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TECHNOLOGICAL REQUIREMENTS FOR ENABLING URBAN AIR MOBILITY (UAM) INTO BRAZILIAN AIRSPACE CONTROL SYSTEM (SISCEAB): A COMPREHENSIVE ANALYSIS

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ABSTRACT

This article addresses concepts such as System Wide Information Management (SWIM), Flight and Flow Information for a Collaborative Environment (FF-ICE) and Trajectory-Based Operations (TBO), as conceptualized by the International Civil Aviation Organization (ICAO) and other aviation agencies. The analysis explores how the integration of these elements will be crucial for the safe and efficient integration of Urban Air Mobility (UAM) in the air traffic systems of the Brazilian Airspace Control System (SISCEAB). The objective of this article was to qualitatively list the challenges and technological, systemic, regulatory and infrastructure advances necessary for the implementation of SWIM, TBO and FF-ICE to enable the conception of UAM in Brazil.

Keywords: 4D-TBO, Urban Air Mobility (UAM), FF-ICE, SWIM, Air Traffic Management (ATM).

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1. INTRODUCTION

Urban Air Mobility (UAM) refers to the use of aircraft to transport people and cargo in urban and suburban areas. The U.S. Federal Aviation Administration (FAA) classifies UAM as part of Advanced Air Mobility (AAM), which also includes regional air transport (FAA, 2023a). UAM, driven by advances in electric propulsion, autonomy, and air traffic management, offers a fast, efficient, sustainable, and affordable solution to urban congestion (ANAC, 2023).

However, UAM faces challenges, particularly with aircraft development and certification, such as for Electric Vertical Take-Off and Landing (eVTOL) vehicles. The FAA's reclassification of eVTOLs as “powered-lift” aircraft has complicated certification timelines (ALCOCK, 2022). Additionally, integrating UAM into existing air traffic systems is complex. The overlap between controlled airspace and UAM operating areas, such as airport zones, requires a new air traffic management (ATM) paradigm. A 2022 study by the German Aerospace Center (GAC) showed UAM traffic could increase air traffic controllers' workload by up to 30%, impacting situational awareness (SCHIER-MORGENTHAL; ABDELLAOUI; METZ, 2023).

To address these challenges, ICAO promotes 4D Trajectory-Based Operations (4D-TBO), which optimizes routes by using precise positioning and time data, reducing delays and increasing airspace capacity (ICAO, 2019). Supported by Flight and Flow Information for a Collaborative Environment (FF-ICE) and System Wide Information Management (SWIM), these technologies form the foundation for safely integrating eVTOLs into UAM within Brazil’s Airspace Control System (SISCEAB), mitigating risks in dense Terminal Control Areas (TMA).

This article outlines the technological, regulatory, and infrastructural advancements needed to implement SWIM, TBO, and FF-ICE for UAM in Brazil. By exploring 4D-TBO’s potential alongside FF-ICE and SWIM, it proposes a framework for safely integrating new air vehicles into UAM under SISCEAB’s jurisdiction. This qualitative research is based on a bibliographic review of documents from ICAO, DECEA, ANAC, and other sources, using a case study methodology adapted from Robert K. Yin (2018) to analyze the integration of these technologies into Brazilian airspace. This research method is appropriate for examining emerging standards and proposing solutions to potential challenges in SISCEAB. Content analysis identified key consistencies and divergences in standards, offering a comprehensive view of the topic and contributing to a deeper understanding of how 4D-TBO, FF-ICE, and SWIM can be effectively implemented in Brazil.

2. LITERATURE REVIEW

UAM has emerged as a promising solution to urban mobility challenges, particularly in large metropolitan areas. The U.S. Federal Aviation Administration (FAA) classifies UAM as a subset of Advanced Air Mobility (AAM), which includes regional air transportation (FAA, 2023a). This concept is driven by technological advancements in electric propulsion, aircraft autonomy, and air traffic management.

