/uuid:004fae47-161e-47e5-9df6-f030a732a08f?collection=research>. Accessed in: February 2018.
- TRA, M. et al. Modeling the intrinsic safety of unstructured and layered airspace designs. In: USA/EUROPE AIR TRAFFIC MANAGEMENT RESEARCH AND DEVELOPMENT SEMINAR (ATM2017), 2017, 12. **Proceedings...** [S.l.: s.n.], 2017.
- VELDHUIZEN, D. A. V.; LAMONT, G. B. Evolutionary computation and convergence to a pareto front. In: LATE BREAKING PAPERS AT THE GENETIC PROGRAMMING 1998 CONFERENCE, 1998. **Proceedings...** [S.l.: s.n.], 1998. p. 221–228.
- VOLF, P. Nas-wide simulation of air traffic with atc behavior model. In: IEEE. INTEGRATED COMMUNICATION, NAVIGATION, AND SURVEILLANCE CONFERENCE (ICNS), 2015. **Proceedings...** [S.l.], 2015. p. O3–1.
- WANG, J. et al. Integration of unmanned aircraft system (uas) voice communications into the faa national airspace (nas). In: IEEE. INTEGRATED COMMUNICATIONS, NAVIGATION AND SURVEILLANCE CONFERENCE (ICNS), 2017. **Proceedings...** [S.l.], 2017. p. 1E1–1.
- WARGO, C. A. et al. Enhancing uas pilot safety by terminal and airport shared information situational awareness. In: IEEE AEROSPACE CONFERENCE, 2017. **Proceedings...** [S.l.: s.n.], 2017. p. 1–12.

WASHINGTON, A. et al. Managing uncertainty in the system safety assessment of unmanned aircraft systems. In: AUSTRALIAN INTERNATIONAL AEROSPACE CONGRESS (AIAC), 2017, 17. **Proceedings...** [S.l.: s.n.], 2017. p. 611.

WEI, W.; DU, Q.; YOUNAN, N. H. Parallel optimization-based spectral transformation for detection and classification of buried radioactive materials. In: IEEE. IEEE NUCLEAR SCIENCE SYMPOSIUM AND MEDICAL IMAGING CONFERENCE (NSS/MIC), 2011. **Proceedings...** [S.l.], 2011. p. 373–376.

XIAOTIAN, E.; ZHANG, J. Holistic thinking and air traffic controllers' decision making in conflict resolution. *Transportation research part F: traffic psychology and behaviour*, Elsevier, v. 45, p. 110–121, 2017.

YANG, C. et al. Trajectory optimization for arrival aircraft using a hybrid ipso-sqp algorithm. In: IEEE. IEEE GUIDANCE, NAVIGATION AND CONTROL CONFERENCE (CGNCC), 2016. **Proceedings...** [S.l.], 2016. p. 2159–2163.

YOUNG, J. E. et al. Modeling weather in simulation and analysis. In: IEEE INTEGRATED COMMUNICATIONS, NAVIGATION AND SURVEILLANCE CONFERENCE (ICNS), 2013. **Proceedings...** [S.l.: s.n.], 2013. p. 1–11.

ZLOTOWSKI, J.; YOGESWARAN, K.; BARTNECK, C. Can we control it? autonomous robots threaten human identity, uniqueness, safety, and resources. *International Journal of Human-Computer Studies*, Elsevier, v. 100, p. 48–54, 2017.

APPENDIX A – COMPLEXITY

The Final Arrival Segment Optimization (FASO) problem considers that: (1) the pilots (human or not) are capable to execute the instructions provided by the ATCo; (2) one important metric apart from ATCo workload is the sequence duration; (3) the airspace constraints are respected (e.g. minimum aircraft separation and CB avoidance).

In this context, this problem can be represented as a particular machine scheduling problem. This problem refers to the scheduling n jobs on m machines in order to minimize the maximum completion time or mean flow time of jobs (SOTSKOV; SHAKHLEVICH, 1995). In order to represent the problem faced in this research to a particular machine scheduling problem, due to the fact that the following assumptions can be established (BIANCO; DELL'OLMO; GIORDANI, 1997):

- Each aircraft landing operation can be represented as a job;
- The IAF corresponds to a machine with capacity equals to one;
- The expected time in which a given aircraft k reaches the IAF corresponds to the ready time r_j of job k ;
- The actual time in which the aircraft k reached the IAF corresponds to the start time of job k ;
- The time the aircraft k intercepts the IAF corresponds to the completion time C_k of job k ;
- The minimum interval between the IAF interception of aircraft k and aircraft i , which is illustrated as the physical minimum separation of 5nm, corresponds to the sequence dependent processing time c_{ki} .

