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# A Mindset-Based Evolution of Unmanned Aircraft System (UAS) Acceptance Into the National Airspace System (NAS)

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**ABSTRACT** The main goal of this research is to evaluate the Air Traffic Controller (ATCo) workload considering the Unmanned Aircraft System (UAS) integration into the National Airspace System (NAS) through fast-time simulations, and including futuristic scenarios in which the ATCo is familiar with manned and unmanned aircraft, i.e., different ATCo mindsets are considered. As these professionals play an essential role in optimizing the airspace operation, maintaining their workload at an acceptable level is essential. However, the integration of new technologies, such as UAS, may present an impact on safety levels from the workload perspective. In this context, the Technology Maturity Level (TML), which is a systematic metric/measurement system that supports assessments of the familiarity of a particular aircraft with ATCos, is proposed. The experiments showed that the integration of UAS into the NAS should be conducted gradually.

**INDEX TERMS** Unmanned aircraft system (UAS), National Airspace System (NAS), Air Traffic Controller (ATCo), safety, workload.

## I. INTRODUCTION

The primary goal of this research is to evaluate the ATCo workload considering the Unmanned Aircraft System (UAS) integration into the National Airspace System (NAS) through fast-time simulations. Also, we consider futuristic scenarios in which the Air Traffic Controllers (ATCos) are familiar with manned and unmanned aircraft and, consequently, different ATCo mindsets. Furthermore, a comparison of UAS impacts on workload during the early stages of its integration and in a long-term future is conducted.

Air transportation has become essential for society and is gradually increasing to meet the demand [33]. The growth in flight numbers leads to a higher revenue whereas making the airspace more complex. There are many challenges to be faced by the authorities in the following years, especially regarding airspace safety and efficiency. In this context, the Air Traffic Control (ATC) plays an essential role in optimizing the airspace operation, especially considering that safety and efficiency are vital aspects of airspace operation [12], [26]. The ATC is divided into ATC units, which is a ''generic term meaning variously, area control center, approach control unit or aerodrome control tower'' [20]. These units are organized in a manner to accommodate all airspace users by the creation of control sectors. The Air Traffic Controllers (ATCo) are responsible for controlling aircraft in each control sector. The ATCo responsible for a given sector must communicate to ATCos responsible for other sectors to provide smooth conduction of aircraft throughout their flights, especially when the aircraft fly through different ATC operation areas.

The ATCo aims to guarantee appropriate safety and efficiency levels to solve issues present in complex situations. Moreover, the Air Traffic Control (ATC) provides Air Traffic Services (ATS) to flights through ATCo instructions. The primary goals of these services include avoiding mid-air collisions and collisions with obstacles and optimizing and maintaining an orderly flow of air traffic [46]. 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

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efficiency, such as aircraft vectoring. In fact, many of these professionals act collaboratively from the beginning to the end of each flight, and as flights evolve through their flight plan and reach sectors limits, new ATCos are assigned for controlling them. However, a challenge currently faced is to maintain the workload level under an acceptable threshold.

Among the several safety threats in airspace operation, mid-air collision can be highlighted, which depends on a set of events despite issues in aircraft mechanical systems, such as high ATCo workload levels and loss of the minimum separation established between aircraft. There has been an effort of authorities toward such events (e.g., ATCo training for critical situations and design of safe standard procedures). Furthermore, in high air traffic density situations, a safer measure of the capacity of a sector is based on ATCo workload [30], i.e., the number of aircraft that can be safely accommodated decreases when there is a higher workload level. As ATCo workload levels are related to safety and there is an understanding by the scientific and the operational communities that airspace complexity is one of the main factor impacting this metric [28]; situations that these professionals are not familiar with tends to be more unsafe once the decision-making process becomes harder. Moreover, several variables compose complexity, such as traffic density and mental factors [8].

In order to improve the airspace operation, new technologies are under development, such as Unmanned Aircraft Systems (UAS) [4] and Decision Support Tools (DST) for ATCos (e.g., Arrival and Departure managers) [38]. These new technologies present advantages in many aspects, such as safety, efficiency and airspace capacity [2], [27]. Furthermore, the DSTs aim to lead ATCos to more effective decisions, which tends to reduce the ATCos workload and, ultimately, to help them to deal with airspace complexity in a better way [28]. Although several situations require these technologies, they may bring uncertainties since ATCos may not be familiar to dealing with them. Furthermore, new technologies that are being integrated into the airspace (e.g., UAS) may be common in the future, which increases the familiarity of ATCo with them.

In this context, the UAS, which play an important role due to the advantages they bring to the airspace (e.g., efficiency) [1], [11] and have been considered a relevant topic in the engineering community due to their applications [10], [24], are systems composed of sub-systems such as Unmanned Aerial Vehicle (UAV), its payloads, the control station and communications sub-systems [4], [10], [13]. There are different types of UAS, such as fully Autonomous Aircraft (AA) and Remotely Piloted Aircraft Systems (RPAS).

In the past few years, there has been a growth in UAS numbers [15] in the National Airspace System (NAS). Hence, there is an interest in integrating these aircraft into the NAS. These aircraft, which can be remotely piloted or fully autonomous and have several military and civil applications, present challenges on its integration. Authorities have to find ways to deal with the new unsafe states being included into the airspace. For example, bugs in software may maneuver the aircraft and assign it to undesired headings. Also, considering RPAS, failures in the Command and Control (C2) link, i.e., the link the pilot uses to communicate to the aircraft, may lead to unsafe states [19], [37].

Furthermore, the relationship between UAS and ATC needs to be well-defined, due to the impacts on the ATC capacity these aircraft may present. Throughout the years, this impact may be lower than it currently is. In fact, the present lack of familiarity regarding the relationship between UAS and ATCo contributes to higher workload levels once there is an uncertainty concerning safe and efficient operations capabilities. As UAS does not operate within the NAS nowadays, this is reasonable to consider that ATC tends to be more careful when controlling a gate-to-gate flight of these autonomous systems. This is due to the hurdles of accepting the interaction of an autonomous system and a human operator in a safety-critical environment. Also, this integration requires different challenges to be addressed, such as specific regulations, policies and procedures, enabling technologies and standards development for dealing with UAS [14]. As the integration of UAS enables new applications and its use may increase in the future [16], developing approaches to integrate it safely is essential.

The Technology Readiness Levels (TRL), proposed by NASA and employed for measuring the readiness of a given aircraft to operate in airspace [31], is a widely used scale. It provides an understanding on the steps needed to develop an aircraft from scratch. In this context, considering the lack of familiarity of ATCo when dealing with UASs and that this familiarity may increase throughout the years, a scale that models this metric is desired. Furthermore, the Technology Maturity Level (TML) is proposed herein aiming to differentiate aircraft by familiarity levels, i.e., the activities performed by ATCo varies according to the TML of each aircraft [36].

This paper is organized as follows: Firstly, section II presents the related works. Then, sections III and IV present a discussion on the integration of UAS into the NAS and the proposed Technology Maturity Level (TML), respectively. After that, sections V, VI and VII respectively present the method adopted in this research, the case studies considered and a discussion on the results achieved. Finally, section VIII shows the conclusion as well suggesting as future works.

