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Swarm-Based Optimization of Final Arrival Segments Considering the UAS Integration in the National Airspace System

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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 in the National Airspace System (NAS), safety challenges regarding this insertion arise from the inclusion of new ways of reaching unsafe states. Although UAS may be used in different situations and brings several advantages to the airspace (e.g., efficiency), it may bring uncertainties due to the lack of familiarity of Air Traffic Controllers (ATCos) in these operations. Furthermore, the Terminal Maneuvering Area (TMA) is a critical control area generally established at the confluence of Air Traffic Service (ATS) routes in which the aircraft tend to be closer to each other. Besides, defining a final arrival segment for a set of aircraft in a complex environment is challenging. Thereupon, the main objective of this research is to propose a parallel swarm-based method for optimizing final aircraft arrival segment design (i.e., routes that connect the final sector to the Initial Approach Fix - IAF) considering the presence of aircraft of multiple Technology Maturity Levels (TML) - including the UAS. 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 using the Technology Maturity Levels (TMLs). Finally, the solutions consider airspace restrictions (e.g., minimum separation between aircraft and bad weather conditions). The experiments conducted show that this approach can build safe and efficient solutions, even in situations with many aircraft.

INDEX TERMS Evolutionary computing, particle swarm optimization, unmanned aircraft systems (UAS), air traffic controller (ATCo), ATCo workload, airspace efficiency.

I. INTRODUCTION

Air transportation is essential for society, and it is increasing steadily due to its importance [31]. The growth in flights number leads to higher revenue despite making the airspace more complex. In fact, there are many challenges to be faced by authorities in the following years regarding safety and efficiency of airspace. In this context, Air Traffic Control (ATC) plays a vital role in optimizing airspace, especially considering that safety and efficiency are critical aspects of airspace operation [15]. The ATC is divided into ATC units, which represent "area control center, approach control unit or aerodrome control tower" [19]. These units are organized to accommodate all airspace users creating sectors. The role of controlling aircraft in each control sector is currently played by Air Traffic Controllers (ATCo). The ATCo responsible for a given sector must communicate with ATCos responsible for other sectors to provide smooth conduction of aircraft throughout their flights.

The ATCo aims to offer appropriate safety and efficiency levels and solve issues present in complex situations. Moreover, ATC provides Air Traffic Services (ATS) to flights through ATCo instructions. These services' main goals include avoiding mid-air collisions, collisions with obstructions and optimizing and maintaining an orderly flow of the air traffic [20]. 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 aircraft vectoring. Indeed, many of these professionals act collaboratively on each flight. As these flights evolve through

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their plans and reach the sectors' limits, new ATCos are assigned for controlling them. However, a challenge currently faced is to maintain the workload[1] level below an acceptable threshold.

Moreover, UAS plays an important role due to the advantages they bring to the airspace (e.g., efficiency) [13]. These systems have been considered a relevant topic in the engineering community [11] and are composed of subsystems. For example, Unmanned Aerial Vehicle (UAV), payloads, control station, and communications sub-systems [4], [11]. As there are different types of UAS (e.g., Autonomous Aircraft - AA - and Remotely Piloted Aircraft Systems - RPAS), there are subsystems that compose some types but not others. For example, the ground station at which the pilot communicates with RPAS is not part of AA, which is a fully autonomous aircraft.

The Terminal Maneuvering Area (TMA), which composes the controlled airspace, is a critical control area generally established at the confluence of Air Traffic Service (ATS) routes in the vicinity of one or more major aerodromes [17] 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 [23]. Its complexity increases according to the airspace configuration (e.g., traffic density and weather conditions). Thus, operations in this particular area are performed carefully, and standard procedures are established to achieve desirable safety and efficiency levels. For example, the Standard Instrument Departure (SID) and the Standard Terminal Arrival Route (STAR).

However, there are situations in which such standard procedures cannot be followed (e.g., 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 [1], [18]. 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 adverse weather conditions (e.g., flight through cumulonimbus - CB -, which are cloud formations that present a real impact on aviation [12]). Finally, defining a final arrival segment leads a set of aircraft from the final sector of the TMA to the final phase of their landing procedures (i.e., the final approach), considering the operation efficiency and safety.

Thereupon, the main goal of this research is to propose a parallel swarm-based method for optimizing final arrival segment design considering the presence of aircraft of multiple Technology Maturity Levels (TML) - including the UAS. 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). Besides, different UAS integration phases are considered, i.e., from the early stages to a mature stage of its operation. Finally, the solutions consider airspace restrictions such as the minimum separation between aircraft and adverse weather conditions, i.e., the presence of cumulonimbus (CB). Hence, the main contributions of this research are (i) the adoption of a novel approach to measuring the integration of UAS in the National Airspace System (NAS), (ii) an optimization method based on the Particle Swarm Optimization (PSO) for designing landing trajectories considering the UAS presence, and (iii) interfaces for applying the optimization model in external applications.

This paper is organized as follows: Section II presents the related works. Sections III shows the concepts related to arrival sequencing and scheduling. After that, Section IV presents the aspects of the Technology Maturity Levels (TML) and the integration of the Unmanned Aircraft System (UAS). Then, Sections V and VI highlight the Particle Swarm Optimization (PSO) and Final Arrival Segment Optimization Model (FASOM), respectively. Thereupon, Sections VII and VIII show, respectively, the case studies and the discussions on the results achieved. Finally, Section IX presents the conclusions of this research.

II. RELATED WORKS

The authors in [14] present a cooperative multi-aircraft Conflict Resolution (CR) method based on co-evolution. The paths are composed of sub-populations considered in a Particle Swarm Optimization (PSO) implementation. The fitness is evaluated by the cooperation among individuals from different sub-populations. This approach brings advantages as fewer parameters and computation and faster convergence. Note that each particle is seen as a point of D-dimension space. Further, an encoding method with an adaptive searching mechanism is introduced to improve the searching efficiency. Compared with Genetic Algorithms (GA) currently used for conflict resolution and path optimization, the results from such approach 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.

Samà *et al.* [41] deals with the TMA aircraft scheduling problem, which requires conflict-free schedules for all aircraft while the overall aircraft delays are minimized. Furthermore, this research also deals with the aircraft landing trajectory optimization problem, which requires a 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. It solves the two problems sequentially based on 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 with simulated Milano

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[1] Workload can be defined as a metric that represents the difficulty of ATCo in understanding a particular situation [32] and can be expressed in terms of seconds.

Malpensa airport instances and considering different optimization lexicographic orders and performance indicators, show performance gaps between the optimized indicators of the two problems. This highlights the multi-objective nature of the problem when different lexicographic optimization approaches are considered.