According to (BIANCO; DELL'OLMO; GIORDANI, 1997), the problem of scheduling considering ready times (which is associated with a estimation of the time that the aircraft

may reach the IAF) and sequence dependent processing time (which is illustrated by the aircraft minimum separation) on a single machine in order to minimize the sum of completion times can be stated as: consider a set $J = \{j | j = 1, 2, \dots, n\}$ of n jobs that must be processed in a single machine and, for each job j , a ready time r_j (represented in this research by the estimation of the time that the aircraft may reach the IAF) and the dependent processing time (represented, in this research, by the aircraft minimum separation) are, respectively, given and dependent on the job position in the sequence (i.e. dependent on the position of the aircraft in the final sector).

In this context, c_{ji} represents the time required by the machine for processing job j immediately before job i (in this research, this is illustrated by the time spent by the aircraft to travel, at least, 5nm due to the fact that this is the minimum separation between two aircraft is the minimum interval the IAF is reached). Finally, considering C_j the completion time of the job j (in our case, the time in which the aircraft intercepts the IAF), the problem considered is to define a schedule that minimizes the total completion time $\sum_{j=1}^n C_j$ (i.e. the minimization of the delivery of all aircraft to the IAF).

As the machine schedule problem has been proved to be NP-hard in (SOTSKOV; SHAKHLEVICH, 1995) and as a solution for a particular machine scheduling problem can be translated in a solution for the problem faced in this research, it is reasonable to consider that our proposal deal with an NP-hard problem (SAMÀ et al., 2017b) (MARINAKIS et al., 2017) (JI; FANG; YAN, 2014).

Moreover, as this problem may not be simple to solve due to its complexity and its the number of possibles solutions (feasible or not) present in the search space, enumerative and deterministic approaches may not be appropriate. The non-deterministic approaches (e.g. PSO), on the other hand, are appropriate for dealing with more complex problems that consider great search regions. Finally, in this research, we consider the usage of a non-deterministic optimization method, the Particle Swarm Optimization (PSO), for dealing with this problem.

APPENDIX B – TRAJECTORIES OF THE AIRCRAFT IN THE EXPERIMENTS

The trajectories, of all aircraft, in the case studies presented in this work are illustrated in this appendix. Firstly, the trajectories of the case study I are presented. Then, the trajectory case study II are illustrated. Finally, the trajectories of the case study III are shown.

B.1 Case Study I

The trajectories of the aircraft, in the case study I, considering the ages 1, 2 and 3 are illustrated, respectively, in Figures 58, 59 and 60. Note that the initial position of the RPAS, MA and AA are, respectively, (2, 25), (15, 15) and (5, 5).

The solution provided by FASOM considering the age 1, which is illustrated in Figure 58, can be described as follow:

- MA
 - **Additional Vectoring Points (VPs):** (9.19, 20.7)
 - **TML:** 10
- RPAS
 - **Additional Vectoring Points (VPs):** (11.08, 28.5)
 - **TML:** 6
- AA
 - **Additional Vectoring Points (VPs):** —

– **TML: 0**

Figure 58: Solution provided by FASOM in case study I (age 1).

Source: The author.

The solution provided by FASOM considering the age 2, which is illustrated in Figure 59, can be described as follow:

- **MA**
 - **Additional Vectoring Points (VPs):** (6.5, 19.79)
 - **TML: 10**

- RPAS
 - Additional Vectoring Points (VPs): (6.5, 29.11)
 - TML: 10
- AA
 - Additional Vectoring Points (VPs): —
 - TML: 6

Figure 59: Solution provided by FASOM in case study I (age 2).

Source: The author.

The solution provided by FASOM considering the age 3, which is illustrated in Figure 60, can be described as follow:

- MA
 - **Additional Vectoring Points (VPs):** —
 - **TML:** 6
- RPAS
 - **Additional Vectoring Points (VPs):** (7.61, 27.75)
 - **TML:** 6
- AA
 - **Additional Vectoring Points (VPs):** (11.2, 10.2)
 - **TML:** 10

Figure 60: Solution provided by FASOM in case study I (age 3).

Source: The author.