## II. RELATED WORKS

Shmelova *et al.* [50] present an approach based on statistical data to deal with the problem of UAV flights considering different tasks in emergency situations. Also, an analysis of the emergency type is conducted and a sequence of actions is defined. The authors present a motivation for the development of their research such as lack of algorithms to recommend actions for the UAV operator in emergency situation, problems in the decomposition of the decision-making process and the lack of structure of Distributed Decision Support System (DDSS) for remotely piloted aircraft. Models are developed in order to determine the optimal landing site in specific situations and to search for optimal flight routes. However, the emergency situations considered do not include levels of familiarity between the ATCo and the UAV.

Pastor *et al.* [40] evaluate the interaction between a RPAS and the Air Traffic Management (ATM) considering that a RPAS is being operated in shared airspace. This evaluation employs human-in-the-loop real-time simulations, which allows simulating activities from both the RPAS Pilot-in-Command (PiC) and the ATCo, from three different perspectives: separation management, contingency management and capacity impact on the overall ATM system. The experiments conducted, realistic and without excessive complexity, presented recommendations to improve the evaluation, e.g. preliminary analysis of traffic to prevent separation conflicts and improvement of an Automatic Dependent Surveillance-Contract (ADS-C) flight intent communication mechanism. Note that in addition to this research, our approach also considers fully autonomous aircraft.

Mcfadyen *et al.* [34] present simple simulations and modelling tools focused on the safety assessment of UAS within the unsegregated airspace. The See and Avoid environment is simulated considering a pair-wise encounter generator, which is based on a hybrid database and a statistical performance evaluation of autonomous decision and control strategies. An unmanned aircraft mission generator is also developed in order to illustrate the impact of multiple unmanned operations on air traffic using real traffic data in Australia. These approaches can be used to address challenging problems faced by civilian UAS integration. However, this paper does not deal with UAS impacts on ATCo workload evaluation.

Ramalingam *et al.* [42] discuss the integration of UAS in non-segregated airspace. The authors state that this integration is a complex system-of-systems problem. Also, the reasons for the difficulty in the integration are analyzed and the considered key challenges (sense and avoid, UAS autonomy, UAS system safety and social-political factors) represent a different view to stakeholders (regulators, system developers and UAS end user). However, this paper does not focus on specific topics such as the evolution of UAS impacts on ATCo operation throughout the years.

Perez *et al.* [41] evaluate the interaction between a RPAS and the ATM in a non-segregated airspace from three perspectives: separation management, contingency management and dynamic mission changes. The workload of the ATCo is also analyzed. The results showed that further research needs to be conducted regarding the RPAS 4D trajectory prediction as well as improved task load and workload models that take into account the RPAS particularities. In addiction to this research, our proposed focus lies on aspects such as the definition of additional activities of ATCo due to UAS integration.

Gimenes *et al.* [43] propose guidelines to support UAS regulations for integrating of fully autonomous UASs into the Global Air Traffic Management System (GATM), and, consequently, into shared airspace. These guidelines are proposed facing three different perspectives: the aircraft itself, the Piloting Autonomous System (PAS) and the integration of autonomous UASs into non-segregated airspace. Considering that there are social and economic interests in UAS applications, enabling this technology to operate along with traditional aircraft is desired. The main issue of this integration is that UAS operations in non-segregated airspace should be regulated by aeronautical authorities, although defining these rules is difficult because there is not a deep understanding of UAS operation as well as how they behave in case of failures (e.g. contingency operations). Throughout the paper, the authors present the guidelines with a different focus. For example, regarding the "aircraft focus", although it is not in the scope of this paper, the authors state that it "should be submitted to at least the same processes and criteria of developing, manufacturing and certification regarding avionic systems of manned aircraft, aiming to reach the same safety levels". Furthermore, the authors highlight that the UAS concept should be based on aeronautical precepts and that the possibility of integrating UASs into airspace depends on specific regulations. In addiction to this effort, our research deals with additional workload related to new technologies, i.e., related to UAS. Also, the authors do not consider future scenarios in which most of the aircraft may be composed of UAS.

Shin *et al.* [49] presents a risk assessment approach that considers vehicular communication. This approach, which is intended for use in automated driving vehicle and is human-centered, relies on sensor fusion (vehicle-to-vehicle wireless communication and radar sensor) for enhancing remote vehicle motion prediction. Achieving safe and efficient vehicle operations may be challenging sometimes due to a variety of reasons (e.g., uncertainty and density). Indeed, the proposition of new ways of assessing the risks of collisions is important for enhancing the safety of both drivers and passengers. For this, the authors develop a risk assessment algorithm that considers the human reaction time for collision avoidance that monitors threat vehicles ahead; its performance is investigated via computer simulations and vehicle tests. This approach makes active safety system of automated vehicle present a more human-like driving intelligence. Finally, the experiments highlighted that the proposed approach reduces the overestimation and underestimation of a conventional radar-only system in safety-critical situations. Conversely, this research focuses on enhancements from the vehicle perspective. Besides, the focus is on ground-based vehicles.

Sesso *et al.* [48] propose a qualitative approach for assessing the safety of UAS operations when using Automatic Dependent Surveillance-Broadcast (ADS-B) systems considering a new testing platform, called Integrated Platform for Test of Embedded Critical Systems (PIpE-SEC), as a possible approach for this safety evaluation. The focus of this research is on the influence of data integrity, which is considered a safety-related parameter. The increase in the UAS presence (in segregated airspace) is pressing authorities to design airspace rules to integrate these aircraft into non-segregated airspace safely although safety issues arise when both manned and unmanned aircraft coexist in the airspace. Furthermore, surveillance and, consequently, data integrity play important roles in controlling these aircraft. In this context, the positional information provided by the ADS-B, which is essential to UASs control systems operation, interacts with the Sense and Avoid Systems (S&AS) of the UAS in order to avoid exposure to unsafe situations. Finally, the authors discuss the use of a methodology previously applied to manned systems for assessing safety and state that the adoption of the presented methodology and tools enables the identification of appropriate scenarios for inserting UAS along with manned aircraft, maintaining the same safety. However, this research does not focus on ATCo workload related to UAS integration.

Oztekin *et al.* [39] propose a systems-level approach to analyze the safety impact based on risk controls of introducing new technologies into the National Airspace System (NAS), such as UAS, considering Safety Management Systems (SMS) principles and existing regulatory structure. Furthermore, the authors present a methodology to identify minimum safety baselines for safe operations in the NAS and show its applicability through a proof-of-concept study. In this context, UAS emerges as a viable technology for potential civil and commercial applications in the NAS, despite requiring a deeper analysis of safety impact. A detailed outline of the concepts and methodologies used for constructing a proof-of-concept study for the proposed approach, which considers related hazards and underlying causal factors, is also presented. Finally, the safety baseline proposed in this research identifies a set of minimum risk controls for conducting safe operations. In addition to this research, although this effort already focuses on the safety of UAS integration, our approach considers specific topics such as the evolution of maturity in UAS operations throughout the years regarding ATCo activities.

