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Full Length Article

Building interfaces between unmanned aircraft systems (UAS), air traffic controllers (ATCo), and the national airspace system (NAS): A software training platform

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ABSTRACT

Nowadays, the development of technologies that improve airspace operation in many aspects is essential since the importance of air transportation for society is increasing. The airspace, although, may become more complex considering the integration of these aircraft due to the issues regarding the social acceptance of autonomous systems (e.g., familiarity between Air Traffic Controller - ATCo - and Unmanned Aircraft System - UAS) and the uncertainty in terms of operation (e.g., hardware failures, software failures, interfaces failures, and misunderstanding of instructions). However, standard procedures (e.g., landing procedures) may not be followed in complex situations due to safety constraints (e.g., loss of minimum aircraft separation). As a result, ATCos play an essential role in maintaining appropriate levels of safety and efficiency by conducting aircraft using Vectoring Points (VPs). Hence, ATCos must be trained to deal with such challenging scenarios, especially in resource-constrained regions, e.g., in the final sector of the Terminal Control Area (TMA), where the aircraft are guided to the landing phase. The primary goal of this research is to propose a framework for training Air Traffic Controllers (ATCos) to deal with complex situations (e.g., considering many aircraft as well as severe weather conditions) in the final sector considering the UAS integration into the National Airspace System (NAS). This approach is divided into a set of modules for (1) proposing the training scenarios, (2) proposing solutions, and (3) evaluating the quality and feasibility of the solutions proposed. The aspects evaluated in the solutions provided for the proposed scenarios are ATCo workload and efficiency.

1. Introduction

Nowadays, the increasing importance of air transportation for society [1] has contributed to the development of technologies that improve airspace operation in many aspects (e.g., efficiency and capacity), such as Unmanned Aircraft Systems (UAS) and Decision Support Tools (DST) for Air Traffic Controllers (ATCos) [2–4]. In many countries, the number of flights leads to high revenue and, indeed, the Air Traffic Control (ATC) acts to improve the airspace efficiency, which can be associated with the profitability of the air traffic [5]. Hence, safety and efficiency are critical metrics in this context. The need for maintaining safety and efficiency at acceptable levels, considering the changes in the airspace (e.g., increase in the number of aircraft), leads procedures to be redrawn according to the characteristics of each region (e.g., Standard Terminal Arrival Routes).

Moreover, as these two metrics may oppose each other, a balanced strategy for dealing with both metrics is desirable. The DSTs, for instance, enhance the Air Traffic Controller (ATCo) operation by supporting the decisions made aiming to optimize the effectiveness, i.e., the ATCo workload (i.e., the time spent by the ATCo in controlling aircraft) related to several activities may be significantly reduced, which enables a better understanding of the current airspace state and complexity [6].

In this sense, the Air Traffic Controllers (ATCos) play an pivotal role in the airspace operation [7]. They work to guarantee appropriate levels of safety and efficiency and to solve problems in the airspace. Furthermore, the process of sequencing can be faced as ordering the aircraft in a manner that safety and efficiency levels are respected in the delivery of these traffics to an objective point [8–10]. In the final sector of the Terminal Control Area (TMA) (i.e., within a resource-constrained region of the airspace), this objective point is the Initial Approach Fix (IAF).

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Before acting in this critical environment, the ATCo must be trained. The training aims to ensure the ATCos can make appropriate decisions when facing simple and challenging airspace scenarios, focusing on safety and efficiency levels. Although there are technologies that are not present in the ATCo operation nowadays and may be included in the following years (e.g., autonomous aircraft), the training process aims to prepare professionals for dealing with real-world scenarios in a progressive approach [11].

In the past few years, there has been a growth in Unmanned Aircraft Systems (UAS) numbers [12]. Still, the presence of UAS in the National Airspace System (NAS) is yet considered a challenge and may represent a reduction in Air Traffic Control (ATC) capacity (e.g., in the final sector of the TMA). This reduction may be caused by the lack of familiarity with the Air Traffic Controllers (ATCos) with this new technology [13, 14]. Additionally, the issues regarding the social acceptance of autonomous systems and the uncertainty concerning operation (e.g., hardware failures, software failures, interface failures, and misunderstanding of instructions) tend to leverage the ATCo workload during the early stages of UAS integration.

The challenges for the safe integration of the UAS into the controlled airspace are diverse since the presence of the UAS represents an additional complexity factor in the airspace [15–17]. Some of them can be highlighted, such as [18]: 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, and acceptance).

In this context, training ATCos to deal with UAS is a complex task since there is no large UAS operation in the controlled airspace. The uncertainty toward the operation of these aircraft (especially in critical scenarios) represents additional complexity factors to the airspace, may increase the workload and, further, may lead the airspace to unsafe states. Training ATCos for dealing with such insertion, especially in critical scenarios (e.g., within the final sector) may lead the airspace to maintain the workload levels throughout the years and, consequently, to the prevention of reaching unsafe states.

The main goal of this research is to propose a framework for training Air Traffic Controllers (ATCos) to deal with complex situations (e.g., considering many aircraft as well as adverse weather conditions) in the final sector considering the Unmanned Aircraft System (UAS) integration into the National Airspace System (NAS). The aspects evaluated in the solutions provided for the proposed scenarios are ATCo workload (defined concerning the number of vectoring points assigned to each aircraft) and efficiency (related to the time spent delivering all aircraft to the final objective point).

This paper is organized as follows: Section 2 presents the works related to our proposal. Secondly, Section 4 shows the aspects of the Unmanned Aircraft System (UAS) and its integration into the non-segregated airspace. After that, Section 5 highlights the aspects of the Air Traffic Controller (ATCo) training. Then, Section 6 presents the framework that is composed by the Final Sector Builder (FSB), the Final Arrival Segment Editor (FASE) and the Final Sector Simulation Tool (FSST), which is the main contribution of this research. Furthermore, Sections 7, 8 and 9 present, respectively, the evaluation method, the case studies and the discussion. Finally, Section 10 presents the conclusions of this research as well as the future directions.

2. Related works

In this section, the related works are shown. Each work presents similarities and differences compared to our proposal, which is discussed as follows.

The authors in [19] describe an experiment based on the development of a tool that illustrates the conflicting portions of aircraft trajectories and its evolution considering additional maneuvers to any aircraft, which shows that a dynamic conflict display could improve human performance on complex conflict situations. Air Traffic Management (ATM) is organized to reduce the exposure of Air Traffic Controllers (ATCos) to complex conflicting situations. The display proposed, tested on forty students, allows the user to check the potential conflicting zones before making a maneuver decision. The experiments, which were conducted considering situations involving 2 to 5 aircraft and a basic and the proposed (enhanced) display, showed that the students' performance in both displays is similar considering situations in which 2 aircraft are considered. In more complex cases (3 to 5 aircraft), on the other hand, the enhanced display of the conflicts was solved more efficiently. Thereupon, the enhanced display presented fewer unsolved conflicts and shorter delays, and the authors suggest that "humans are better able to manage complex situations with the help of our conflict visualization tool". Although this is an outstanding contribution, it does not consider integrating the Unmanned Aircraft System (UAS) into the National Airspace System (NAS) airspace or, more specifically, within the Final Sector.

In [20], the authors present an investigation into how the difficulty of performing complex tasks influences emotional states, cognitive workload, and task performance. Indeed, complex activities require additional attention and high precision, especially in critical scenarios (e.g., airspace). Hence, the authors employ both quantitative and qualitative measurements (e.g., the recording of pupil dilation). The participants were asked to solve a number of air traffic control tasks using an immersive approach in the "eXperience Induction Machine" (XIM). The authors developed a model which integrates personality, workload, and affective theories, and the results of the experiments indicated that the difficulty faced by ATCos in performing tasks has a direct influence on cognitive workload as well as on the self-reported mood (although mood and workload seem to change independently). Finally, the authors suggest that personality affects both mood and performance. In addition to this research, our proposal deals with the training of ATCos in dealing with Unmanned Aircraft Systems (UAS), i.e., our proposal is focused on the complexity related to the ATCo operation in futuristic scenarios.

In [21], the authors aim to measure the impact of error types on air traffic safety. This assessment is conducted considering the influence of subjective factors, i.e., this measurement cannot be expressed precisely. As Air Traffic Management (ATM) is also performed by ATCos using Decision Support Tools (DST) (e.g., Arrival and Departure managers), providing the ATCos with a visualization of the traffic situation in the airspace and enabling situational awareness is essential. Hence, errors sometimes occur in visualization systems despite efforts to improve their reliability. In this sense, the authors developed a fuzzy model for obtaining a tool enabling the simulation of the impact of various factors on traffic safety assessment. The results indicate that the most critical factors are when the ATCo remains unaware of the breakdown and the total time the ATCo does not have full knowledge of the traffic situation. Note that waiting for the ATCo to notice an error in Traffic Situation Visualization System (TSVS) and to take any corrective action can considerably impact the time spent if there is no complete knowledge of the traffic situation. Thus, alerting functions to warn the controller there is a possibly incorrect traffic situation image may be appropriate in this context. Finally, in addition to this research, our proposal aims to enable ATCo training, consider the UAS presence, and focus on safe and efficient operations.