Ahmed *et al.* [1] 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). The paths are built to guide the aircraft from the Initial Approach Fix (IAF) to the FAF considering intermediate waypoints called Intermediate Fix (IF). 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 [40], the authors proposed mixed-integer linear programming formulations to optimize, in 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 (e.g., in the major European airports) since 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 selecting solutions that present considerable quality in balancing the various Key Performance Indicators (KPIs).

Alonso-Ayuso *et al.* [3] 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 by 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 a short computing time. Furthermore, a comparison between the results from using the state-of-the-art MINO solvers and SMILO performance in a broad testbed is also considered, which showed that both presented similar solutions, but the proposed approach requires a minimal computing time. Finally, the authors highlight that for large-size instances (e.g., above five aircraft), the computing time is higher than the one required by real-life operational applications. Other meta-heuristics can minimize the computing time without deteriorating the SMILO solution as a future research line. However, this research does not consider the operation of UAS into the non-segregated airspace.

Marinakis *et al.* [30] 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 a different equation for the velocities update of particles is considered in the proposed algorithm, 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, many continuous local search algorithms are used and tested in many modified instances, 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.

Although there are also initiatives dealing with complex control problems in different fields (e.g., [16], [24], and [47]), our primary goal is to propose a parallel swarm-based method for optimizing final arrival segment design considering the presence of aircraft of multiple Technology Maturity Levels (TML).

III. ARRIVAL SEQUENCING AND SCHEDULING

The sector in which the aircraft intercept the Initial Approach Fix[2] (IAF) is called the Final Sector (FS). All aircraft are slower in this sector than in other sectors of the airspace (about 180kts[3]). In fact, the height is reduced (around 6000ft[4]). In common operations, all aircraft are expected to enter this sector with a considerable space between them, enabling the ATC to conduct them more simply to the IAF. Indeed, IAF is the fix the aircraft must reach to start the final approach procedure.

However, in complex situations, this sector may receive many aircraft at the same time and with nearly-minimum separations. Also, the Final Sector (FS) may present challenges in weather conditions with cumulonimbus (CBs).

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[2] Fix can be defined as a type of a point on the surface of the earth located at a specific geographical location (i.e., at a specific position) that simplifies the conduction of aircraft as well as the separation maintenance [19].

[3] $1kt = 1.852\ kilometers/hour$.

[4] $1ft = 0.3048m$.

These factors tend to turn the sequencing and scheduling of these aircraft into a very challenging activity due to its complexity and the need for quick solutions.

Regarding airspace operation, severe weather is an important factor that results in flight delays [12], [25]. For example, estimating the capacity of a set of sectors in a given airspace region during weather events is an important part of air traffic management [33]. In this context, the definition of trajectories that avoid these adverse situations is desired. An important player in bad weather conditions is the cumulonimbus (CB).

CB [9] 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. 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 [9], [26].

The size of these cloud formations may vary widely. However, the CB is faced as a circle in a 2D environment with a radius of 2 Nautical Miles (nm). This size is adopted once it is a reasonable size for a CB, according to specialists consulted. Moreover, this value is intended to be changed during the fine-tuning process of future works. Furthermore, in this research, we consider the clouds to be fixed in a specific position since, during the initial phase of the aircraft approach, there are small variations in their positions.

Thereupon, the components of the problem faced in this research are illustrated in Figure 1. The black point represents the aircraft from a macro perspective. The blue circle represents the minimum separation of the aircraft - if any other aircraft does not respect this separation, the provided solution is unfeasible. The red circle illustrates the cumulonimbus - i.e., a restricted region due to its severe weather condition. The green square represents additional Vectoring Points (VPs) that can be assigned to the aircraft. Finally, the red square illustrates the Initial Approach Fix (IAF), i.e., the aircraft's final objective point.

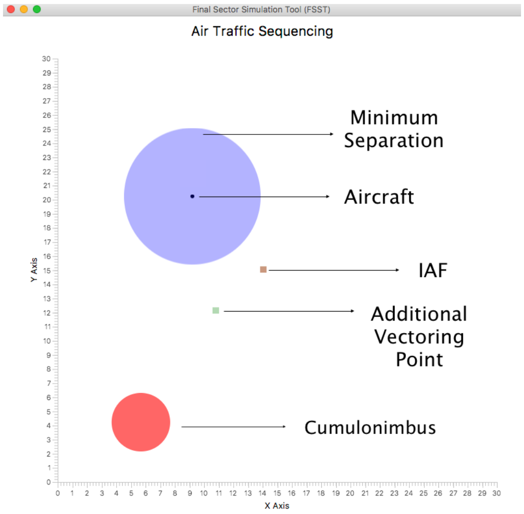

FIGURE 1. Components of the problem faced in this research.

IV. TECHNOLOGY MATURITY LEVEL (TML) AND UNMANNED AIRCRAFT SYSTEM (UAS)

The Technology Readiness Level (TRL) is 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." It has been used in NASA space technology planning and NASA Management Instruction [28]. This scale measures how far a given technology is from its operation in the airspace and is appropriate for supporting the integration of new technologies smoothly by identifying at which development level a particular technology is. From this standpoint, new and disruptive technologies tend to present an additional cognitive workload for ATCo due to the lack of familiarity. The increase in the time spent on cognitive activities may lead to an increase in the planning process. Furthermore, the additional cognitive workload may also affect the time spent in surveillance. For example, UAS is a disruptive technology that lacks operation in the National Airspace System (NAS), which leads to a lack of liability, social acceptance, and operational experience.

The Technology Maturity Level (TML) is 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 proposed by the authors [5], [37]. This scale is based on three main factors that represent barriers for autonomous vehicles in general to operate [2], [5], [10]: (i) Liability; (ii) social acceptance; and (iii) operational experience. The levels vary from 0 up to 10 and represent familiarity, which may increase throughout the years of aircraft operation (i.e., considering the increase of liability, social acceptance, and operational experience). Thus, the aircraft may be referred to as its TML to simplify the workload evaluation. TML is related to the uncertainty of operations and the fragility is a product of complexity by uncertainty [29]. In this context, TML is related to the uncertainty in operation, whereas fragility is related to impacts on the ATCo workload and, ultimately, on safety levels.