An architecture that provides data and software services to enable a set of UAS platforms to operate into non-segregated airspace (including, terminal, en route and oceanic areas) is presented in [17]. The authors present the general architecture and a Sense and Avoid (SAA) testbed implementation to quantify the benefits. This architecture, based on a Service-Oriented Architecture (SOA) with open standards, aims to support UAS operations by offering a set of services to meet their requirements (e.g., command, control, and data management). The proposed approach is considered a guidance and offers architectural best practices. Finally, even considering that a SOA architecture makes some aspects of certification more challenging, this approach presents some advantages and can be implemented in a manner to meet performance requirements. Note that certification may be more straightforward considering the use of formal service contracts, with comprehensive interface and quality of service specifications, and governance process in this SOA architecture. However, this research does not evaluate ATCo workload and how UAS impact the airspace throughout the years.

## III. UAS INTEGRATION INTO THE NATIONAL AIRSPACE SYSTEM (NAS)

Unmanned aircraft system (UAS), which is an important business considering its potential and applications [10], is a system composed of sub-systems such as unmanned aircraft vehicle (UAV), its payloads, the control station and communications sub-systems [4], [10]. UAS has been employed in different scenarios and presents advantages in many applications, such as reducing the risks associated with pilots in applications (e.g., video surveillance) [11]. Furthermore, the sub-systems that compose the UAS have specific responsibilities that represent important aspects of the whole system operation, such as:

- **Control Station (CS):** represents the control center of the operation. This component enables the operator to conduct the aircraft properly through specific interfaces [4].
- **Payload:** is the extra mass the aircraft needs to carry, and is defined depending on the mission purpose. For example, in sensing applications, equipment such as cameras, sensors, and other payloads may be required, and the aircraft needs to operate such that it optimizes the process of gathering the desired data [25].
- **Aerial Vehicle:** represents the unmanned aircraft vehicle (UAV). This component is related to the aircraft operation characteristics, such as the speed and altitude at which it operates. The UAV performance may vary widely depending on the mission considered.
- **Navigation Systems:** this component plays the role of providing an understanding of the position of the UAV, at any moment in time, to the operator, during the flight, and to the UAV, in emergency procedures such as "return to base" capability [4].
- **The Launch, Recovery and Retrieval Equipment:** this component acts, with several available systems, in the most crucial phase regarding safety in the aircraft operation: landing and take-off [7].
- **Communications:** it is responsible for establishing the communication between the operator and the aircraft. This component is divided into two links: the uplink, which represents the communication between the operator and the aircraft, and the downlink, which deals with the communication between the aircraft and the operator [4].
- **Interfaces:** define the manner the components of UAS interact with each other. For example, the protocol considered in the communication between the operator and the aircraft must be implemented in both systems in order to establish the data transference [4].
- **Interfacing with other Systems:** defines the manner the UAS interacts with the world, i.e., the manner it interacts with other systems [4].

UAS can be divided into two main categories concerning piloting: Remotely Piloted Aircraft Systems (RPAS) and Autonomous Aircraft (AA). RPAS stands for a system with an operator, i.e., the aircraft is not fully autonomous.

The International Civil Aviation Organization (ICAO) has been working to understand, to define and to integrate the RPAS aiming to provide an international regulatory framework [19]. An essential aspect of RPAS is the command and control (C2) link, which connects the Remote Pilot Station (RPS) and the RPAS for controlling the flight [19]. However, this link may fail and the aircraft must thus become a fully autonomous system.

The Autonomous Aircraft (AA) are piloted by intelligent software, i.e., intelligent algorithms pilot these aircraft instead of human pilots. The piloting process can employ different Artificial Intelligence (AI) techniques, such as Reinforcement Learning (RL). Although there are many advantages of using of this technology in the NAS (e.g., risk reduction and efficiency improvement [1], [3], [5], [9], [45], [52]), its interaction with other modules may lead the system to unsafe states. For example, the misunderstanding of instructions provided by ATCos and the lack of proper communication with other AAs in critical situations. Note that there is a concern towards understanding how these aircraft communicate and how precise they are in following instructions provided by the ATC. Indeed, this concern relies on the hurdles of accepting the interaction of an autonomous system and a human operator in a safety-critical environment. Self-driving car, for example, is an autonomous system that still has a path to be fully accepted by society and raises some discussions on how these systems can be integrated into safety-critical environments [3].

In terms of weight, UASs can be classified into three categories [44], as illustrated in Table 1. Class one represents the small UASs, which have many applications in a smaller environments. Class two represents medium-sized aircraft, varying in weight up to 600kg. Finally, aircraft heavier than 600 kg are classified in class three. This research considers a futuristic scenario in which UAS represent large commercial aircraft models and aircraft of class three.

**TABLE 1. Categories of UAS in terms of weights, adapted from [44].**

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

In order to accomplish many missions, the UAS must operate within the NAS. However, this integration may present issues such as impacts on safety levels.

According to ICAO [18], ‘‘the airspace will be organized and managed in a manner that will accommodate all current and potential new uses of airspace, for example, UAVs and that any restriction on the use of any particular volume of airspace will be considered transitory’’. Furthermore, although rules for UAS flights are defined for segregated airspace [19], the increasing interest in the use of UAS for different applications (military and civilian) requires to a need for integrating them into the NAS. For this, the safety levels must not be compromised [19]. SESAR highlights four requirements to integrate Remotely Piloted Aircraft Systems (RPAS) safely, which can also be applied to other types of UAS (e.g., fully autonomous aircraft) [47]:

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

In this context, an effort to maintain acceptable ATCo workload levels is essential regarding safety [36].

Workload can be defined as a metric that represents the difficulty of ATCo in understanding a particular situation [35], expressed in terms of seconds and measured by the interaction of various factors (e.g., exposition time to the controlling operation, ATCo experience, and current mental state [8]) that compose the airspace complexity (illustrated in Figure 1). The workload can be considered a function of (1) the geometrical nature of air traffic, (2) the operational procedures and (3) practices used to handle the traffic and the characteristics of the ATCos. Note that all these aspects are related to complexity once the geometrical structure may hinder the aircraft separation assurance, the procedures executed may lead to conflicts due to intersections with other procedures (e.g., Standard Terminal Arrival Routes - STARs - of different airports may present some intersections), and the manner of handling the aircraft may lead the airspace to reduced-separation scenarios [35].

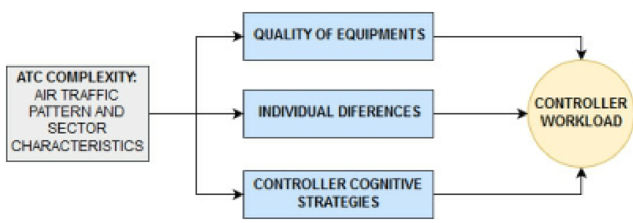


**FIGURE 1. Several variables that affect ATCo workload [8].**

The workload itself is evaluated by the time spent by ATCo when controlling traffic in a given sector when the ATCo performs a set of tasks divided into a set of activities. Each activity has a specific duration, generally expressed in seconds. Activities can be cognitive, i.e., related to the mental work of the ATCo to perform the air traffic control, and non-cognitive, i.e., related to communications, for example. Cognitive workload, or mental workload, represents all the mental activities the ATCo performs in air traffic control. It can vary broadly depending on many factors such as familiarity of the ATCo with the scenario (e.g., a scenario with UAS in its early stages of its integration). Thus, the complexity of a sector is related to the ATCo mental workload, and assessing this inside a sector provides an estimation of the associated complexity [53]. Finally, as UAS is considered a new technology in the NAS which the ATCo may not be familiar with yet, it tends to increase the mental ATCo workload due to the lack of familiarity [36], i.e., the duration of communication and surveillance tasks may also be increased. Furthermore, the familiarity between ATCo and UAS may increase in the future as the number of operations of these aircraft rises and, in a long-term future, the UAS may operate safely along with manned aircraft.