The literature highlights that eVTOLs will be key to implementing UAM (Porsche Consulting, 2021). ANAC (2023) emphasizes that UAM offers faster, more efficient, and accessible transportation, helping alleviate urban congestion. However, significant challenges remain, particularly in aircraft development and certification. The FAA's reclassification of eVTOLs as “powered-lift” aircraft has directly affected certification timelines (ALCOCK, 2022). Experts have also noted that companies face production cost difficulties and that infrastructure, including

vertiports and charging systems, must advance more rapidly (Leeham News and Analysis, 2022a, 2022b).

Key documents from ICAO, FAA, DECEA, and ANAC were selected for their relevance in outlining technological and regulatory trends for UAM, offering a comprehensive view of the challenges for airlines, operators, and the infrastructure needed for this disruptive technology. The literature shows that SWIM, based on technologies like Internet Protocol (IP) and Service Oriented Architecture (SOA), creates an "information network" (DECEA, 2019). Interoperability, data security, and governance are critical for ensuring system compatibility and the authorized, secure use of information (ICAO, 2015).

The article is based on ICAO "*Manual on SWIM Concept*" (2015) and DECEA documents (DCA 351-5/2019), which illustrate SWIM practical applicability and real-time data integration capabilities, vital for systems like 4D-TBO and FF-ICE. The FF-ICE concept, outlined in the ICAO manual (2012), emphasizes collaboration across ATM system participants, optimizing trajectories and reducing air traffic controller workloads.

These documents offer a solid foundation for integrating FF-ICE with other management systems, such as 4D-TBO, enhancing operational efficiency and safety in global ATM, especially in UAM implementation. Current literature underscores that implementing 4D-TBO requires technological advances in data communication and automation. Benefits include reduced mid-air collision risks, increased predictability, and fewer delays, optimizing airspace use (ICAO, 2019). Interoperability between systems, as detailed in ICAO (2019) and FAA (2015) documents, is crucial for implementing this concept.

This study builds on literature that contextualizes key air traffic management concepts and technologies, including UAM, SWIM, FF-ICE, and 4D-TBO. Documents from ICAO, FAA, DECEA, ANAC, and other relevant sources were prioritized for their applicability and direct support in developing the ideas proposed in this study.

3. THE POTENTIAL OF 4D-TBO, FF-ICE AND SWIM FOR THE INTEGRATION OF UAM INTO SISCEAB

The technologies examined in this study - SWIM, FF-ICE, and 4D-TBO - are interdependent and complementary, essential for creating a safer, more efficient, flexible, and sustainable air transport system (ICAO, 2019; ANAC, 2023). The rise of UAM necessitates an advanced ATM system capable of handling large volumes of low-altitude aircraft. SWIM provides the critical communication infrastructure for efficient data exchange (DECEA, 2019), while 4D-TBO optimizes airspace usage through four-dimensional trajectory management (ICAO, 2019; DECEA, 2024). FF-ICE enhances this by facilitating real-time information sharing among ATM participants, enabling collaborative planning and decision-making (ICAO, 2012).

Integrating UAM into SISCEAB requires a new ATM paradigm capable of managing low-altitude UAM traffic alongside conventional operations (DECEA, 2024). In this context, 4D-TBO, FF-ICE, and SWIM offer innovative solutions to safety, capacity, and efficiency challenges in UAM integration.

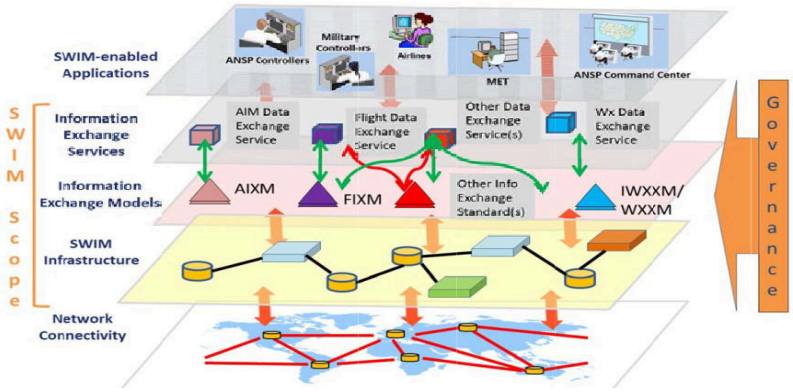
3.1 The Potential of System-Wide Information Management (SWIM) for UAM