For example, a particular case of the TML concept application relies on the insertion of the Unmanned Aircraft System (UAS) in the National Airspace System (NAS). The UAS represents a vital business direction considering its potential and applications [11]. This is a system composed of sub-systems (e.g., Unmanned Aircraft Vehicle (UAV), payload, control station, and communications sub-systems [4], [11]) and has been employed in different scenarios. Many advantages can also be achieved from the UAS operation (e.g., reducing the operation risks) [13], and some mission requires its insertion in the National Airspace System (NAS). However, this integration may present issues such as impacts on safety levels. Thereupon, the ATCo workload is defined and measured by the interaction of several factors [35], [37] and represents the difficulty of ATCos in dealing with a particular situation [32]. Indeed, elevating the ATCo workload might lead the airspace to unsafe states [7], [27], [48].

V. PARTICLE SWARM OPTIMIZATION (PSO)

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 [22]. This research adopts the PSO due to its high-performance and flexibility. This method has become a candidate for many optimization problems with successful applications [6], [42], [45]. The movement of each particle during the PSO execution considers their current velocity, the current best solution found by the particle (cognitive influence, i.e., the influence of the experience of the particle itself), and the current best solution found by the swarm (swarm influence, i.e., the influence of the experience of the whole set of particles) [6]. In this context, two attributes drive the PSO operation: *pbest* (particle best), which is an attribute of each particle and represents the current best solution achieved by that particle, and *gbest* (global best), which is an attribute of the PSO and represents the current best global solution, i.e., the best solution achieved by all particles. Thus, the concept of fitness, employed in all evolutionary computation paradigms, is adopted [22].

The process of updating the velocities and the positions of each particle are respectively presented in Equations 4 and 5 [43]. To update the velocity for a given decision variable of a given particle p_i, three aspects are considered: inertia (Equation 1), cognition (Equation 2) and the social aspect (Equation 3). In this sense, parameter i identifies which particle is being considered, whereas the d represents the dimension of the particle considered.[5] Note that $rand()$ represents a function that generates a random number between 0 and 1 from an uniform distribution.

$$\lambda_{id} = \underbrace{w \times v_{id}}_{Inertia} \tag{1}$$

$$\alpha_{id} = \underbrace{c_1 \times rand() \times (pbest_{id} - x_{id})}_{Cognitive} \tag{2}$$

$$\theta_{id} = \underbrace{c_2 \times rand() \times (gbest_d - x_{id})}_{Social} \tag{3}$$

$$v_{id} = \lambda_{id} + \alpha_{id} + \theta_{id} \tag{4}$$

$$x_{id} = x_{id} + v_{id} \tag{5}$$

The solutions exploration process is illustrated in Figure 2. These approach uses special features alongside the traditional PSO version. The first state considers all aircraft flying directly to the IAF - i.e., a solution without searching. In this context, a generation is a set of states composed of the same number of decision variables in total. The first state composes the generation 1, which does not present decision variables. If this is a feasible solution in terms of airspace constraints (minimum separation and CBs), the PPSO execution is finished with an optimal solution.

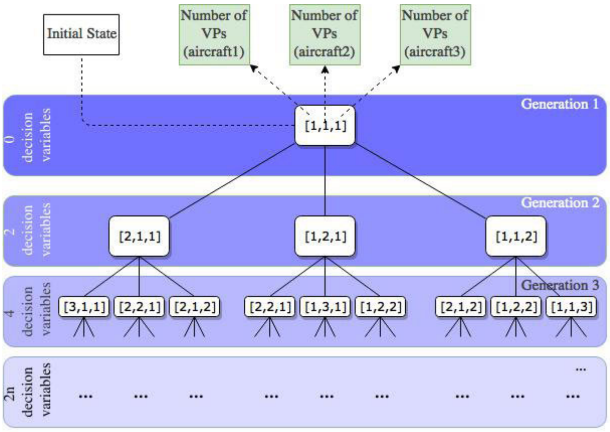

FIGURE 2. State generations and their decision variables.

In a situation where the position of the CB forces the aircraft to consider an alternative trajectory, additional VPs are required. The new generation (generation 2) is composed of three elements. All the states of generation 2 present two decision variables to be considered in the PPSO operation. Along with the parallel processing of critical steps within the PPSO execution, the evaluation of each state is also performed in separate threads. Hence, the algorithm creates new state 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.

Furthermore, the position of the particle is updated (Equation 5). The current position x_i of particle p_i is added to the new velocity v_i,[6] considering all the components of this vector, i.e., this sum is conducted considering all decision variables d. The execution of PSO is based on the following steps: Firstly, the required parameters are set. Secondly, the initial positions and velocities of each particle are randomly generated, and the iteration count (g) is set to 0. Then, if the current solution is non-dominated[7] considering the objective function, this is added to the Pareto-optimal solutions set. This step is optional and may vary widely depending on the objective function. For example, one may consider all feasible solutions to be added to analyze the proposed solutions further. Finally, if the integration count (g) equals the iteration limit, the set of solutions found is returned.

Moreover, the Parallel Particle Swarm Optimization (PPSO), or Synchronous PPSO, is a method based on the

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

[6] Note that, in PSO, the velocity represents how a particle changes its position in a given iteration and is an abstraction of the physical velocity, i.e., as this is a dimensionless value, it can be summed to the current position.

[7] A 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) solution x_i is not strictly better than x_k in at least one objective [36].

traditional PSO but considers parallel processing for reducing the execution time [46]. This manner of implementing the PSO is adopted herein once there is a need for short response times in the problem faced. As it may take some time to process all particle characteristics, especially if the number of particles is large, parallel processing enables the search to be performed quickly. In this sense, the achievement of the benefits provided by parallel execution depends on the computer's processing power, i.e., a computer that cannot process multiple threads may not present significant improvements in performance if executing a parallel application. To implement parallel algorithms in Java language, one should consider using the Java Threading Application Programming Interface (API) [38]. This API enables the user to build and process different threads (using Thread class) in a parallel fashion.

The PPSO execution process is very similar to the traditional PSO implementation. However, two steps are executed in parallel: (i) the quality (or fitness) evaluation ("Objective value evaluation") and (ii) the positions and velocities update ("Get the new positions and velocities of particles"). These two stages are bottlenecks of the PSO execution and the employment of multiple threads for conducting independent computations in parallel may reduce the algorithm response time considerably. Finally, other architectures can be explored in future works, such as parallel processing islands.

VI. FINAL ARRIVAL SEGMENT OPTIMIZATION MODEL (FASOM)

In this Section, we introduce the Final Arrival Segment Optimization Method (FASOM) for optimizing aircraft sequencing in the final sector, considering the UAS presence and different Technology Maturity Levels (TMLs). Firstly, considerations on the Final Arrival Segment Optimization (FASO) are presented. Secondly, the architecture of the FASOM is shown. Finally, a discussion on topics related to the solution selection module is presented.