## IV. TECHNOLOGY MATURITY LEVEL (TML) PROPOSITION

The NASA Technology Readiness Levels (TRLs) aim to measure how far a given technology is from its operation in airspace. This proposal 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" and has been used in the NASA space technology planning and in the NASA Management Instruction [31]. This scale is useful for integrating new technologies smoothly by identifying precisely at which development level the technology is.

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

In this sense, there is a lack of the UAS operation (both remotely piloted and fully autonomous) into the National Airspace System (NAS) and, ultimately, a lack of liability, social acceptance, and operational exposure regarding the UAS presence [23], [54]. The surveillance is an impacted activity once there is uncertainty regarding the aircraft capability of understanding and executing instruction. In turn, the communication activities are also affected due to the time spent in defining proper manners to give a specific instruction.

The Technology Maturity Level (TML) is a systematic metric/measurement approach that supports assessments of the familiarity of a particular aircraft with ATCos. Thus, it also enables a consistent comparison of familiarity of the ATCo with different aircraft types [36]. This scale is based on three main factors that represent barriers for autonomous vehicles in general to operate [1], [9], [36]: (i) Liability; (ii) social acceptance; and (iii) operational exposure. The levels represent the familiarity, which may increase throughout the years of aircraft operation (i.e., considering the increase of liability, social acceptance, and operational exposure). Thus, the aircraft may be referred to as its TML level in order to simplify the workload evaluation.

The TML are related to the uncertainty of operation. According to Equation 1, [32], fragility is a product of complexity and uncertainty. In this context, TML is related to the uncertainty in operation and the challenges of controlling the airspace are related to complexity (e.g., high density and bad weather conditions), whereas fragility is related to impacts on the ATCo workload and, ultimately, on safety levels.

$$Complexity \times Uncertainty = Fragility \tag{1}$$

The levels of TML are illustrated in Table 2. TML 0, "Incipient Technology", highlights a technology without enough exposure to safe and efficient operations. TML 1, "High operation uncertainty", refers to the early development of technology, i.e., the phase in which liability, social acceptance and operational exposure of the technology are extremely low. In TML 2 ("Considerable operation uncertainty"), the level of uncertainty is a bit smaller, whereas in TML 3 ("Reduced operation uncertainty") the level of uncertainty is considerably reduced. These levels could be achieved by the technology using different techniques (e.g., marketing campaigns on new technologies).

**TABLE 2. TML multiplication factors.**

| TML | Description | Multiplication Factor | Additional Activities |
|---|---|---|---|
| 10 | High Operation Certainty | 1 | X |
| 9 | Acceptable Operation Certainty | 1.1 | X |
| 8 | Considerable Operation Certainty | 1.2 | X |
| 7 | Extensive Exposure to Operations | 1.3 | X |
| 6 | Small Exposure to Operation | 1.4 | ✓ |
| 5 | Operation Beginner | 1.5 | ✓ |
| 4 | Pre-Operation | 1.6 | ✓ |
| 3 | Reduced Operation Uncertainty | 1.7 | ✓ |
| 2 | Considerable Operation Uncertainty | 1.8 | ✓ |
| 1 | High Operation Uncertainty | 1.9 | ✓ |
| 0 | Incipient Technology | 2 | ✓ |

TML 4 ("Pre-Operation") illustrates the capability of the technology (from liability, social acceptance and operational exposure) to operate in specific domains (e.g., controlled environments, reduced operations, and tests). TML 5 ("Operational Beginner") represents a developing technology that can be integrated safely with reduced numbers. TML 6 ("Small Exposure to Operations") illustrates a level at which the technology presents a certain number of safe operations, i.e., there is a certain level of liability, social acceptance and operational exposure regarding the given technology.

TML 7 ("Extensive Exposure to Operation") and TML 8 ("Considerable operation certainty") represent levels at which the technology has considerable exposure to safe operations. This indicates that impacts on operation (e.g., ATCo workload) tend to be reduced.

Finally, TML 9 ("Acceptable operation certainty") and TML 10 ("High operation certainty") refer to a higher certainty level, in which the technology is liable, accepted from the social point of view and has demonstrated a capability of operating safely.

Thereupon, note that the classification of aircraft regarding TML is expected to be conducted by airspace authorities. Indeed, authorities from different regions (e.g., United States and Europe) share many aspects of airspace regulation, but there are differences in some regards (e.g., the United States is a countries with a large territorial area, whereas Europe is composed of several countries that have to control the airspace collaboratively). In this sense, the difference between levels (e.g., the difference among a considerable operation certainty, acceptable operation certainty, and high operation certainty) might be posed from distinct regards in different regions.

For instance, some countries might be more open to the inclusion of autonomous aircraft than others. This highlights a potential for high TMLs to be assigned to autonomous aircraft earlier in some countries. Finally, the process of classification and evolution of the aircraft regarding the TMLs as well as a baseline approach that can be used worldwide are intended to be investigated in future works.

Furthermore, measuring the impact each TML presents on ATCo performance (e.g., workload) is not a simple task. In order to model the impact on cognitive activities performed by this professional, Table 2 presents a multiplication factor for each TML. These factors are then multiplied by the time spent in performing the same activity considered a familiar and well-established technology (e.g., a commercial aircraft operating in the NAS nowadays). Note that these multiplication factors are presented in a linear distribution once we present an approach for dealing with new technology integration. Although we use this linear distribution as a first approach to our experiments, extensions can be proposed by further investigation on how this multiplication factor changes according to the TML.

Note that the multiplication factors are applied to cognitive activities (e.g., communication and surveillance).

For all aircraft the ATCo is expected to perform a set of activities in order to ensure safe and efficient operations. These activities rely on (i) basic aircraft surveillance for ensuring instruction understanding, (ii) basic surveillance for multiple aircraft vicinity, (iii) definition of instructions to be followed, (iv) definition of traffic planning strategies, (iv) communication with Tower (TWR) about the current arrival demands, (v) operate simultaneously with TWR according to the requests agreed [20].