B.2 Case Study II

The trajectories of the aircraft, in the case study II, considering the ages 1 2 and 3 are illustrated, respectively, in Figures 61, 62 and 63. Note that the initial position of the AA1, AA2, RPAS and MA are, respectively, $(20.5, 29.95)$, $(23.9, 35.34)$, $(19.6, 1.2)$ and $(24.55, 4.7)$.

The solution provided by FASOM considering the age 1, which is illustrated in Figure 61, can be described as follow:

- AA1
 - Additional Vectoring Points (VPs): (23.9, 35.3)
 - TML: 0
- AA2
 - Additional Vectoring Points (VPs): —
 - TML: 0
- RPAS
 - Additional Vectoring Points (VPs): (14.7, 16.9)
 - TML: 6
- MA
 - Additional Vectoring Points (VPs): (23, 18.5)
 - TML: 10

Figure 61: Solution provided by FASOM in case study II (age 1).

Source: The author.

The solution provided by FASOM considering the age 2, which is illustrated in Figure 62, can be described as follow:

- AA1
 - Additional Vectoring Points (VPs): (15.5, 12)
 - TML: 6

- AA2
 - Additional Vectoring Points (VPs): —
 - TML: 6
- RPAS
 - Additional Vectoring Points (VPs): (30, 19.4)
 - TML: 10
- MA
 - Additional Vectoring Points (VPs): (26.1, 19.4)
 - TML: 10

Figure 62: Solution provided by FASOM in case study II (age 2).

Source: The author.

The solution provided by FASOM considering the age 1, which is illustrated in Figure 63, can be described as follow:

- AA1
 - **Additional Vectoring Points (VPs):** (26.6, 14.4)
 - **TML:** 10

- AA2
 - Additional Vectoring Points (VPs): (6.28, 37.9)
 - TML: 10
- RPAS
 - Additional Vectoring Points (VPs): —
 - TML: 6
- MA
 - Additional Vectoring Points (VPs): (19, 0.8)
 - TML: 6

Figure 63: Solution provided by FASOM in case study II (age 3).

Source: The author.

B.3 Case Study III

The trajectories of the aircraft, in the case study III, considering the ages 1 2 and 3 are illustrated, respectively, in Figures 64, 65 and 66. Note that the initial position of the RPAS1, RPAS2, MA1, MA2 and AA are, respectively, (27.5, 27.95), (17.45, 29.95), (16.2, 0.6), (16.5, 15.05) and (27.35, 2.25).

The solution provided by FASOM considering the age 1, which is illustrated in Figure

64, can be described as follow:

- RPAS1
 - **Additional Vectoring Points (VPs):** (16.5, 1.4)
 - **TML:** 6
- AA
 - **Additional Vectoring Points (VPs):** —
 - **TML:** 0
- MA1
 - **Additional Vectoring Points (VPs):** (12.9, 21.8)
 - **TML:** 10
- RPAS2
 - **Additional Vectoring Points (VPs):** —
 - **TML:** 6
- MA2
 - **Additional Vectoring Points (VPs):** (7.4, 19.9)
 - **TML:** 10

Figure 64: Solution provided by FASOM in case study III (age 1).

Source: The author.

The solution provided by FASOM considering the age 1, which is illustrated in Figure 65, can be described as follow:

- RPAS1
 - **Additional Vectoring Points (VPs):** (35.5, 24)
 - **TML:** 10

- AA
 - Additional Vectoring Points (VPs): —
 - TML: 6
- MA1
 - Additional Vectoring Points (VPs): —
 - TML: 10
- RPAS2
 - Additional Vectoring Points (VPs): (33.5, 27.1)
 - TML: 10
- MA2
 - Additional Vectoring Points (VPs): (21.3, 28.1)
 - TML: 10

Figure 65: Solution provided by FASOM in case study III (age 2).

Source: The author.

The solution provided by FASOM considering the age 1, which is illustrated in Figure 66, can be described as follow:

- RPAS1
 - Additional Vectoring Points (VPs): (13.7, 38)
 - TML: 6

- AA
 - Additional Vectoring Points (VPs): —
 - TML: 10
- MA1
 - Additional Vectoring Points (VPs): —
 - TML: 6
- RPAS2
 - Additional Vectoring Points (VPs): (20.7, 2.7)
 - TML: 6
- MA2
 - Additional Vectoring Points (VPs): (6.2, 31.2)
 - TML: 6

Figure 66: Solution provided by FASOM in case study III (age 3).

Source: The author.