A. CONSIDERATIONS

In this section, we present the considerations that must be highlighted regarding the optimization process. Firstly, we present the problems that may occur in the airspace and, consequently, should be avoided in the solutions provided in the optimization process. Finally, the definitions of feasible and infeasible solutions are provided.

1) THE PROCESS OF OPTIMIZING AIRCRAFT SEQUENCING

The main goal of the optimization process is to provide safe and efficient solutions for given situations in the airspace. Figure 3 shows the characteristics of the problem faced. Firstly, the aircraft may enter the sector from different points. After that, all aircraft have objective positions to reach (IAF) at a time interval (deadline). In some cases, the final sector may have more than one IAF and aircraft coming from different directions may be assigned to different IAFs.

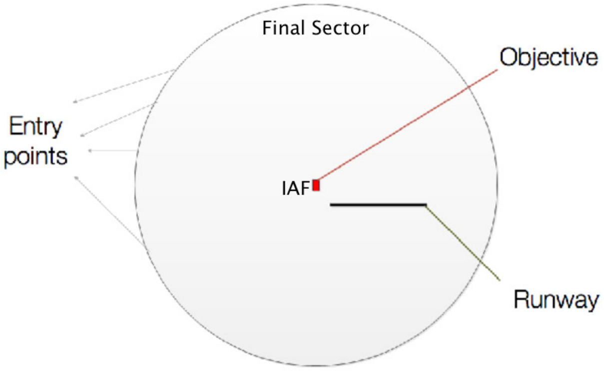


FIGURE 3. Sequencing in the final sector.

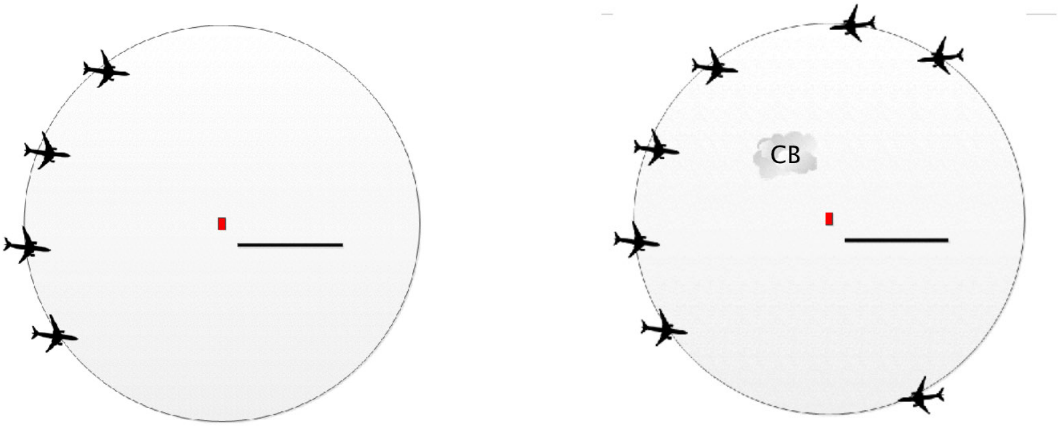
Figure 4 depicts the difference between two given scenarios that might be faced in the airspace. The first is composed of four aircraft that share the same IAF. The second case presents a more complex environment. The number of aircraft is increased to seven and a there is a CB nearby the IAF. These scenarios become complex due to the number of aircraft and the factors that harden the their delivery to the highlighted IAF.

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. Possible solutions for both scenarios can present different levels of ATCo workload depending on the Technology Maturity Level (TML) of each aircraft.

In fact, the priority of each aircraft presents a considerable impact on sequencing solutions. From the ATCo workload standpoint, the TML of each aircraft indicates which of them must be prioritized. For example, if an aircraft presents a lower TML (e.g., UAS currently operating in the NAS) 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 establishing vectoring points for the others, which present a higher TML. Establishing additional VPs for aircraft with higher TMLs tends to present a lower ATCo workload than establishing additional VPs for aircraft with lower TMLs. Indeed, 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 the efficiency (respecting the safety constraints, such as minimum separation).

2) SOLUTION DEFINITION

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



(a) Scenario I (b) Scenario II

FIGURE 4. Comparison between two scenarios of different complexities.

Moreover, the representation of solutions in these environments can be expressed as in Equations 6, 7 and 8. The sequencing solution, i.e., the set of final arrival segments, is presented in Equation 6. A final arrival segment for a given aircraft can be defined as a collection of Vectoring Points (VPs) that guides the aircraft from the final sector's entry to the IAF.

$$S = [segment_1, segment_2, \ldots, segment_m], \tag{6}$$

The segments are defined in terms of the number of aircraft in the situation, i.e., m represents the index of the last aircraft and, consequently, the number of aircraft. The segments are presented in Equation 7. 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 given that $1 \leq k \leq m$, $n_k > 0$, $vp^k_{n_k} = IAF_k$. Each vectoring point is expressed as a tuple (x,y) into the Cartesian plane and the last vectoring point assigned to each aircraft ($vp^k_{n_k}$) represents the IAF assigned to it.

$$Segment_k = [vp^k_1, vp^k_2, \ldots, vp^k_{n_k}] \tag{7}$$

Finally, Equation 8 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.

$$state = [n_1, n_2, \ldots, n_m] \tag{8}$$

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) composing the aircraft segment in a given situation. Each element of the state refers to the number of VPs assigned to each aircraft. In this context and from the workload evaluation standpoint, it is reasonable to consider IAF as VP since the ATCo must act, communicate with, and monitor the aircraft conducted to the IAF. In fact, in vectoring, the ATCo must guide the aircraft to this point using an additional VP.

Finally, the problem faced in this research considers that: (1) pilots (human or not) are capable of executing 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 can thus be faced as a machine schedule problem, which has been proved to be NP-hard in [44]. Furthermore, it is reasonable to consider that our proposal deals with an NP-hard problem [21], [30], [39].

B. ARCHITECTURE

To appropriately achieve the desired results in the optimization process, different responsibilities should be assigned to different modules. For example, the optimization process is different from the process of input reading and should be performed in different parts of the system. In order to accomplish this, Figure 5 depicts the FASOM architecture.

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

1) AIRSPACE BUILDING

The first module of FASOM is the Airspace Building Module. Its main goal is to receive external data and transform it into a format the Optimization Module can understand, i.e., this module acts as an interface. Firstly, a JSON file is provided with the data needed to build the airspace (i.e., the JSON file describes the scenario), 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.