Additionally, lower TMLs (0 - 6) require the ATCo to perform additional activities (presented in Table 3). This is faced as a requirement since conducting additional tasks tends to reduce the uncertainty level of the operation. These activities and their duration are proposed by former Air Traffic Controllers (ATCos) and researchers in Air Traffic Management (ATM). However, future calibrations on the activities performed as well as on their duration may be considered. These additional activities are [37]:

- **Surveillance for the Aircraft:** time for surveillance, in order to avoid conflicts in case of C2 failure;

**TABLE 3.** Duration (in seconds) of additional activities [37].

| Activity | Duration (s) |
|---|---|
| Surveillance for the Aircraft | 10 |
| Surveillance for other traffics in the Aircraft vicinity | 10 |
| Anticipation of instructions | 3 |
| Anticipation of Traffic Planning | 3 |
| Coordination to TWR about Aircraft traffic | 3 |
| Additional information to TWR | 2 |
| Receiving TWR requests | 3 |
| Executing TWR requests | 3 |

- **Surveillance for other traffic in the Aircraft vicinity:** time for surveillance traffics in Aircraft vicinity, in order to avoid conflicts in case of C2 failure;
- **Anticipation of instructions:** due to links ATCo-Pilot and Pilot-Aircraft or ATCo-Aircraft, there is uncertainty concerning the proper execution of the instructions by the aircraft. Thus, anticipating the instructions performed by ATCo is necessary;
- **Anticipation of Traffic Planning:**due to the lack of ATCo familiarity with UAS operation, anticipation of traffic planning performed by ATCo is also needed;
- **Coordination to TWR about Aircraft traffic:** Aircraft (TML 0-6) traffic is considered traffic of particular characteristics. Thus, it is fundamentally careful coordination;
- **Additional information to TWR:** in some cases, the APP makes traffic spacing to sequence the aircraft traffic, and particular coordination to TWR is necessary;
- **Receiving TWR requests:** to received aircraft, due to local traffic, it is possible that TWR makes particular requests to APP;
- **Executing TWR requests:** execution time of requests from the TWR;

Moreover, in a long-term future, the TML may increase and be higher than 10, which leads to a reduction of the multiplication factor and, ultimately, a reduction in the ATCo workload. This depends on the automation of aircraft, the automation of ATCo activities, and on the level of independence of the aircraft regarding ATCo instructions.

Finally, an essential aspect of the TML scale is that it is not related to UAS exclusively, i.e., this scale can be applied to any aircraft. Since UAS does not currently operate in the National Airspace System (NAS), it is reasonable to consider that these aircraft have a low TML. However, considering a long-term future, it is reasonable to consider that the TML of UAS may increase due to their operation throughout the years.

## V. METHOD

In order to show the applicability of our approach, the Total Airport and Airspace Model (TAAM) is employed. TAAM, which is widely used for air traffic simulation, is a fast-time gate-to-gate simulator [51].

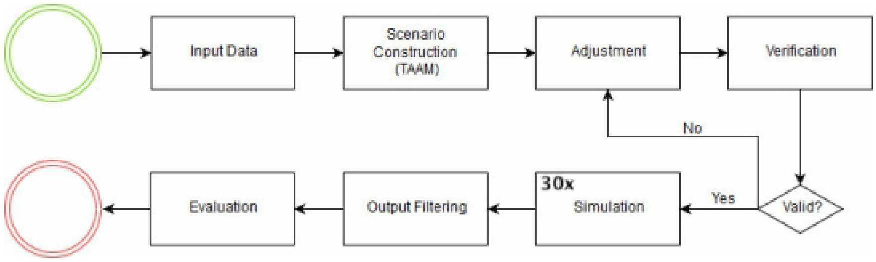


**FIGURE 2.** Method adopted in this research.

TAAM presents key features for supporting airspace analysis such as variation of scenarios, 3D multi-color models, ground functionality (e.g., terminals, runways, and taxiways), airside functionality (e.g., terminal airspace, SIDs/STARs and flow management) and direct output to database tools [22].

This simulator has been used for aviation analysis and regional studies, i.e., small subsets of airports and airspace, although there is a growing interest in using TAAM for much larger scenarios [6]. Also, it can help airlines to optimize their operation by, for example, planning operations regarding cost efficiency and aircraft substitutions, optimizing schedule design, managing the introduction of regional jets and proposing manners to reduce delays and to increase efficiency [21].

This research exploits the capabilities of TAAM in order to simulate the proposed scenarios as well as to extract the outputs. Thus, the experiments are conducted from the ATCo workload perspective. The method adopted in this research is illustrated in Figure 2.

Firstly, in the input data phase all the data needed for the simulation process is collected, such as aircraft performance data, the set of schedules considered during the simulations and TML of aircraft. The aircraft models must be set as well as the schedule of flights.

Secondly, in the scenario construction (TAAM) phase, all the collected data is fed into TAAM simulator. In this phase, the airspace is built, and the sectors/airports of the study must be highlighted. Thereupon, the schedule of all flights must be included.

Thirdly, the adjustment of the simulation tool is conducted. In this phase, the workload (or TML) associated with each flight must be inputted. Note that the TML of Manned Aircraft (MA), Remotely Piloted Aircraft System (RPAS), and Autonomous Aircraft (AA) may vary depending on the inputs provided at this stage.

After that, the verification process is conducted to evaluate the considered inputs (e.g., schedule, performance, and TML). In case of the values are not valid, a new adjustment is needed. Otherwise, the simulation can be executed.

The simulation phase consists of 30 fast-time simulations executions, in which all events are logged. In this phase, the fleet information (i.e., the percentage of MA, RPAS, and AA) provided beforehand is used to assign types to aircraft randomly. MA, RPAS, and AA are considered aircraft with the same performance and size, i.e., the difference lies in the piloting concept. Indeed, using different aircraft models would present impacts on the ATCo workload for piloting types and also for performance differences. Furthermore, the workload computed herein for each scenario is based on (i) the default ATCo activities available in TAAM and on (ii) the additional activities assigned to aircraft with a low TML (6 - 0).

Then, the output filtering stage is responsible for selecting the data that fits in the scope of this research (i.e., output data related to the trajectory of all aircraft, the ATCo workload and the activities performed), e.g., selecting events that occur in specific sectors. Also, it is essential to define the period time of the analysis.

Finally, the evaluation stage is responsible for evaluating the results to verify the impact of MA, RPAS and AA insertion into the NAS, in terms of workload.

## VI. CASE STUDIES

In this section, the case studies considered herein are presented. The set of fleet considered in the case studies is presented in Table 4. The first fleet is composed of Manned Aircraft (MA). In the second fleet, Remotely Piloted Aircraft Systems (RPAS) are included, with 20% of presence. In fleet three, Autonomous Aircraft (AA) are integrated (20%), whereas the number of MA and RPAS is the same. Fleet four represents a considerable reduction in MA numbers (20%), whereas RPAS and AA numbers are equal (40%). The fifth fleet presents only UAS with 20% of RPAS presence and 80% of AA presence. Finally, the sixth fleet only considers AA (100%). During the simulation process specific fleets are chosen to demonstrate the workload according to a specific age.

The variations in TML throughout ages considered in the case studies are presented in Table 5. The first age represents the moment at which UAS is integrated into the NAS, i.e., MAs are hugely the most used aircraft type. This leads

**TABLE 4.** Set of fleets considered in this research.

| Fleet | MA (%) | RPAS (%) | AA (%) |
|---|---|---|---|
| 1 | 100 | 0 | 0 |
| 2 | 80 | 20 | 0 |
| 3 | 40 | 40 | 20 |
| 4 | 20 | 40 | 40 |
| 5 | 0 | 20 | 80 |
| 6 | 0 | 0 | 100 |

**TABLE 5.** Ages (in terms of TML evolution) considered in this research.

| Age | TML | | |
|---|---|---|---|
| | MA | RPAS | AA |
| I | 7 - 10 | 0 | 0 |
| II | 7 - 10 | 3 - 6 | 0 |
| III | 7 - 10 | 7 - 10 | 3 - 6 |
| IV | 3 - 6 | 3 - 6 | 7 - 10 |
| V | 1 - 2 | 1 - 2 | 11 - 12 |

the MA to present maximum TML 10 (''High operation certainty''), whereas both RPAS and AA present maximum TML 0 (''High operation uncertainty'').