The authors, in [22], propose a scenario exploration technology that provides a platform for Federal Aviation Administration (FAA) Academy trainees and instructors to exercise a variety of scenarios in the Air Traffic Control (ATC) domain. The FAA Academy, in which the ATC training program relies on simulation-based training, is continuously optimized regarding its usability. However, the current training scenarios are generated manually by experienced ATCos, and the effort in translating them into a machine-understandable language is also conducted manually. The technology proposed by the authors provides a platform for instructors and trainees to explore various training exercises, considering scenario specification and exploration. Indeed, this is achieved by employing a model-driven approach and extending the

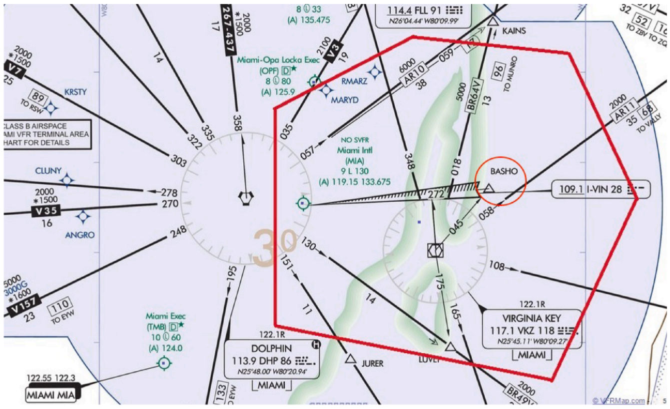

Fig. 1. Final Sector of KMIA TMA (Miami) (Adapted) [25].

domain-specific Aviation Scenario Definition Language (ASDL). This project, which has just been launched and is still under development, considers the use of ASDL Graphical User Interface (GUI) to generate new scenarios using drag-and-drop options for scenario elements (with automatic generation of XML script of scenarios). In our proposal, we employ a similar approach for building the scenarios (i.e., the scenarios, which are also built using drag-and-drop options, are translated into JSON scripts). Besides, our focus is to include the UAS in the ATCo training within the Final Sector.

In [23], the authors introduce a head and eye tracking system for pilot training in a flight simulator that can collect and merge the data in 2D screen or advanced 3D models (i.e., it can be adapted to be applied to different environments). Considering that there is a lack of standardized assessment of scanning performance and situation awareness for pilots, even assuming that both are vital aspects in the pilot operation, this approach enables an automatic evaluation to be conducted and may bring advantages to several research fields considering certain upgrades. Note that this approach is used in the research flight simulator of the Centre for Aviation. Although this proposal aims to be used in pilot training, a similar approach (in terms of enabling training in different scenarios) is considered in our contribution, but focuses on ATCos. On the other hand, future applications of this research may include Remotely Pilot Aircraft Systems (RPAS) operators training, which is also included in our approach.

3. Arrival sequencing and scheduling

The Final Sector (FS) is a critical sector in the Terminal Control Area (TMA). This is the last sector in the aircraft trajectory to land in a specific airport, i.e., the aircraft intercepts the Initial Approach Fix[1] (IAF) inside the FS. This sector is the focus of our research and is highlighted by a red polygon illustrated in Fig. 1. Hence, the aircraft operations herein are slower than in other regions of the NAS (around 180kts[2]). Besides, the height is reduced (around 6000ft[3]). Furthermore, the aircraft are expected to enter FS with a minimum separation between them, which enables the ATC to provide simpler instructions for achieving 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 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 Fig. 1 since the area chart does not illustrate IAFs.

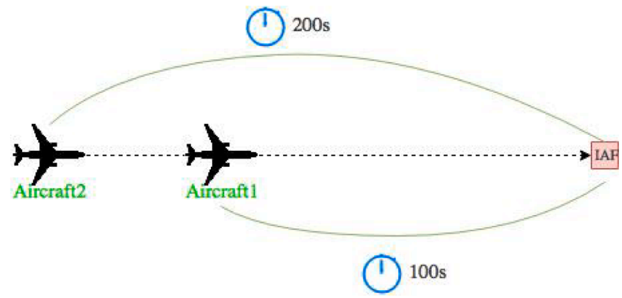

Fig. 2. Delivery of aircraft to the IAF considering expected time duration.

Moreover, complex situations may lead several aircraft to enter the FS in a short period and with reduced separations. Albeit difficult, this scenario can become more challenging in case of severe weather conditions (e.g., Cumulonimbus - CBs - presence). These factors may make the sequencing and scheduling of these aircraft a very challenging activity since precise instructions and short response time are required from the ATCo.

Fig. 2 illustrates an example of aircraft being delivered to the IAF following the sequence *s*, which presents as expected arrival time for aircraft 1 and 2 are 100s ($x_{s_1} = 100s$) and 150s ($x_{s_1} = 100s$), respectively. However, in order to respect the minimum separation established, the Minimum Separation Time (MST) between both aircraft is 100s ($MST_{s_1,s_2} = 100s$). As the time in which 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. Finally, the goal is to establish a sequence in which the last aircraft to be delivered achieves the IAF as quickly as possible.

Thereupon, severe weather conditions may present considerable impacts in the airspace and may cause flight delays [26,27]. For instance, estimating the sectors' capacity in a given airspace region during severe weather events is essential to Air Traffic Management (ATM) responsibilities [28]. In this context, the definition of trajectories for avoiding adverse situations is a desired skill for Air Traffic Controllers (ATCo). For instance, Cumulonimbus is one factor of bad weather conditions.

Cumulonimbus (CB) [29] 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. These formations are composed of water droplets and ice crystals and contain nearly the entire spectrum of flying hazards, including extreme turbulence. Furthermore, they are considered the ultimate manifestation of instability concerning airworthiness and should be avoided at all times [29, 30].

Defining sizes for CBs is a problematic challenge once these cloud formations may vary widely. In our proposal, we adopt a circle in a 2D environment with a radius of 2 Nautical Miles (nm). This assumption considered the consultancy of actual Air Traffic Controllers (ATCo) from the University of São Paulo with more than 10 years of hands-on experience. Note that this shape is an approximation of real formations, and the different shapes and sizes can also be used but are in the scope of future works. Finally, the cumulonimbus may move in different directions. However, in this research, we consider the clouds fixed in a specific position since their movement is based on long periods (e.g., many hours).

4. Unmanned aircraft system (UAS) integration into the national airspace system (NAS)

The Unmanned Aircraft System (UAS) has sparked the interest of the engineering community in the past few years [31]. These new technologies present several applications on small scales (e.g., firefighting) and

[1] 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 facilitates the conduction of aircraft as well as the separation maintenance [24].

[2] $1kt = 1.852 kilometers/hour$

[3] $1ft = 0.3048m$

Table 1
Impacts of Technology Maturity Level (TML) on communication and surveillance [36].

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

large scales (e.g., search and rescue). UAS is composed of subsystems (e.g., communication system and control station) [31,32] and can be classified in terms of size and piloting. However, there is a challenge regarding this aircraft in non-segregated airspace. In [33], 4 requirements to conduct this integration[4] safely are defined as:

- "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".

Thereupon, the UAS can be classified into three categories concerning weight [34]: (1) Small UAS; (2) Medium UAS; (3) Large UAS. Class One (small UAS) represents the UAS with many applications in smaller scenarios, with a weight less than or equal to 149 kg. Class Two (medium UAS) weighs up to 600kg. Finally, Class Three (large UAS) weighs more than 600 kg. In this research, large UAS with size and performance similar to commercial aircraft are adopted to measure the impacts on workload. Concerning piloting systems, furthermore, the UAS can be classified as Remotely Piloted Aircraft Systems (RPAS), which considers a pilot that acts on the ground, and Autonomous Aircraft (AA), which is fully autonomous.

Hence, to conduct all aircraft throughout the airspace in complex situations, Vectoring Points (VPs) must be defined. The definition and assignment of VPs lead the ATCo to perform a set of activities [35]. This research proposes a list of ATCo activities based on more than 10 years of hands-on ATC experience. Furthermore, extensions of this list can be adopted in future research once the method proposed herein can be adapted to deal with different situations. Finally, note that the duration of each activity is estimated empirically based on the experience of these specialists. Still, these values act as inputs for our proposal once the method can be applied in situations with different time duration.