2) OPTIMIZATION

The second and intermediate module is the Optimization Module, in which the actual optimization process is executed.

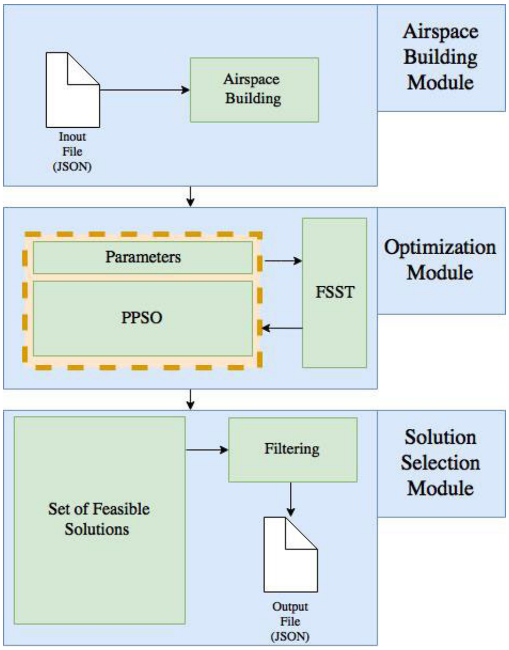


FIGURE 5. **Architecture of the final arrival segment optimization model (FASOM).**

It aims to offer feasible solutions in terms of aircraft sequencing, considering the input data provided. The optimization method adopted in this research, the Parallel Particle Swarm Optimization (PPSO), is employed to achieve this set of feasible solutions considering parameter variation. This method is adopted due to its high-performance in several applications (optimization tasks) and its advantages in comparison to other techniques, such as Evolutionary Algorithms (EA) and Genetic Algorithms (GA) [6], [8], [43], [45]. Indeed, PSO has presented good results, but this depends on the characteristics of the problem and the parameters' configuration. In some problems, EA and GA may outperform the PSO in terms of the solution's quality and search efficiency.

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

- **Search Duration:** 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:** iterations for particle shuffling;
- **Vectoring points per aircraft:** Limit for the path building in terms of VPs.

One suitable manner of performing the optimization process is using states, which are collections of the number of VPs composing the aircraft segments in a given situation, as presented in Section VI-A2. Regarding a state-driven optimization process, the search must consider a different state at the time, i.e., the number of VPs assigned to each aircraft must remain the same during part of the PSO execution. For example, considering the state [1, 2] for a situation with two aircraft, different solutions (feasible or not) can be provided. In this sense, we search for 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, other states are considered in the search if there are no solutions provided by the method. There is a need for a short response search to explore different states to find feasible solutions. 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., defining a specific deadline is necessary to ensure 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, which limits the duration execution in milliseconds of the search within a state. This parameter is considered for all the states explored. The second parameter is the iteration slice, representing the number of iterations of the PSO for shuffling the positions and velocities of all particles. The traditional PSO and PPSO do not include this shuffling process, but we include it to avoid local optima. Sometimes, reasonable solutions may retain particles around a specific region into the search space. However, better solutions may also be found in other regions. For example, suppose all particles are located around an area distant from 0 in all the axes with a set of good solutions. In that case, even if much better solutions are located around the beginning of all axes (i.e., an area near to 0 in all axes), 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 prevents the particles from moving around a limited region in the search space and facilitates exploring different areas (that may present better solutions than those already discovered). This process consists of changing the position and velocities of the particles considering random values. Thus, the particle tends to search in different regions of the search space.

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

The optimization process evolves accordingly to the process depicted in Figure 2. In this case, the feasibility and quality of the proposed solutions are evaluated by the FSST, as illustrated in Figure 5. For each solution provided, verification of its quality and feasibility is performed. This figure shows the PPSO approach within an orange box. This indicates that the PPSO could be replaced by other methods (e.g., Genetic Algorithms). This highlights that extensions of this research might consider different techniques. Finally, a set of feasible solutions is provided in appropriate data structures to the next module (i.e., the solution selection module).

C. SOLUTION SELECTION

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 National Airspace System (NAS) may make the controlling process more difficult, impacting 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 to measure the quality of different solutions.

In this context, Equations 9 and 10 shows the objective functions (f_1 and f_2) adopted in this research. The former 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. Function f_1 is thus defined in terms of the numbers of VPs (nVP_i) assigned to the 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.

$$Min\, f_1 = \sum_{i=1}^{m} nVP_i \times W_{TML_i} \tag{9}$$

The latter refers to the sequencing duration. Function f_2 is defined in terms of distance d_l traveled by the last aircraft delivered l. A speed of 180 knots is considered for all aircraft since the operation takes place within the final sector.

$$Min\, f_2 = \frac{d_l}{180kts} \tag{10}$$

Finally, the process of ordering the solution in the solutions set and then picking the most appropriate solution is conducted considering Equation 11. In this equation, α and β respectively represent the weight associated with the minimization of f_1 (workload) and the weight associated with the minimization of f_2 (duration). These values vary from 0 to 1 ($\alpha + \beta = 1$). Besides, these values are defined by the user of the optimization tool, i.e., the end-user may prioritize workload or efficiency in the solution selection. Finally, the f_3 enables to choose one solution combining Equations 9 and 10. Furthermore, 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 [34] to be used in the same equation. Note that 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 prevent the result from being infinite in cases in which the maximum value is equal to the minimum value.

$$Min\, f_3 = \alpha \frac{f_1^k - min(f_1)}{1 + (max(f_1) - min(f_1))} + \beta \frac{f_2^k - min(f2)}{1 + (max(f_2) - min(f2))} \tag{11}$$

VII. CASE STUDIES

This Section 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 herein can solve several situations in the final sector, considering the airspace constraints. For all the case studies, the objective function illustrated in Equation 11 is used.

As we aim at adopting the optimization process in a balanced way, in which α and β are set to 0.5, i.e., they have the same priority for the solution selection.[8] This approach is considered for achieving solutions with good results in both objectives, but these values can be adjusted according to the user's preferences (e.g., regulatory authorities). Thus, f_1 is related to the ATCo workload, whereas f_2 is related to the sequencing duration. For example, if 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.

However, the goal herein is to show the applicability of the proposed strategy. Thus, parameters c_1, c_2 and w of PSO are all set to 1. This highlights that all aspects have the same priority during the particles' position and velocity update. Besides, the influence of each PSO parameter is also in the scope of future works. Moreover, the number of particles within the swarm increases by 50 for each additional decision variable.