The second age also represents an early stage of the UAS integration into NAS, but with a slight increase in its acceptance. However, only RPAS presents an increase in its TML (maximum TML 6 - ''Small Operation Experience'') once it is reasonable to consider that the technology used to pilot the aircraft remotely tends to be accepted before the technology that makes the aircraft to fly autonomously [5], [55].

At age III, the acceptance of AA and RPAS evolve to maximum TMLs 10 (''High operation certainty'') and 6 (''Small Operation Experience''), respectively. Note that, at this age, RPAS achieved the same TML as MA (TML 7).

Age IV presents a twisting point concerning technology acceptance. As autonomous vehicles present advantages to the airspace [1], [3], [5], [9], [45], [52] and their use may increase from ages III to V, it is reasonable to consider that the number of operations tends to increase. Thus, the acceptance of fully autonomous aircraft also tends to increase, reaching maximum TML 10 (''High Operation Certainty''). In turn, operation with human pilots may decrease from ages III to V. This highlights a reduction in MA and RPAS operations, which may impact the liability and acceptance levels. Hence, the maximum TML of MA and RPAS are considered to be 6 (''Small Operation Experience''). Due to the advantages AA may offer to the airspace operation, it is reasonable to consider that the ATCo workload may drop.

Finally, age V presents a very futuristic scenario in which human pilots are a minority in the airspace operation. This reduction tends to impact the technology acceptance and to reduce the maximum TML to 2 (for both, MA and RPAS). Conversely, the level of AA autonomy may enable the airspace to improve the system efficiency (e.g., autonomous ATC equipment) and reduce the ATCo workload to levels below those currently achieved in normal operations. Hence, the TML of AA becomes 12.

In order to consider a reduction on MA's TML, the hypothesis that familiarity comes from exposure is employed. Indeed, current airspace operations only consider MA. The operations conducted during the first years of autonomous aircraft integration into the NAS are expected to be very careful and restrictive. However, when several successful operations of RPAS and AA are achieved, their acceptance tends to rise. Thereupon, considering that fully autonomous aircraft shall achieve, in a future state, a high acceptance and that these aircraft bring many benefits regarding airspace efficiency, it is reasonable to consider that autonomous aircraft will be more present in future operations. Then, if the presence of MA decreases, ATCos will naturally reduce their exposure to these aircraft and, in a long-run, its TML might decrease. Two reason that support this hypothesis are: (i) the new generations of ATCo can be trained considering only autonomous aircraft once they are more efficient; and (ii) although current ATCos might keep familiar with MA even if its presence is reduced, future generations of ATCo can find autonomous aircraft more trustworthy regarding instruction execution. Finally, if the TML of all aircraft types (MA, RPAS, and AA) are considered to be the same, the factor that will impact the ATCo workload is the number of aircraft instead of their TMLs.

During the simulation process, specific ages are chosen to demonstrate the impacts on the workload related to each fleet. In this case, the traffic of a busy day in Brazilian airspace is considered. Also, all aircraft in this research are represented as the Boeing 737 model, to maintain the same performance of UAS and manned aircraft. The Terminal Area São Paulo (TMA-SP) is considered the area of study. In it, many aircraft arrive or depart from/to many airports (e.g., Campinas, Congonhas, and Guarulhos). This area, which has many crossings, contains the busiest airport in Brazil, the International Guarulhos Airport. This research considers sectors 1 and 6, which are feeder sectors of Guarulhos Airport. These sectors, as well as Guarulhos Airport, are illustrated in Figure 3.

The simulations consider 6 busy hours, from 8 UTC (Universal Time Coordinated) up to 14 UTC (Universal Time Coordinated), which is the busiest period of Guarulhos Airport, and 274 flights arriving and departing from/to it. The percentage of MA, RPAS, and AA is considered in the schedule. Considering the 274 flights, the order in which different

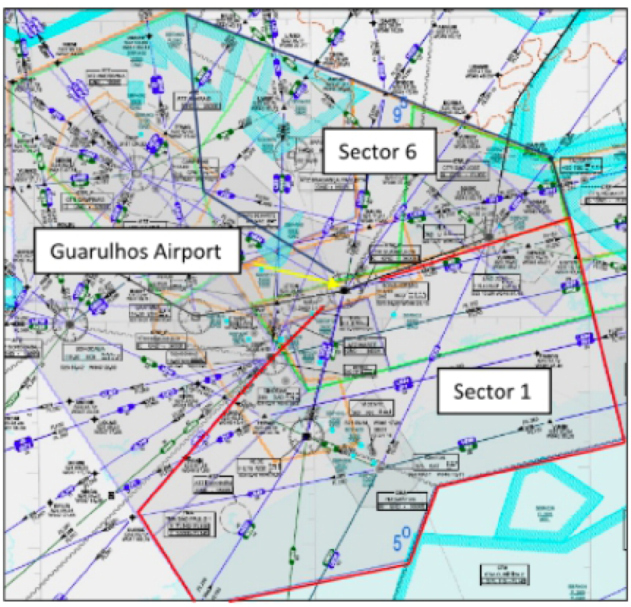


**FIGURE 3.** Sectors considered in this research: Sectors 1 and 6 of TMA-SP.

aircraft (MA, RPAS, and AA) is scheduled randomly. This randomness presents differences in results. Some flights tend to spend more time in a given sector. In this case, 30 simulations were conducted in each experiment, i.e., for each combination of fleet and age. Thus, a more precise result can be measured, considering the mean and the standard deviation of all simulations.

The TML interval of a sample of aircraft is represented as follows: if the TML of the sample varies from 7 to 10, 10% of this sample is composed of aircraft with TML 7, 10% is composed of aircraft with TML 8, 30% with TML 9 and 50% with TML 10.

In case the TML of the aircraft in a sample varies from 3 to 6, 10% of the sample is composed of aircraft with TML 3, 10% with TML 4, 30% with TML 5 and, finally, 50% with TML 6.

The main goal of adopting this distribution is to model a realistic traffic as most aircraft (which represent the NAS scenarios currently faced by the ATC and present higher TMLs) but also considering new airspace users in smaller numbers (which represents futuristic scenarios and present lower TMLs).

In case the TML of the aircraft in a sample varies from 1 to 2, 50% of the sample is composed of aircraft with TML 1 and 50% by aircraft with TML 2. Finally, in the case in which the TML variation is higher than 10, the numbers of aircraft with each TML are equal. For example, a sample with TML variation from 11 to 12 considers 50% of aircraft with TML 11 and 50% of aircraft with TML 12. This distribution of TMLs in samples enables considering mixed environments, which may be more complex and present variations in workload.

Finally, in all the case studies, the workload threshold, i.e., the maximum acceptable workload to maintain the safety levels, of 80% of an hour of control team workload [29], [30], is used to compare the workload of the fleets. Considering 6 hours of operation and 2 sectors, the ATCo workload threshold is 34560.0 seconds.

### A. CASE STUDY I

The primary goal of this experiment is to evaluate the workload related to age I, i.e., during the early stage of the UAS integration into the NAS. At this age, the TML of Manned Aircraft (MA) varies from 7 to 10, whereas the TML of Remotely Piloted Aircraft System (RPAS) and Autonomous Aircraft (AA) is the same (0). All the 6 fleets are considered for measuring the impacts of the UAS presence on ATCo workload. Finally, the acceptable workload threshold is also illustrated. The results of the simulations are shown in Figure 4.