The activities performed by the ATCo in defining Vectoring Points (VPs) are: (1) Vectoring point definition (a position that a single aircraft must fly to, with a mean duration of 5 s); (2) Heading definition ("the direction in which the longitudinal axis of an aircraft is pointed, usually expressed in degrees from North" [24], with a mean duration of 5 s); (3) Communication (mean duration: 15 s); and (4) Surveillance (mean duration of 5 s);

However, the duration of each activity may change according to the familiarity of the ATCo with the aircraft (which involves familiarity itself, but also social acceptance and certainty regarding safe). In this context, the Technology Maturity Level (TML), a measurement system that measures the familiarity between the ATCo and the aircraft and varies from 0 to 10, can be employed [36]. Aircraft with higher TMLs are related to operations with lower workload levels, whereas aircraft with lower TMLs are related to operations with higher workload levels. For instance, nowadays, it is reasonable to consider that the UAS has a lower TML, whereas the Manned Aircraft has a higher TML since the ATCos are used to deal with MA but are not used to deal with UAS (which do not operate in the non-segregated airspace) [13] (i.e., considering the UAS as TML 0 and MA as TML 10 is a reasonable approach to the current scenario).

Finally, Table 1 illustrates the multiplication factors related to each TML, i.e., additional time spent by the ATCo in controlling different aircraft. Note that the activities considered to be impacted (communication and surveillance) involve cognitive aspects. Furthermore, the linear scale highlights the evolution of technology maturity, but different scales can also be used depending on the problem faced and the hypothesis considered.

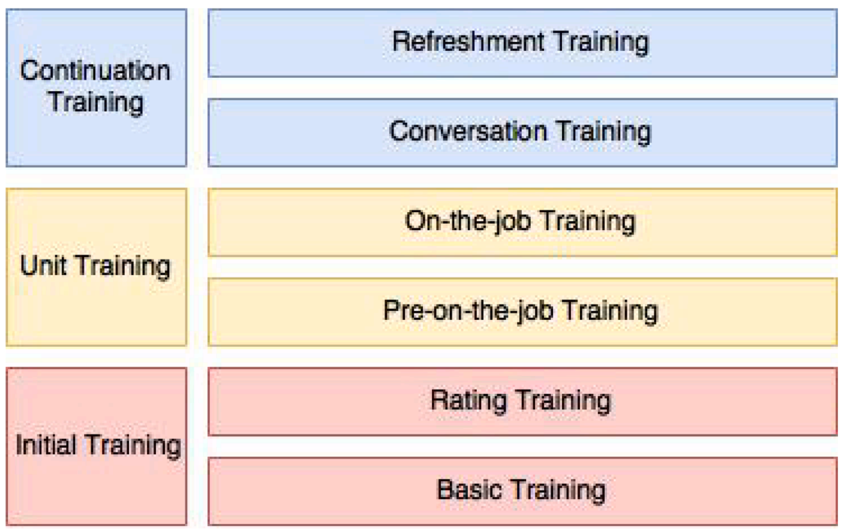

Fig. 3. Initial training, unit training, and continuation training [11].

[4] Note that these rules are defined for RPAS but can be applied to UAS in general.

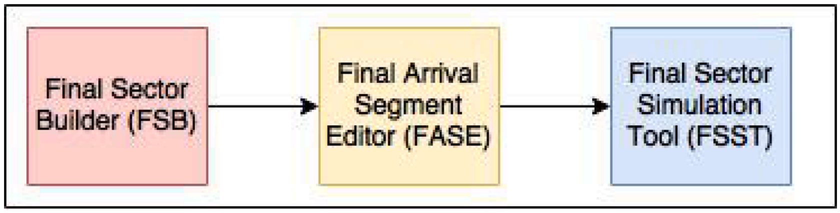

Fig. 4. Structure of the training framework proposed in this research.

5. Training air traffic controllers (ATCos)

In order to control the air traffic properly, there is a set of (competency-based) training activities that each ATCo must accomplish. According to [11], the main benefits of implementing a competency-based training program are:

1. Assurance that ATCOs can act appropriately;
2. Evaluation of operational personnel;
3. Identification of personnel performance gaps; (3) Enhancement of individual skills;
4. Development of effective training and evaluation methods;
5. Enabling effective change management processes (e.g., adoption of new equipment).

In this context, according to the International Civil Aviation Organization (ICAO) [11], the progression of air traffic controller training can be divided into three phases (illustrated in Fig. 3): Initial Training, Unit Training, and Continuation Training.

The Initial Training is divided into two parts: Basic and Rating training. The Basic Training consists of theoretical and practical training on fundamental knowledge, skills, and attitudes related to basic operations. The main goal of this phase is to build a solid foundation for dealing with challenging and straightforward scenarios. The Rating Training, on the other hand, is related to developing skills and attitudes related to a specific rating.

The Unit Training is divided into two parts: Pre-on-the-job and On-the-job Training. The Pre-on-the-job Training is related to site-specific operational procedures, tasks, and technical systems, i.e., simulations can prepare the student for the real operating environment at a unit. On the other hand, On-the-job Training enables the acquisition of unit-specific routines and procedures under the supervision of a qualified instructor.

Finally, the Continuation Training is divided into two parts: Conversation, which is training designed to provide skills for changes in the operational environment, and Refreshment Training, which is focused on reinforcing the existing competencies of air traffic controllers to provide a safe and efficient flow of air traffic.

Hence, the approach proposed in this research for training ATCos for dealing with UAS can be considered to be located beside the Pre-on-the-job Training once the evaluation is conducted in a simulated environment.

6. Framework for training ATCos considering the UAS presence

This Section presents the framework for ATCo training considering the UAS presence. Fig. 4 shows how this framework is structured. Firstly, the challenging scenarios are built using the Final Sector Builder (FSB). Then, the trainees, who are considered future Air Traffic Controllers (ATCos), can provide their solutions using the Final Arrival Segment Editor (FASE). Finally, the quality and feasibility of the solutions are measured using the Final Sector Simulation Tool (FSST). In this Section, each module is explained.

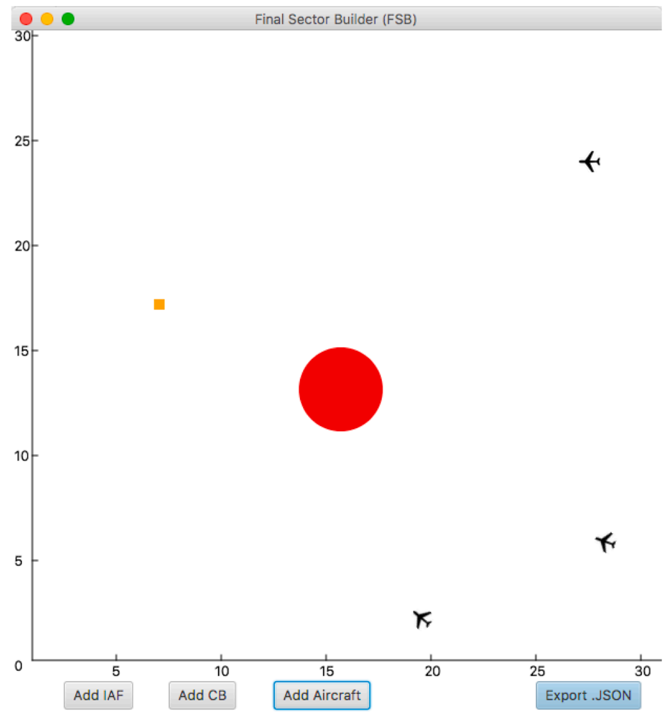

Fig. 5. Final Sector Builder (FSB).

6.1. *Final sector builder (FSB)*

The first step toward the ATCo training regarding decision-making is the scenario building by the instructor. These senior and experienced professionals clearly understand what constitutes a simple and complex situation in the airspace context. Their knowledge is employed to build real-world challenges. To ensure the ATCo can perform effectively in real and complex scenarios, the building process of these training scenarios must be conducted precisely. Concerning scenario constructions, the instructor must be able to communicate the characteristics of a given scenario (e.g., aircraft positions and weather conditions), i.e., errors during the information parsing may make the scenario different from what the instructor planned. This may lead the training process to be less effective than expected. On the other hand, the interface must be constructed to enable the instructor to build scenarios easily, i.e., errors during information provision must be avoided.