The evaluation of the solutions provided is performed using the Final Sector Simulation Tool (FSST) [37]. This simulation platform aims to evaluate the ATCo workload and efficiency in aircraft sequencing in the final sector considering the UAS presence. This tool also considers the Technology Maturity Level (TML) for measuring the workload related to each aircraft, which is evaluated based on the number of Vectoring Points (VPs) assigned to each aircraft and its TML. Furthermore, the feasibility of the solutions is also verified, considering the minimum aircraft separation requirements and CB avoidance. In this research, the minimum aircraft separation adopted is 5NM, and the CB is considered to be a circle in a 2-dimensional space with a radius of 2NM.

The evolution of TML throughout ages is presented in Table 1. Each age represents a specific era in terms of UAS acceptance, i.e., this does not represent one single year, but a period reasonably longer than that. The values present in this Table are parameters to our method validated with specialists, i.e., in future works, these values may be precisely adjusted (e.g., by regulatory authorities).

Finally, 800ms is the time limit searching for each state, which seems to be a reasonable response time once the aircraft in this time interval change their position slightly from the perspective of the whole final sector. Indeed, this reduced and feasible value is compatible with the need for real-time solutions. The experiments are performed in

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

TABLE 1. Ages (in terms of TML evolution) considered in this research.

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

a High-Performance Computer (32 virtual CPUs 2.2Ghz, 128GB RAM).

The first case study presents a simpler scenario in which the weather conditions are favorable and considers three 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 adverse conditions. Finally, the third case study focuses on showing the applicability of our proposal in a complex environment, composed of 5 aircraft operating in the airspace with adverse weather conditions.

A. CASE STUDY I

The first case study of this research considers a simple scenario illustrated in Figure 6. In this scenario, three aircraft are considered (MA, RPAS, and AA). The RPAS is set in position (5, 25), whereas the MA and the AA are respectively set in the positions (15, 15) and (5, 5). Finally, the Initial Approach Fix (IAF) is set at (5, 15).

To build the final arrival segments for these aircraft, FASOM is employed. Considering age 1, the feasible solution provided by this optimization method is illustrated in Table 2. In this solution, the MA (aircraft 1, TML10) is assigned to an additional VP, which is set in the position (9.19, 20.7), as well as the RPAS (aircraft 2, TML6), which is assigned to an additional VP in 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.

TABLE 2. 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	——

Considering age 2, the solution (described in Table 3) is similar to that proposed considering age 1, i.e., 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 aircraft 3 (AA), which still presents the lowest TML (6), flies directly to the IAF.

The solution provided at age 3 (depicted in Table 4) for this scenario is different. Aircraft 3 (AA) achieved the highest TML (10) and is assigned to an additional VP set in the position (11.2, 10.2), whereas aircraft 2 (RPAS) presents a reduction in its TML (6) and is assigned to an additional VP set at (7.61, 27.75). In turn, aircraft 1 (MA), which also presented a reduction in the TML (6), is not assigned to an additional VP, i.e., this aircraft flies directly to the IAF.

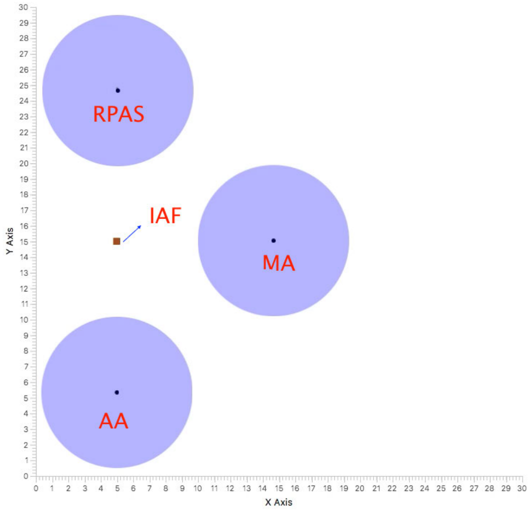

FIGURE 6. Scenario adopted in case study I.

TABLE 3. 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	——

TABLE 4. 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)

The solutions presented for all ages (highlighted in Tables 2, 3 and 4) presented the results, in terms of duration (of delivering all aircraft to the IAF), workload and elapsed time (of processing time) presented in Table 5. These results are similar in terms of processing time, whereas the duration varies slightly.

TABLE 5. Results from 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

Moreover, the solutions adopted in this experiment considering TML age 1 delivered the aircraft with the lowest

TML (AA, TML 0) with higher priority. 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 because the optimization process is not conducted in terms of the sequence in which the aircraft will be delivered. Instead, the optimization process considers the number of additional VPs each aircraft is assigned to. In this case, regardless of the sequence in which the aircraft are delivered, the solutions focus on reducing the number of VPs assigned to each aircraft (prioritizing the aircraft with lower TMLs). Indeed, the same sequencing is achieved, even considering the differences in TMLs between these two ages. Finally, the solution provided for 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). Regarding the results from Case study I, presented in Table 5, the workload levels are similar at all ages. This illustrates that, regardless of the TML age (i.e., regardless of the aircraft's TML variation), the solutions provided maintained the workload level stable. Finally, the elapsed processing time is considerably short for real-time applications once the highest duration presented (4.6s) represents a short distance traveled by aircraft, i.e., all aircraft do not move dramatically in 4.6s, highlighting this is a short response time.

B. CASE STUDY II

The second case study of this research considers a more challenging scenario illustrated in Figure 7. In this scenario, four aircraft are considered (MA, RPAS, and two AA). The two AA are set in positions (23.9, 35.34) and (20.5, 29.95), respectively. The RPAS is set in position (19.6, 1.2) and the MA is set in the position (24.55, 4.7). The IAF is present in 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).

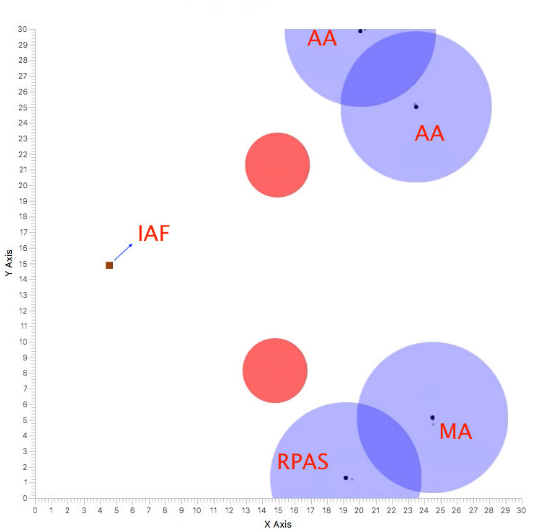

FIGURE 7. **Scenario adopted in case study II.**

The solution provided by FASOM for this scenario, considering TML age 1, is described in Table 6. In this feasible solution, aircraft 2 (AA with TML 0) flies directly to the IAF, whereas the other 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, in position (23.0, 35.3), (14.7, 16.9) and (23.0, 18.5) before going to the IAF.