**FIGURE 4.** Results from Case Study I: variation in ATCo workload (in seconds) considering different fleets at TML age I.

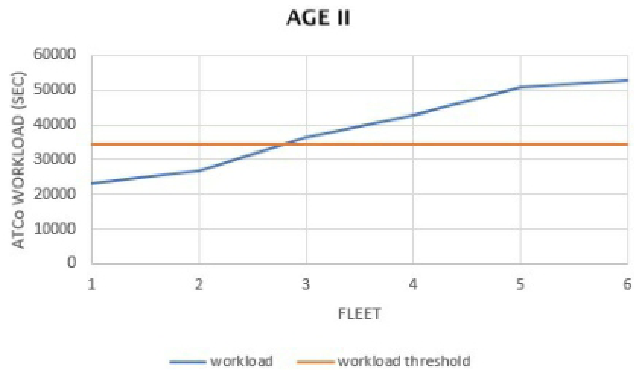


**FIGURE 5.** Results from Case Study II: variation in ATCo workload (in seconds) considering different fleets at TML age II.

### B. CASE STUDY II

Case study II aims to evaluate the workload related to age II, i.e., still during the early stages of the UAS integration into the NAS. At this age, the TML of MA varies from 7 to 10. However, although the TML of AA is the same of case study I (0), the TML RPAS varies from 3 up to 6. All the 6 fleets are considered in order to measure the impacts of the UAS presence on ATCo workload. The results of the simulations are shown in Figure 5.

### C. CASE STUDY III

In case study III, our focus is to measure the workload related to age III, i.e., a stage in which autonomous vehicles have a higher acceptance to be included into the NAS, especially the RPAS. At this age, the TML of MA still varies from 7 to 10. However, the TML of RPAS and AA increased. The TML of RPAS varies from 7 to 10 whereas the TML of AA varies from 3 to 6. Furthermore, all the 6 fleets are considered for measuring the impacts of different flights on ATCo workload. Figure 6 illustrates the results of the simulations.

### D. CASE STUDY IV

The fourth case study shows the impacts on the workload of the different fleets considering age IV, in which the TML of MA and RPAS dropped, varying from 3 to 6, whereas the TML of AA rose, varying from 7 to 10. This age represents a futuristic scenario, in which the autonomous vehicles tend to be preferred in comparison to piloted vehicles. Figure 7 depicts the simulations conducted in this case study.

### E. CASE STUDY V

The last case study shows the impacts on the workload of the different fleets considering age V, in which the TML of


**FIGURE 6.** **Results from Case Study III: variation in ATCo workload (in seconds) considering different fleets at TML age III.**


**FIGURE 7.** **Results from Case Study IV: variation in ATCo workload (in seconds) considering different fleets at TML age IV.**


**FIGURE 8.** **Results from Case Study V: variation in ATCo workload (in seconds) considering different fleets at TML age V.**

MA and RPAS dropped and varies from 1 to 2 whereas the TML of AA rose. Note that, at this stage, the AA presents a high level of Independence regarding ATCo instructions. Furthermore, the familiarity of ATCo with this technology is higher than ''mature''. This leads to new TMLs that represent reductions in workload due to the lack of uncertainty of aircraft operation and to the aircraft independence. In this case, the over-mature relationship of ATCo with AA leads it to vary between TML 11 and 12, which represents, respectively, multiplication factors of 0.9 and 0.8 of activities duration (communication and surveillance). Figure 8 shows the results of the simulations.

## VII. DISCUSSION

The case studies presented in the previous section highlight the impact of different fleets on the workload. Case studies I and II presented similar results. They consider ages of similar TML distribution, i.e., the only difference is the increase in the TML of RPAS. Note that only fleets 1 and 2 presented a workload lower than the workload threshold. This indicates that the UAS (both RPAS and AA) numbers operating into the National Airspace System (NAS) may be considerably reduced in order to maintain the workload at an acceptable level, considering TML ages I and II.

In case study III, although there is an increase in the initial workload level, i.e., the workload level of fleet 1, the workload remains below the threshold considering fleets 1, 2, 3 and 4. This is because the TML of UAS (both RPAS and AA) increase considerably at this age, i.e., this indicates that more fleets that include UAS operate considering an acceptable workload level due to the TML evolution.

Yet in case studies IV and V, there is a substantial increase in workload level in fleets that consider small numbers of UAS (RPAS and AA), i.e., fleets with high numbers of MA (e.g., fleets 1, 2 and 3). At this stage, the TML of RPAS and AA rose considerably, leading the workload level to levels below the threshold. In both case studies, fleets 1, 2 and 3 present workload above the workload threshold, i.e., this indicates that the MA numbers operating in the NAS considering TML ages IV and V may be considerably reduced to maintain the workload at an acceptable level once there will be a change in ATCos mindset and they may be very familiar with UAS.

However, in case study IV, fleet 4 presents workload below the workload threshold. After that, fleets 5 and 6 present a decrease in this metric. In turn, case study V does not reach an acceptable workload level considering the fleet 4. However, considering ages IV and V and the variation of TML between them, the workload achieved in fleet 6 in case study V is the lowest workload measured in all the experiments because, at age V, there is an over-mature familiarity of ATCo with AA, which leads to a substantial reduction of workload. Finally, MA operations in age V lead to remarkable increases in workload levels.

Tables 6 shows the workload achieved in all the experiments and their respective standard deviation. Note that in all the cases, the standard deviation achieved was minimal. Note that some standard deviations are equal to 0 seconds. These values are achieved in cases in which differences in flights schedule order does not impact the ATCo workload. This only happens when the TMLs of the aircraft considered in the sample are equal, e.g., fleet 6 considers only AA and, at age I, these aircraft present only one TML (0).

In both tables, the red cells represent the worst results. These experiments, which consider high UAS numbers at early ages, showed that including UAS radically during its

**TABLE 6.** Workload (Wkl) and Standard Deviation (std), in seconds, achieved in all experiments.

| Fleet | Age | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | I | | II | | III | | IV | | V | |
| | Wkl | Std | Wkl | Std | Wkl | Std | Wkl | Std | Wkl | Std |
| 1 | 23122.46 | 48.505 | 23140.46 | 54.15 | 23164.83 | 55.49 | 41848.12 | 61.17 | 49383.49 | 21.88 |
| 2 | 29155.18 | 178.73 | 26892.92 | 97.84 | 23126.41 | 57.49 | 41864.98 | 45.36 | 49374.98 | 20.97 |
| 3 | 41073.7 | 214.68 | 36576.22 | 171.01 | 26808.83 | 99.46 | 38157.72 | 99.46 | 43260.45 | 202.82 |
| 4 | 47095.7 | 193.45 | 50810.31 | 138.6 | 30666.99 | 127.97 | 34330.17 | 138.3 | 36796.7 | 202.38 |
| 5 | 53030.0 | 0 | 50810.31 | 107.96 | 38147.12 | 82.95 | 26865.21 | 102.27 | 24352.29 | 191.81 |
| 6 | 53030.0 | 0 | 53030.0 | 0 | 41851.35 | 54.17 | 23149.57 | 48.91 | 18231.7 | 30.51 |