However, the training scenarios generation and the process of translating them into a machine-understandable language are usually conducted manually [22]. The automation in providing this information with user-friendly interfaces may reduce the effort in building complex situations and increase the precision (or error avoidance) of this process. Furthermore, the training approaches employed nowadays need to consider the presence of UAS, i.e., the UAS operating as a large aircraft. In this context, the Final Sector Builder (FSB) aims to offer the instructors a simple drag-and-drop user interface for building (simple or complex) scenarios effectively within the final sector of the Terminal

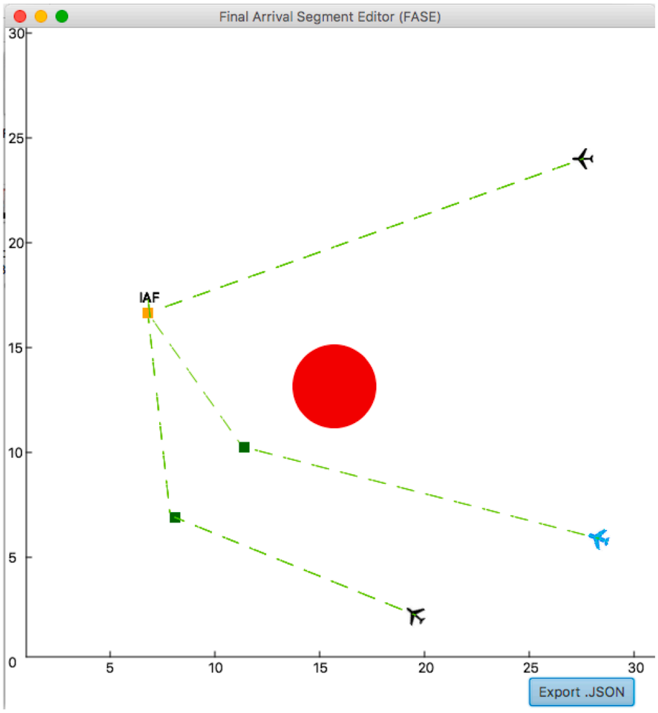

Fig. 6. Final Arrival Segment Editor (FASE).

Control Area (TMA). This tool also allows the instructors to add aircraft of different Technology Maturity Levels (TMLs), i.e., manned and unmanned aircraft can be represented in these scenarios. The interface of the FSB is illustrated in Fig. 5. The elements of this interface are explained as follows:

- **x- and y-axis:** The axis act to identify the aircraft position. Although the final sector may assume different geometric forms, an area of 900NM^2 can be considered a reasonable area for a final sector;
- **Aircraft icons:** Represent the aircraft and their respective headings;
- **Orange Square:** Represents the Initial Fix Approach (IAF). Considering the operation of the aircraft within the Final Sector, the main objective of the aircraft (or the objective point) is the IAF. After reaching this point, the aircraft can be conducted to the actual landing procedures;
- **Red circle:** Represents the Cumulonimbus (CB). Note that, in this research, the CB presents a radius of 2NM;
- **"Add Aircraft" button:** This button allows the instructor to add aircraft to the airspace. When clicked, the FSB asks the user to input the TML and the heading of the aircraft;
- **"Add IAF" button**: This button allows the instructor to add IAFs to the airspace. The number of IAFs may vary depending on the airspace structure. After added, the IAFs can be moved using the mouse;
- **"Add CB" button:** This button allows the instructor to add CBs to the airspace. After added, the CB can be moved using the mouse;
- **"Export.JSON" button:** Allows the user to export the built airspace in JSON format to enable communication with the following module (FASE).

6.2. Final arrival segment editor (FASE)

The third step toward the ATCo training in terms of decision-making is the solution proposed by the trainees. This is a critical phase in which the trainees provide solutions for challenging real-world situations. The training process for ATCos must expose the trainees to situations that may happen in the airspace. These situations may be simple or complex, depending on the airspace configuration. This exposure, conducted in simulated environments during the Pre-on-the-job training phase (presented in Section 5), elevates the maturity of students in understanding which decision must be taken in critical scenarios. Furthermore, the solutions provided are intended to be, further, compared to the solutions provided by instructors to measure their quality and feasibility, i.e., an appropriate user-friendly is desired not only for building the scenarios but also for enabling a proper solution provision.

However, the training scenarios provided nowadays do not consider the presence of the UAS. Indeed, these autonomous aircraft are not included as large aircraft, which is regarded as a reasonable size in futuristic applications. Hence, these autonomous aircraft can be included in high resource-constrained areas, such as the final sector of the TMA, and be controlled along with other aircraft. In this context, approaches that employ the level of familiarity between the aircraft and the ATCo may be considered, i.e., for instance, each aircraft can be assigned to a TML (presented in Section 4) and the definition of Vectoring Points (VPs) to guide them are directly related to this level.

The Final Arrival Segment Editor (FASE) aims to offer the users (instructor and trainees) a simple interface for building solutions for vectoring problems present in the final sector. This tool allows the construction of final arrival segments, i.e., paths that the aircraft must follow to be delivered to the Initial Approach Fix (IAF) and, further, to the airport. This interface imports data from the FSB and requires the user of the mouse to set the Vectoring Points (VPs) for each aircraft.

The interface of the FASE is illustrated in Fig. 6. The elements of this interface are explained as follows:

- **Green squares:** Represent the Vectoring Points (VPs), i.e., positions that the aircraft must fly to before going to the IAF. To define VPs, the user must click in the aircraft and, then, in the desired position for the VP;
- **Green Lines:** The path the aircraft fly through.

6.3. Final sector simulation tool (FSST)

The second step toward the ATCo training regarding decision-making is the measurement of the quality provided. In this phase, the instructors can verify the solutions' effectiveness, i.e., the efficiency and ATCo workload levels can be checked. The verification of the solutions provided can be conducted in different ways. Indeed, airspace efficiency can be related to the time spent delivering a set of aircraft to an objective point. Although there are different approaches to face this metric (e.g., the interval in which the aircraft are delivered), the ATCo workload is a more complex metric to measure. This is due to the several factors that impact this metric (e.g., communication with other ATCos, mean flight time, the mix of aircraft performance, emergency operations, conflict by distance, heading change, speed differences, mean aircraft separation, frequency congestion, level changes, the horizontal distance between aircraft and mean distance traveled [6,37]).

However, measuring these metrics in scenarios considering the presence of UAS, which can be considered an additional complexity factor, is a challenge. On the other hand, apart from the challenge of quantifying the efficiency and the ATCo workload, the assurance of the respect of airspace restriction, i.e., the feasibility of the solution, is an essential factor. Examples of airspace restrictions applied within the final sector are the minimum aircraft separation and the avoidance of Cumulonimbus (CB), which are cloud formations that present a real impact on aviation [26]. The Final Sector Simulation Tool (FSST), proposed in [36], aims to evaluate the ATCo workload and efficiency in aircraft sequencing in the final sector considering the UAS presence. This tool employs the Technology Maturity Level (TML) for measuring the workload related to each aircraft. The workload measurement is conducted regarding 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 and CB

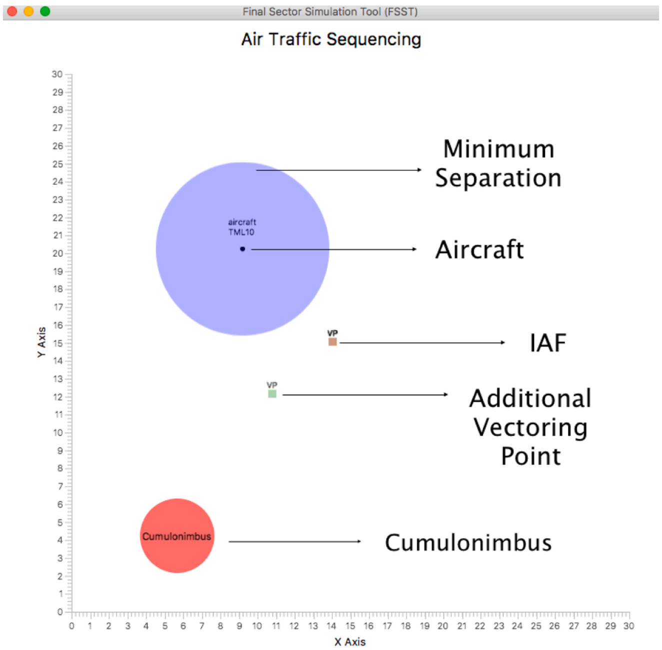

Fig. 7. Final Sector Simulation Tool (FSST).

avoidance. In this research, the minimum aircraft separation adopted is 5NM, and the CB is regarded as a circle in a 2-dimensional space with a radius of 2NM. Note that these assumptions are intended to be variable in future works, i.e., the size of the CB and the minimum separation between aircraft may change accordingly to the characteristics of the situation.

The interface of the FSST is illustrated in Fig. 7. The elements of this interface are explained as follows:

- Black Point: The aircraft from a macro perspective;
- Blue Circle: The minimum separation of the aircraft. Note that if any other aircraft does respect this separation, the provided solution is unfeasible.