TABLE 6. **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)

The solution presented in age 2 is detailed in Table 7. Aircraft 2 (AA, TML 6) goes directly to the IAF. However, 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, in positions (20.0, 13.7) and (26.1, 19.4).

TABLE 7. **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)

Considering the TML age 3, the solution provided is considerably different. In this solution, described in Table 8, both AA (TML 10) are assigned to additional VPs before going to the IAF, set in 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.

TABLE 8. **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)

The results from the solutions provided in this case study, considering TML ages 1, 2 and 3, are illustrated in Table 9. Thus, all metrics are similar considering the different ages, i.e., the optimization method proposed herein can adapt the search for finding solutions with reduced ATCo workload regardless of the age considered (which changes the ATCo workload related to each aircraft).

TABLE 9. 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

Furthermore, 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 VPs[9]: the RPAS or one of the AA. In this sense, considering 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 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 from the other aircraft. The experiments conducted in Case study II (Table 9) illustrate the similarity in terms of workload levels that the solutions present considering the TML age variation. This shows that FASOM provided feasible solutions maintaining the workload levels and considering similar solutions duration. Finally, the processing time is a bit higher, achieving up to 10.014s, because this scenario is more challenging than the scenario presented in the case study I.

C. CASE STUDY III

The last case study of this research consider a complex scenario, illustrated in Figure 8, in which five aircraft (two MA, two RPAS and one AA) are present. The two RPAS are set in positions (27.5, 27.95) and (17.45, 29.95), whereas the two MA are set in (16.2, 0.6) and (16.5, 15.05), respectively. The only AA present is this scenario is set in position (27.35, 2.25). Furthermore, the IAF is set at (1.55, 14.95), whereas there are CBs in positions (8.9, 14.2), (14.95, 21.8) and (24.6, 13.95).

In order to deliver the set of aircraft presented in this scenario, considering TML age 1, FASOM proposed the solution described in Table 10. In this feasible solution, aircraft 2 (AA, TML 0) and 4 (RPAS, TML 6) flies directly to the IAF. Aircraft 1 (RPAS, TML 6) is assigned to position (16.5, 1.4) before going to the IAF. Similarly, aircraft 3 and 5 are respectively assigned to positions (12.9, 21.8) and (7.4, 19.9) before reaching the objective point (IAF).

The solution provided considering TML age 2, illustrated in Table 11, selected aircraft 2 (AA) and 3 (MA) to fly directly to the IAF. The two RPAS present in this scenario, aircraft 1 and 4, respectively fly to 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 in position (21.3, 28.1).

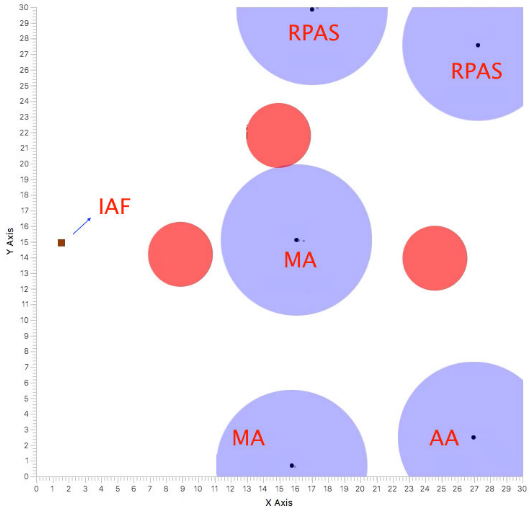

FIGURE 8. Scenario adopted in case study III.

TABLE 10. 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)

TABLE 11. 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)

Finally, the last experiment, which considers TML age 3, considers the solution described in Table 12. In this solution, the AA (aircraft 2) and one of the MA (aircraft 3) are guided to the IAF directly. In this context, both RPAS (aircraft 1 and 4) are conducted indirectly, i.e., to additional VPs located in positions (13.7, 38.0) and (20.7, 2.7). Thus, the other MA (aircraft 5) flies in the direction of position (6.2, 31.2) before going to the IAF.

TABLE 12. 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)

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[9] If both aircraft are delivered without one additional VP, the solution is not feasible once the separation of these two aircraft in the region near to the IAF is lower than 5nm.

The quality of the solutions proposed by FASOM for this case study, considering the TML age variation, is depicted in Table 13. Similarly to case studies I and II, each metric's results (duration, workload, and elapsed time) are similar considering all ages.

TABLE 13. **Results from 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

Moreover, this experiment provided different solutions throughout the TML age variation. In this scenario, the solution leads two out of three aircraft (one of the RPAS, one of the MA, and/or AA) to the IAF without additional VPs. At 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 TML ages 2 and 3, the AA (TMLs 6 and 10) and one of the MA (TMLs 10 and 6) are chosen to be delivered directly. Finally, the other aircraft are assigned to additional VPs. In terms of the results from Case study III, although the workload is similar throughout the TML ages, a certain level of instability is verified compared to the results of the other case studies (i.e., differences regarding the workload level). This is because 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. Note that in 10.4s, the aircraft fly approximately 0.05NM whether the speed is close to 180kts. This highlights that this is a feasible calculation time once the aircraft will not dramatically change its position in this period.

VIII. DISCUSSION

The duration of the solution, considering the TML ages variation, for each case study, is illustrated in Figure 9. This chart shows that the results from different case studies are considerably different, but considering the age variation, each case study presented slight differences in each experiment.

The workload of case studies II and III are similar, as illustrated in Figure 10. At TML age 1, the workloads of both cases are very similar and they start to spread out throughout the TML age variation. Furthermore, the case study I presents a lower workload level. The variations of the results achieved within the same case study are slight, i.e., the optimization method proposed can adapt the search for finding solutions with reduced ATCo workload regardless of the age considered (which changes the ATCo workload related to each aircraft).