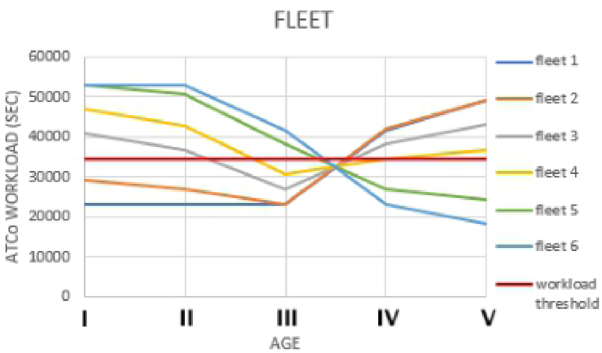


**FIGURE 9.** Variation of ATCo workload (in seconds) considering different fleets throughout TML ages.

early integration may be not feasible. The workload achieved (53030.0 seconds) is much higher than the workload threshold (34560.0 seconds). The orange cells illustrate the experiments that resulted in unacceptable workload levels. They vary from values close to the threshold (e.g., 36576.22 seconds, achieved considering fleet 3 at age II) up to much higher values.

The blue cells illustrate the experiments with acceptable workload levels. As some blue cells represent experiments that include RPAS and AA presence, it is reasonable to consider that they can be integrated safely throughout the TML ages. Finally, the green cell presents the best result achieved regarding workload. In this simulation, only AA are considered, and the age adopted presents high TML levels for AA, achieving over-mature familiarly levels (TML 11 and 12). Furthermore, MA and RPAS, which have low TMLs at age V, are not included in this experiment.

Figure 9 presents a comparison of the evolution of fleets, concerning workload impact, throughout the TML ages. Fleets 1 and 2 present an acceptable workload at age I. On the other hand, at the same age, fleets 3, 4, 5 and 6 present unacceptable workloads. Throughout the TML ages, the workload of fleets 3, 4, 5 and 6 drops whereas the workload of fleets 1 and 2 rises. There is a common intersection point between ages III and IV, in which all fleets present acceptable workloads. From this point onwards, fleets 5 and 6 start to decrease the workload whereas the other fleets present an increase in this metric. Finally, in age V, fleets 5 and 6 are the only fleets that present acceptable workload levels.

Although the ATCo workload (and their standard deviation) for each experiment is highlighted in Table 6, a normal mental condition is assumed. Besides, the current level of automation of ATC activities is also assumed. However, situations in which the ATCo workload is over the normal due to the cognitive status (e.g., stress, lack of confidence, and emotional impacts of an unexpected large number of aircraft in the airspace) can become quite common in the future once the complexity of these operations tends to rise. Conversely, the automation of ATC activities is also expected to be present in future operations, which may reduce the ATCo workload.

In both cases, Table 6 can be considered to compute the adjusted workload ($wkl_{adjusted}$). Thereupon, a multiplication factor $\omega$ can be used to represent the impacts of the ATCo exposure to highly complex scenarios and unusual mental status (e.g., ATCo dealing with emotional impacts of an unexpected large number of aircraft in the airspace). On the other hand, a multiplication factor $\phi$ can be used to represent the benefits regarding the reduction of ATCo workload offered by the partial automation of the ATC activities. These factors can be expressed as illustrated in Equation 2.

$$wkl_{adjusted} = wkl + (\omega \times wkl) + (\phi \times wkl) \tag{2}$$

Regarding the impacts of unusual mental conditions, $\omega$ is expect to assume a positive real value $0 \leq \omega \leq 1$ ($\omega \in \mathbb{R}$) once these conditions represent an increase in the system complexity from the ATCo's perspective. However, $\omega$ can also be greater than 1 in extreme cases. Similarly, $\phi$ is expect to assume a negative real value $-1 \leq \phi \leq 0$ ($\phi \in \mathbb{R}$) once these automation of ATC activities is expected to decrease the system complexity from the ATCo's perspective. Finally, the investigation on how $\omega$ and $\phi$ varies according to the ATCo mental status and the automation of ATC activities are in scope of future works.

## VIII. CONCLUSION

This paper presented an evaluation of ATCo workload considering the UAS integration into the National Airspace System (NAS). For this, we adopted fast-time simulations. Thus, the Total Airspace and Airport Modeller (TAAM) was employed considering a typical day in busy airspace. Hence, different fleets composed of Manned Aircraft (MA), Remotely Piloted Aircraft Systems (RPAS) and Autonomous Aircraft (AA), as well as different ages concerning the familiarity in the relationship between ATCos and the types of aircraft. The ATCo workload, i.e., the time spent by the

ATCo when controlling traffics, was measured exploiting the combination of ages and fleets.

Furthermore, ATCo workload is a metric related to safety, since higher workload levels lead to low airspace capacity and complexity factors immediate impact this metric. It is reasonable to consider that UAS integration into the NAS is a complexity factor and, consequently, may present impacts on ATCo workload. A radical insertion regarding UAS numbers may impact the ATCo workload and safety levels considerably.

In order to measure the familiarity of ATCo with different aircraft, the Technology Maturity Level (TML) is adopted. This scale is a systematic metric/measurement system that supports assessments of the familiarity of a particular aircraft with Air Traffic Controllers (ATCOs) and may evolve throughout the years of UAS operation, i.e., the familiarity of ATCo with UASs may increase. Note that the TML of the aircraft impacts the time spent by ATCo in communication, surveillance and even cognitive activities when controlling aircraft. Furthermore, in a long-term future, it is reasonable to consider that the familiarity between ATCo and AA may be over-mature, which, instead of increasing the workload, decreases it.

The experiments conducted aimed to show the impacts of the UAS integration throughout the TML ages concerning ATCo workload. The ATCo workload measured in TML age I presented acceptable levels of ATCo workload only considering MA and a slight insertion of RPAS. At this age, most of the traffics are composed of AA and RPAS, and the workload reaches unacceptable levels. The evolution of TML ages reduced the impacts of the integration of UASs (RPAS and AA) on ATCo workload gradually. Finally, in a long-term future, the AA presets lower impacts on ATCo workload, and the lowest workload level was achieved in an experiment that considered only AA at TML age V, i.e., in a long-term future, it is reasonable to consider that AA may outperform MA and RPAS regarding impacts on safety.

The main contribution of this research is to highlight that the UAS integration into the National Airspace System (NAS) must be conducted gradually according to the evolution of ATCo familiarity with this technology. Thus, a radical integration of UAS may present unacceptable impacts on ATCo workload and, ultimately, on safety levels. Besides, integrating UAS appropriately may conduct fully Autonomous Aircraft (AA) operations to present even lower workload impacts in a long-term horizon. This may also lead the airspace to replace MA and RPAS to AA.

As future works, the authors intend to: (i) conduct validations considering human-in-the-loop simulations; (ii) evaluate impacts of UAS integration into NAS on airspace capacity; (iii) associate TML with current regulatory authorities and how to apply this concept to ATC; (iv) analyze scenarios that include adaptive TMLs depending on the region the aircraft are operating; (v) evaluate the multiplication factor adopted in Table 2 based on practical experience; (vi) evaluate the duration of the ATCo activities presented in Table 3 based on practical experience; and (vii) evaluate the ATCo workload considering UAS integration in the the NAS and possible automation of some activities performed by the ATCo.

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