7. Evaluation method

This Section describes the evaluation method, i.e., the approach employed for applying our proposal in different situations. The evaluation method is illustrated in Fig. 8. Firstly, the instructor provides the data to build the scenario (Input Data). The scenario, then, is automatically built considering the provided information in the format of a JSON file (Scenario Building).

Secondly, the solutions are provided by the instructor and trainees (Input Solution Data) and built (Solution Building) to be verified. Then, a verification (Verification) of the data provided is conducted. If the data is not valid, the solution must be provided again. Otherwise, the simulation is conducted (Simulation). After the simulation, an output analysis is undertaken (Output Analysis), and, finally, the evaluation process indicates the feasibility and quality of the solutions provided (Evaluation).

Moreover, Fig. 9 illustrates this process from the training process perspective. Firstly, the instructor informs the scenario presented to the students in the scenario-building phase. This phase is conducted by using FSB.

After that, the solutions are provided by the instructor and by all students. The solution provided by the instructors is, further, compared to the solutions provided by the students to verify if the efficiency and ATCo workload levels of the solutions provided by the students are acceptable.

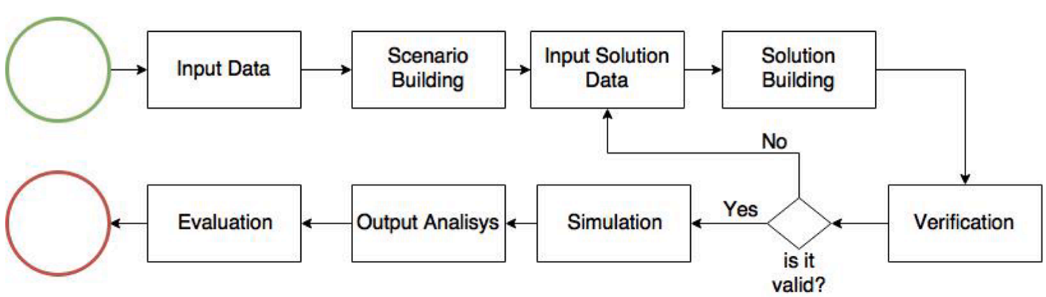

Fig. 8. Evaluation method adopted in this research.

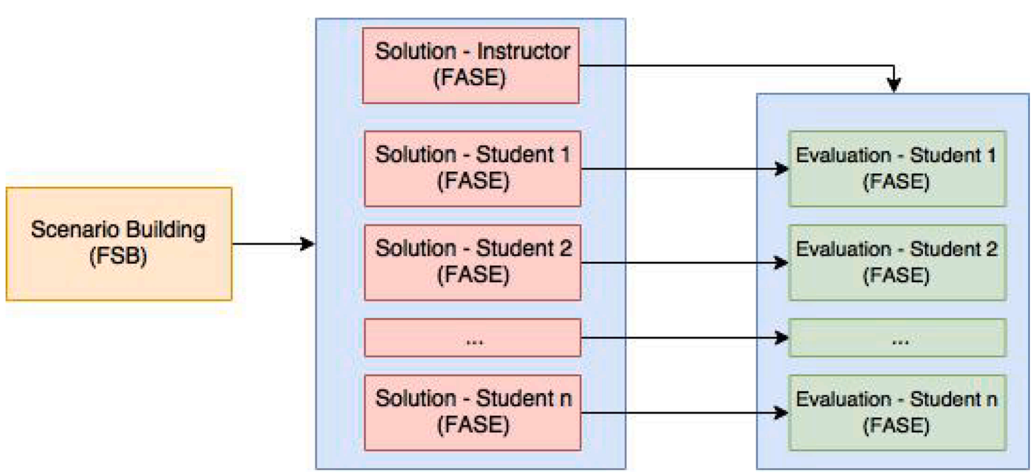

Fig. 9. Training method considered in this research.

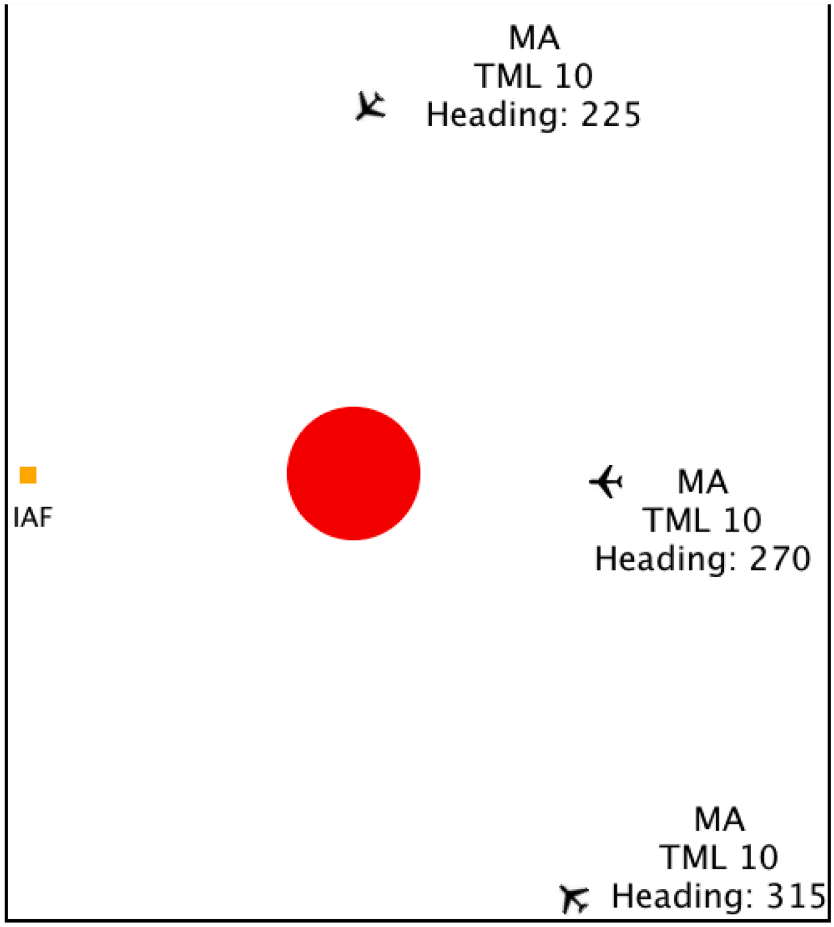

Fig. 10. Scenario considered in the case study I.

Finally, the evaluation of the solutions provided by the students is measured and compared to the solution provided by the experienced instructor. Hence, the students can prove their capability of dealing with complex situations, including UAS in a simulated environment.

8. Case studies

In this section, the case studies are presented. Adopting the training method presented in Fig. 9, the main goal of this section is to show how our proposal can be applied to different training scenarios. Firstly, a more straightforward scenario is presented. Secondly, a more challenging scenario is considered. Finally, the training in a complex scenario is conducted.

The experiments consider an experienced ATCo as the instructor, who proposes the scenarios and their respective solutions. Also, we assume the simulated behavior of three trainees based on the average solutions proposed during ATCo training. The case studies' objective is to highlight our proposal's applicability. Finally, in the experiments, we consider an early stage of the UAS integration in the NAS airspace, in which the Manned Aircraft (MA) presents TML 10 and the Remotely Piloted Aircraft System (RPAS), and the Autonomous Aircraft (AA) present, respectively, TMLs 5 and 0.

8.1. Case study I

The primary objective of this case study is to show the applicability of our proposal in a simple scenario composed of three aircraft. Firstly, scenario building is presented. Then, the solutions are proposed. Finally, the evaluation is conducted.

8.1.1. Scenario building

The scenario considered in the first case study is presented in Fig. 10. In this scenario, three Manned Aircraft (MA) are present, i.e., the first scenario does not consider the presence of the UAS. The headings of these aircraft are 225, 270, and 315 degrees. Furthermore, a Cumulonimbus (CB) in a vital region is represented by the red circle. Note that all aircraft have a TML 10.

8.1.2. Solutions proposal

The solutions proposed for this problem are illustrated in Fig. 11. The solution (a) proposed by the instructor is a reference solution for those proposed by the trainees 1 (b), 2 (c), and 3 (d).

8.1.3. Evaluation

The results achieved in the FSST evaluation for each solution are presented in Table 2. The solution proposed by the instructor presented the lowest duration and ATCo workload. The solution proposed by trainee 1 presented a considerable increase in the duration but maintained the ATCo workload level. The solution proposed by trainee 2 presents a slight increase in comparison to the solution proposed by the instructor regarding duration. Finally, the solution proposed by trainee 3 presents a similar result to the experienced ATCo.