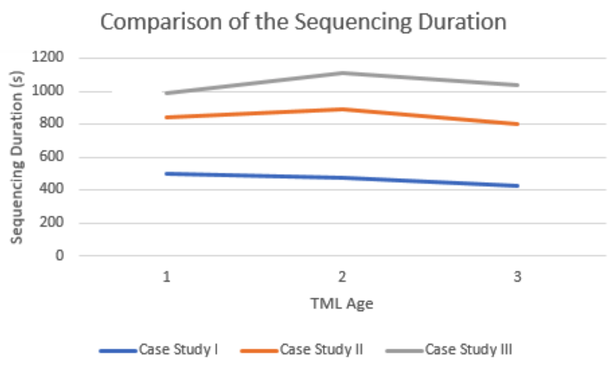

FIGURE 9. **Comparison of the sequencing duration achieved in case studies I, II and III considering the TML age variation.**

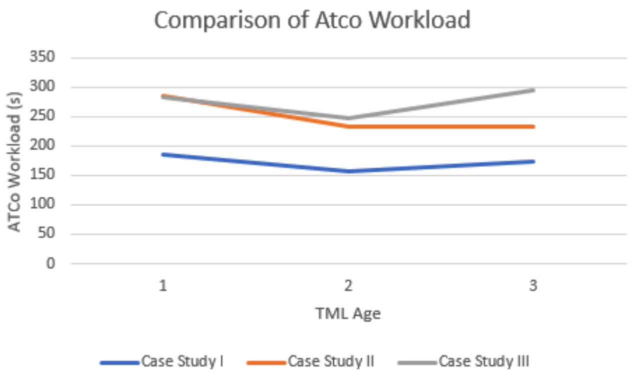

FIGURE 10. **Comparison of the ATCo workload achieved in case studies I, II and III considering the TML age variation.**

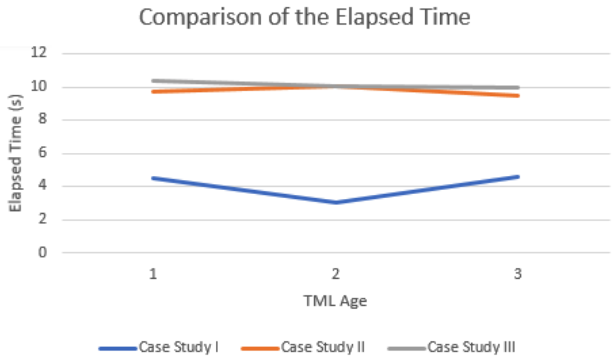

FIGURE 11. **Comparison of the elapsed time achieved in case studies I, II and III considering the TML age variation.**

Finally, Figure 11 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., the case study I represents a simpler scenario). The results showed that the FASOM provided feasible and good solutions, which are adapted according to the TML of each aircraft to maintain the workload and duration levels stable. This stability is also illustrated in the comparison of the results from each case study.

IX. CONCLUSION

Since air transportation is essential for society, it is steadily increasing, and new technologies (e.g., UAS) are being proposed and integrated into the National Airspace System (NAS), making methods for optimizing their operation and enabling a smooth integration important. In this context, in order to introduce the UAS into challenging scenarios (e.g., those which consider adverse 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, controlling aircraft in TMA considering adverse weather conditions and the UAS presence is a complex task. To overcome this challenge, supporting tools must consider airspace restrictions, different aspects of each aircraft, and the role of the ATCo in this context. This research proposed a parallel swarm-based method for optimizing final aircraft arrival segment design considering the UAS presence, performed from the ATCo workload and sequencing duration standpoints. The main contributions presented are (i) the adoption of a novel approach to measuring the integration of UAS in the National Airspace System (NAS), (ii) an optimization method based on the Particle Swarm Optimization (PSO) for designing landing trajectories considering the UAS presence, and (iii) interfaces for applying the optimization model in external applications. The solutions consider airspace restrictions (e.g., minimum separation between aircraft and adverse weather conditions) and are provided at short response times (e.g., 4.6s in case study I, 10s in case study II, and 10.4s in case study III in our experiments).

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

- **Performing several experiments to highlight the optimization boundaries:** One possible direction is to perform several experiments (e.g., thousands of scenarios) using a high-end data center and considering different parameters (e.g., different speed intervals and different sectors of the airspace). This will highlight the patterns that compose simple and challenging situations. This would also support the airspace complexity evaluation;
- **Analysis of the trade-off between workload and efficiency:** This refers to the further investigation on how the efficiency and workload levels are affected if different weights are assigned to each metric. This will highlight the thresholds between efficiency and workload as well as identify the appropriate interval for the weight assignment procedure;
- **Measuring the TML evolution of different aircraft types throughout the years:** In this research, TML ages are considered in the experiments. Although the ages are different from each other, one challenge and future direction is how to measure the evolution of the TML throughout the year from many perspectives (e.g., operational and regulatory);
- **Measuring the impacts of parameters changes in the FASOM results:** As the focus of this research is to propose a method for optimizing the operation of UAS in the Final Sector, one future direction is to analyze the parameter variation in order to find the best parameters combination for each scenario. This variation considers the parameters of PPSO, such as the number of particles and values of c_1 (cognitive aspect), c_2 (social aspect) and w (inertia);
- **Employing different architectures of optimization in FASOM:** As 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 in the 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 the 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 lies in how the set of aircraft can be guided to the IAF considering this issue. The optimization of arrival segments considering a problematic aircraft in the final sector is a challenging task;
- **Priority Establishment of UAS sequencing in the National Airspace System (NAS) 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 familiarity (TML), one alternative approach is to consider the priority level. One example of prioritized aircraft 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 currently employed;
- **Optimization of UAS operation in TMA:** Although our proposal is developed to be applied to the final sector, which is part of the TMA, there are several situations faced in larger scenarios that may be considered in future works. For example, as the area is considerably larger, it is reasonable to consider many aircraft. Examples of

applications are airspace resilience (e.g., problems in airports) and impacts of weather conditions in a long period (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 Air Traffic Control (ATC):** One of the challenges of the future directions of this research is the automation of the ATC and ATCo. For example, approaches such as ATC Maturity Level (AML), which represents the level of maturity and autonomy of a system in terms of acting in controlling manned and unmanned aircraft (e.g., different approaches for modeling the relationship between the autonomous ATC with UAS and between the autonomous ATC and MA can be developed).
- **Non-linear scaling for Vectoring Points (VPs) definition:** In this investigation, the workload associated with the definition of VPs for a given aircraft is the same regardless of the number of VPs. However, future works could also focus on different models that compute different workload levels depending on the configuration of the airspace (e.g., number of VPs, weather conditions, and number of aircraft);
- **Optimization of final arrival segments for UTM and Urban Air Mobility (UAM):** The application of the proposed approach in a critical task has the potential to support the future decision-making process in the airspace. Similarly, this concept can be extended to different contexts, e.g., UTM and UAM.

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