8.2. Case study II

The primary objective of this case study is to show the applicability of our proposal in a more challenging scenario, which, compared to the first case study, is more impacted by the weather conditions. The scenario is firstly built and the solutions are proposed. Finally, the

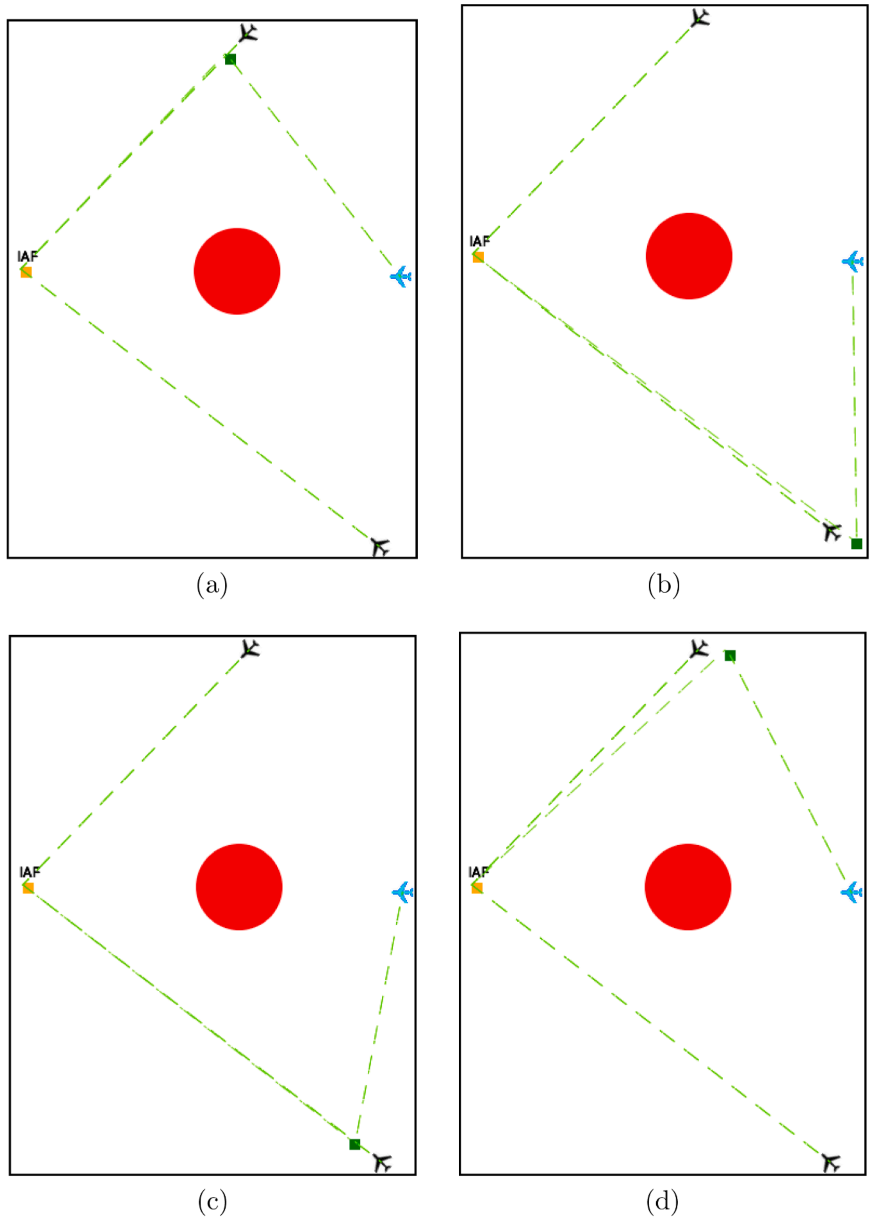

Fig. 11. Solutions provided by in Case Study I (a) the instructor, (b) trainee 1, (c) trainee 2, and (d) trainee 3.

Table 2
Results of the proposed solutions (Case Study I).

Author	ATCo Workload (s)	Duration (s)
Instructor	120	534
Trainee 1	120	704
Trainee 2	120	652
Trainee 3	120	575

evaluation process is conducted.

8.2.1. *Scenario building*

The scenario adopted in this case study is illustrated in Fig. 12. Three aircraft are considered: two Remotely Piloted Aircraft System (RPAS) (TML 5 with headings of 225 and 270 degrees) and one MA (TML 10 with a heading of 315 degrees). Hence, this case study includes the presence of UAS (RPAS). Furthermore, two Cumulonimbus (CB) present a considerable impact on the situation complexity due to their positions.

8.2.2. *Solutions proposal*

The solutions proposed for this problem, illustrated in Fig. 13, highlights the differences in the decision made by the instructor and the trainees. Solution (a) is the one proposed by the instructor. The solutions (b), (c), and (d) are presented, respectively, by trainees 1, 2, and 3.

8.2.3. *Evaluation*

The results of the solution proposed by each trainee are shown in Table 3 preceded by the results achieved with the solution proposed by the instructor. In this experiment, trainee 3 proposed a solution that cannot deliver the aircraft to the IAF respecting the airspace restrictions, i.e., this is an infeasible solution.

8.3. *Case study III*

The main objective of this case study is to show the applicability of our proposal in a complex scenario composed of five aircraft. Firstly, the scenario is built. Secondly, the solutions are proposed. Finally, the evaluation process is conducted.

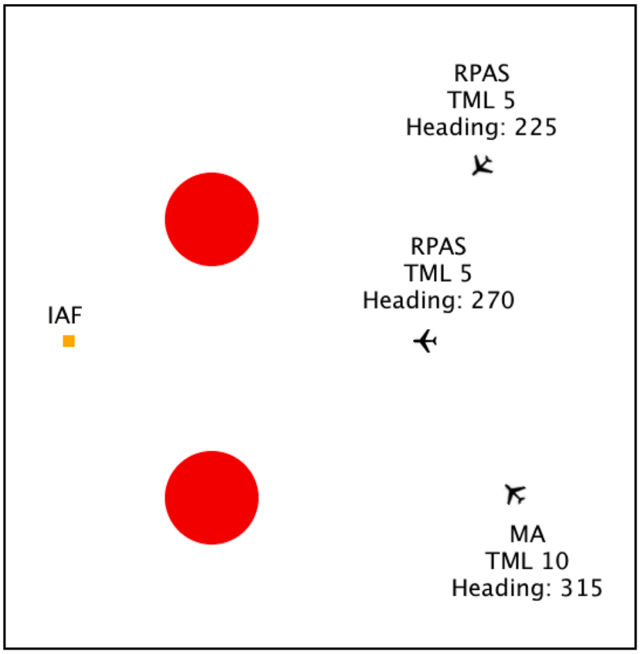

Fig. 12. Scenario considered in the case study II.

8.3.1. Scenario building

The final case study presents the scenario faced in Fig. 14. This scenario presents a more complex situation due to the number of aircraft and the mix of types. Five aircraft are considered: Two Autonomous Aircraft (AA), with TML 0 and headings of 225 and 270 degrees, and three Manned Aircraft (MA), with TML 10 and headings of 180, 315, and 360 degrees. Finally, the CBs are positioned in similar regions to those in case study II.

8.3.2. Solutions proposal

The solutions proposed, presented in Fig. 15, differ considerably from each other due to the complexity of the scenario. However, although the duration and the ATCo are different for each solution, all solutions are feasible (i.e., all of them respected the airspace constraints).

8.3.3. Evaluation

Table 4 shows all results achieved concerning ATCo workload and duration to verify the quality of the feasible solutions proposed by the trainees. In this case, the solution provided by trainee 3 presented the closest result to the solution proposed by the instructor. Furthermore, the difference concerning workload is also slight since the ATCo workload evaluation is conducted regarding the number of VPs, which are similar.

9. Discussion

The results achieved in the experiments showed that the trainees' answers might vary considerably depending on the complexity of the scenarios. In the first case study, the ATCo workload achieved for all solutions is the same since the number of Vectoring Points (VPs) defined are the same and, in this proposal, the workload evaluation is conducted

Table 3
Results of the proposed solutions (Case Study II).

Author	ATCo Workload (s)	Duration (s)
Instructor	131	558
Trainee 1	161	760
Trainee 2	131	641
Trainee 3	infeasible	infeasible

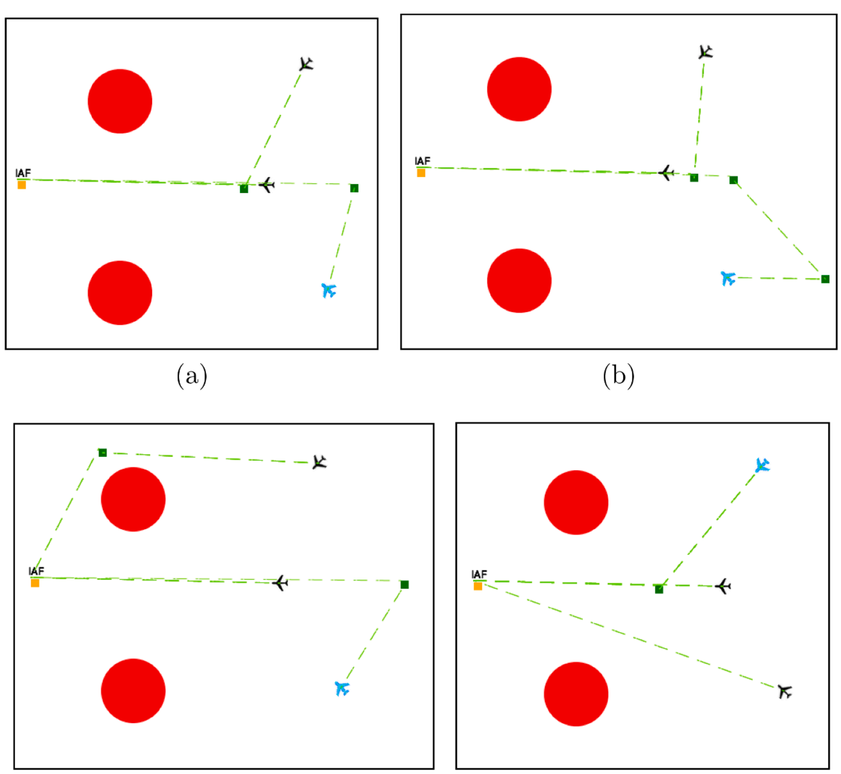

Fig. 13. Solutions provided by in Case Study II (a) the instructor, (b) trainee 1, (c) trainee 2, and (d) trainee 3.

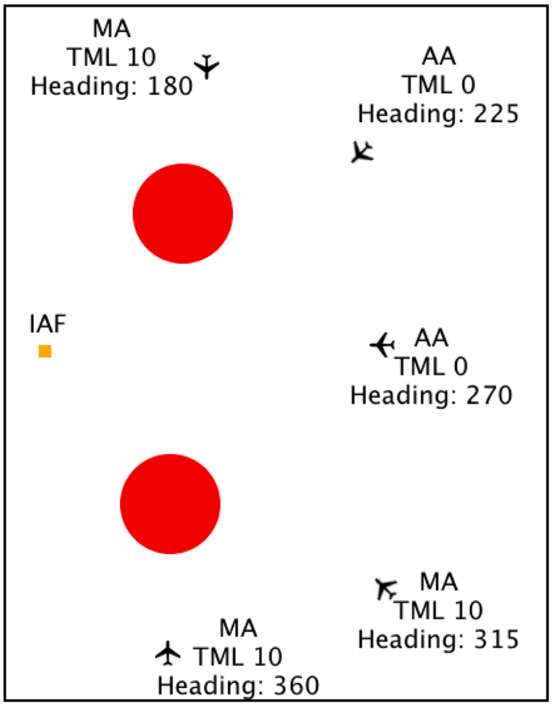

Fig. 14. Scenario considered in the case study III.

in terms of these points. On the other hand, there is a difference in terms of the duration of the solutions. For instance, the difference in duration between the solution proposed by the instructor and that proposed by trainee 1 is 170 s.

Furthermore, the profiles observed during the experiments were the risk-averse (trainee 1), which tends to maintain the aircraft more separated; the risk-taking (trainee 3), which tends to let the aircraft closer to each other; and the balanced (trainee 2), which relies on the middle of the risk-averse and the risk-taking profiles.

The risk-taking trainee presented the best result in the first case study. However, in the second one, the separation of the aircraft does not respect the minimum separation criteria, and the solution was considered infeasible. This highlights the importance of safety aspects in airspace operation, i.e., there is a need to optimize efficiency, but safety constraints must be respected.

Finally, the last case study presented a complex scenario in which the results achieved by the solution proposed by the instructor differed considerably in comparison to those proposed by the trainees. The best result among the trainees presented 30 s of additional ATCo workload and 151 s of additional duration. In contrast, the risk-averse solution presented 120 s and 198 s of additional ATCo and duration, respectively.

10. Conclusion

This research presents an approach for dealing with the training of ATCos considering the presence of UAS. The integration of these aircraft represents a challenge from the Air Traffic Control (ATC) perspective, and preparing the ATCos is essential for maintaining the airspace safely. Considering a focus on aircraft vectoring within the final sector of the Terminal Control Area (TMA), the framework proposed allows instructors to build different scenarios. Different aspects are considered, such as bad weather conditions (represented by the presence of cumulonimbus) and different aircraft types (using the TML), i.e., Manned Aircraft (MA), Remotely Piloted Aircraft System (RPAS) and Autonomous Aircraft (AA).

The case studies highlighted the applicability of our proposal. Different scenarios were considered, combining bad weather conditions, different aircraft types (MA, RPAS, and UAS), and different positions for all objects (CB< aircraft and objective point). Indeed, a gamified approach to teaching ATC concepts is built, and the instructor can create several scenarios to simplify the insertion of UAS into the National Airspace System (NAS).

The solutions proposed were evaluated and compared regarding efficiency and ATCo workload level based on the Technology Maturity Level (TML) system. Thus, solutions that presented a more significant separation between the aircraft (i.e., the solutions that ensured the aircraft were well-separated) presented a more considerable duration, i.e., reduced efficiency. On the other hand, the solutions that reduced the separation between the aircraft presented a higher efficiency but, in some cases, may lead the airspace to unsafe states. The best solutions in this context rely on the middle of safety and efficiency, balancing the distance between the aircraft to maintain the safety and efficiency levels.

Finally, this research presents several possibilities for future extensions. Some future directions are:

- The development of tools for enhancing the teaching and learning processes for different areas of airspace operation. One example is the takeoff procedure in complex situations;
- Automation of the solution proposal and automatic verification of trainees' performance. For instance, a platform for self-paced learning could employ such a framework for offering a learning environment to a wider public;
- The proposal of strategies for training ATCos for all training phases pointed in [11] (Initial, Unit and Continuation training);
- The proposal of a multi-agent framework for training ATCos in communication with the aircraft. This could employ voice processing techniques to measure the effectiveness of voice instructions;
- The proposal of a method for integrating our proposal with different approaches for building a real-time simulation environment for training different airspace operators (e.g., ATCos and pilots).

CRediT authorship contribution statement

Euclides Carlos Pinto Neto: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Derick Moreira Baum:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jorge Rady de Almeida:** Writing – review & editing, Validation, Software, Methodology, Investigation, Conceptualization. **João Batista Camargo:** Writing – review & editing, Validation, Software, Methodology, Investigation, Conceptualization. **Paulo Sergio Cugnasca:** Writing – review & editing, Validation, Software, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.treng.2024.100266.

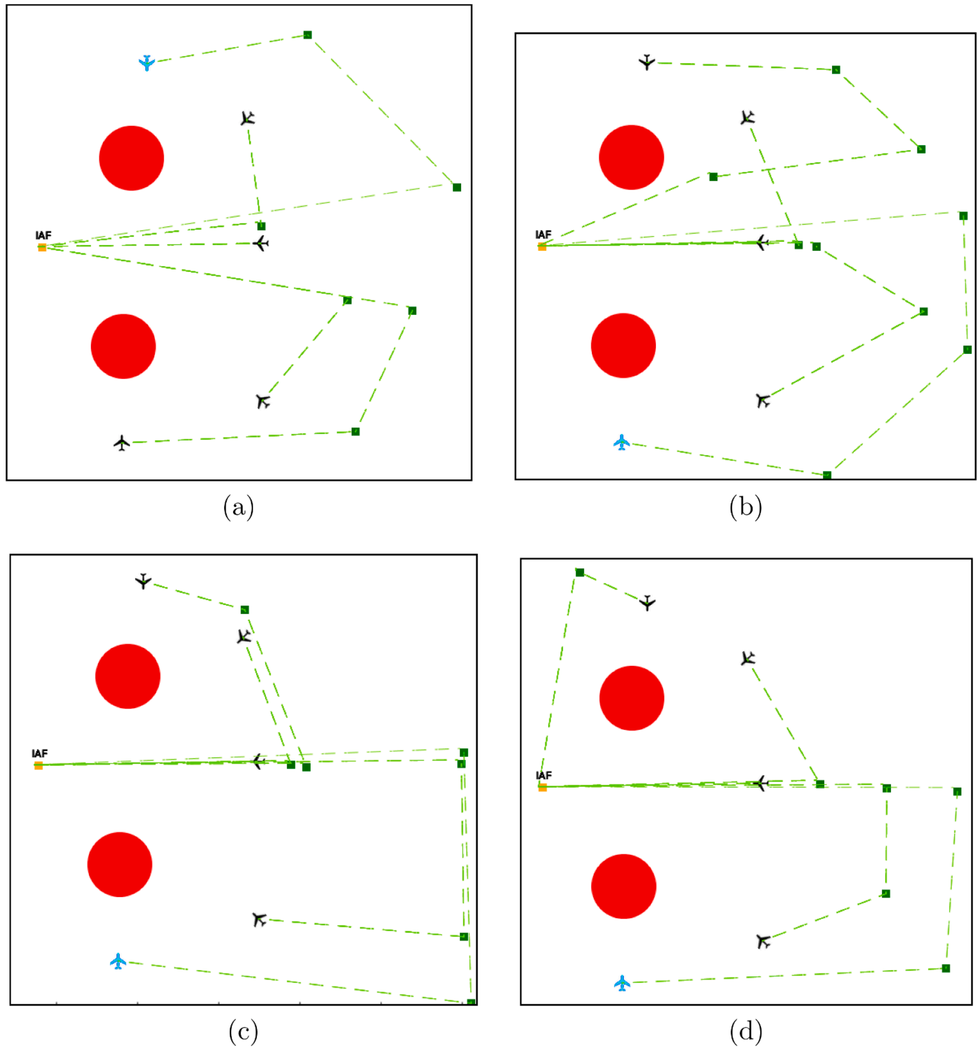

Fig. 15. Solutions provided by in Case Study III (a) the instructor, (b) trainee 1, (c) trainee 2, and (d) trainee 3.

Table 4
Results of the proposed solutions (Case Study III).

Author	ATCo Workload (s)	Duration (s)
Instructor	260	1007
Trainee 1	380	1205
Trainee 2	320	1310
Trainee 3	290	1158

References

[1] S. Marquart, M. Ponater, F. Mager, R. Sausen, Future development of contrail cover, optical depth, and radiative forcing: Impacts of increasing air traffic and climate change, J. Clim. 16 (17) (2003) 2890–2904.
[2] T. Noskievič, J. Kraus, Air traffic control tools assessment, MAD-Mag. Aviat. Dev. 5 (2) (2017) 6–10.
[3] R.J. Reisman, Air traffic management blockchain infrastructure for security, authentication, and privacy (2019).
[4] M.E. Baltazar, T. Rosa, J. Silva, Global decision support for airport performance and efficiency assessment, J. Air Transp. Manage. (2018).
[5] Finavia, Efficiency is backbone of airport competitiveness, 2015.
[6] A. Majumdar, W. Ochieng, Factors affecting air traffic controller workload: multivariate analysis based on simulation modelling of controller workload, Transp. Res. Rec. J. Transp. Res. Board (1788) (2002) 58–69.
[7] R. Woltjer, Exploring resilience at interconnected system levels in air traffic management. Exploring Resilience, Springer, 2019, pp. 105–112.
[8] Y. Li, D.-M. Nie, X.-X. Wen, Y.-y. Gao, Arrival aircraft optimal sequencing based on teaching-learning-based optimization algorithm with immunity. IOP Conference Series: Earth and Environmental Science 189, IOP Publishing, 2018, p. 062003.
[9] V. Riahi, M.H. Newton, M. Polash, K. Su, A. Sattar, Constraint guided search for aircraft sequencing, Expert Syst. Appl. 118 (2019) 440–458.
[10] M. Brittain, P. Wei, Autonomous aircraft sequencing and separation with hierarchical deep reinforcement learning. Proceedings of the International Conference for Research in Air Transportation, 2018.
[11] ICAO, Manual on air traffic controller competency-based training and assessment - doc 10056, 2016.
[12] D. Guerin, Consideration of wake turbulence during the integration of remotely piloted aircraft into the air traffic management system. 2015 International Conference on Unmanned Aircraft Systems (ICUAS), IEEE, 2015, pp. 926–935.
[13] J. Złotowski, K. Yogeeswaran, C. Bartneck, Can we control it? Autonomous robots threaten human identity, uniqueness, safety, and resources, Int. J. Hum.-Comput. Stud. 100 (2017) 48–54.
[14] A. Bye, Future needs of human reliability analysis: the interaction between new technology, crew roles and performance, Saf. Sci. 158 (2023) 105962, https://doi.org/10.1016/j.ssci.2022.105962.
[15] P. Kopardekar, J. Rios, T. Prevot, M. Johnson, J. Jung, J. Robinson, Unmanned aircraft system traffic management (UTM) concept of operations. AIAA Aviation Forum, 2016.
[16] R.B. Ferreira, D.M. Baum, E.C.P. Neto, M.R. Martins, J.R. Almeida, P.S. Cugnasca, J.B. Camargo, A risk analysis of unmanned aircraft systems (UAS) integration into non-segregate airspace. 2018 International Conference on Unmanned Aircraft Systems (ICUAS), IEEE, 2018, pp. 42–51.
[17] J. Pérez-Castán, F.G. Comendador, A. Rodríguez-Sanz, I.A. Cabrera, J. Torrecilla, RPAS conflict-risk assessment in non-segregated airspace, Saf. Sci. 111 (2019) 7–16.
[18] L. Grindle, D.L. Hackenberg, Unmanned aircraft systems (UAS) integration in the national airspace system (NAS) project: KDP-A for phase 2 minimum operational performance standards (2016).
[19] N. Durand, J.-B. Gotteland, N. Matton, Visualizing complexities: the human limits of air traffic control, Cognit. Technol. Work (2018) 1–12.

[20] M. Truschzinski, A. Betella, G. Brunnett, P.F. Verschure, Emotional and cognitive influences in air traffic controller tasks: an investigation using a virtual environment? Appl. Ergon. 69 (2018) 1–9.
[21] J. Skorupski, P. Ferduła, The influence of errors in visualization systems on the level of safety threat in air traffic, J. Adv. Transp. 2018 (2018).
[22] B. Chhaya, S. Jafer, W.B. Coyne, N.C. Thigpen, U. Durak, Enhancing scenario-centric air traffic control training. 2018 AIAA Modeling and Simulation Technologies Conference, 2018, p. 1399.
[23] F. Ferrari, K.P. Spillmann, C.P. Knecht, K. Bektas, C.M. Muehlethaler, Improved pilot training using head and eye tracking system. Eye Tracking for Spatial Research, Proceedings of the 3rd International Workshop, ETH Zurich, 2018.
[24] ICAO, Air traffic management - doc 4444, 2016.
[25] AirNav, Miami international airport area chart (ARC), 2016, (https://www.airnav.com/airport/KMIA). Accessed: October 2022.
[26] M. Fromm, R. Bevilacqua, R. Servranckx, J. Rosen, J.P. Thayer, J. Herman, D. Larko, Pyro-cumulonimbus injection of smoke to the stratosphere: observations and impact of a super blowup in northwestern canada on 3–4 August 1998, J. Geophys. Res. Atmos. 110 (D8) (2005).
[27] Y. Liu, C. Han, H. Qi, Z. Zhu, Aircraft rerouting decision-making model under severe weather. Information Science and Control Engineering (ICISCE), 2016 3rd International Conference on, IEEE, 2016, pp. 814–818.
[28] J.S. Mitchell, V. Polishchuk, J. Krozel, Airspace throughput analysis considering stochastic weather. AIAA Guidance, Navigation, and Control Conference 19, 2006.
[29] F.A.A. FAA, Advisory circular - aviation weather, 2016.
[30] F. Ludlam, Cumulonimbus, OSTIV Publ. 4 (1956) 145–148.
[31] G. Fasano, D. Accado, A. Moccia, D. Moroney, Sense and avoid for unmanned aircraft systems, IEEE Aerosp. Electron. Syst. Mag. 31 (11) (2016) 82–110, https://doi.org/10.1109/MAES.2016.160116.
[32] R. Austin, Unmanned Aircraft Systems: UAVS Design, Development and Deployment 54, John Wiley & Sons, 2011.
[33] SESAR, RPAS ATM CONOPS, 2017.
[34] J. Romero, L. Gomez, Proposal for RPAS integration into non-segregated airspaces. Integrated Communications, Navigation and Surveillance Conference (ICNS), 2017, IEEE, 2017.pp. 6C2–1
[35] E.P. Neto, D.M. Baum, C.E. Hernandez-Simões, J.R. Almeida, J.B. Camargo, P. S. Cugnasca, An airspace capacity-based safety assessment model considering UAS integration. Unmanned Aircraft Systems (ICUAS), 2017 International Conference on, IEEE, 2017, pp. 961–970.
[36] E.C.P. Neto, D.M. Baum, J.R. Almeida, J.B. Camargo, P.S. Cugnasca, Evaluating safety and efficiency in aircraft sequencing in final approach considering the UAS presence. XXXI Congresso de Pesquisa e Ensino em Transportes, 2017.
[37] A. Dervic, A. Rank, ATC complexity measures: formulas measuring workload and complexity at stockholm TMA, 2015.