SWIM enables secure, efficient, and scalable data exchange across aviation systems by creating an interoperable environment through standardized protocols (ICAO, 2015). Built on Internet Protocol (IP) and Service-Oriented Architecture (SOA), it forms a network that connects various aviation actors (DECEA, 2019).

As outlined in ICAO "*Manual on SWIM Concept*", its principles (interoperability, security, and governance) ensure seamless data flow and protect data integrity while managing access. SWIM supports initiatives like 4D-TBO and FF-ICE by facilitating real-time data exchange, enhancing operational efficiency and decision-making.

In UAM, SWIM is critical for connecting ATM systems, onboard aircraft systems, and vertiport management, allowing real-time information sharing and collaboration (DECEA, 2019). SWIM's standardization and data reuse reduce costs, fostering innovation and encouraging new service development. However, its implementation must address significant cybersecurity challenges to ensure system integrity and resilience.

Figure 01 – SWIM Global Interoperability Framework (ICAO)



Source: Doc 10039 AN/511 MANUAL ON SWIM CONCEPT / ICAO, 2015

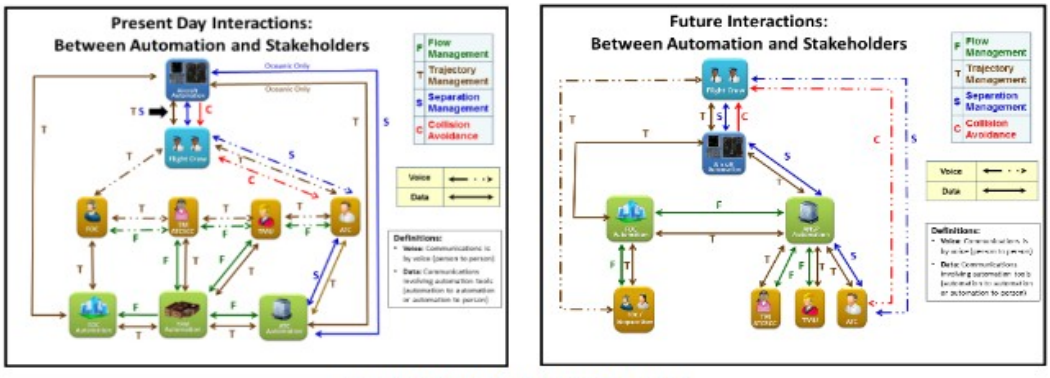
3.2 The Potential of 4D Trajectory-Based Operations (4D-TBO) for UAM

4D-TBO leverages four-dimensional coordinates (latitude, longitude, altitude, and time) to optimize airspace usage, improve capacity, and reduce delays, while enhancing operational efficiency and predictability (ICAO, 2016; ICAO, 2019). The ICAO Global TBO Concept highlights the collaborative sharing of trajectory information among all ATM participants (ICAO, 2019).

Effective 4D-TBO implementation requires advancements in air-to-ground communication, precise navigation systems, and automation to support collaborative management and conflict resolution. This enables more direct routes, reducing travel distances, fuel consumption, and delays, while improving safety through enhanced conflict management (ICAO, 2019).

In high-density environments like UAM, 4D-TBO is vital for ensuring safe and efficient operations, particularly for eVTOLs in low-altitude urban areas. It supports the Free Route Airspace (FRA) concept, allowing greater route planning flexibility, optimizing flight time, and reducing fuel consumption (DECEA, 2024).

Figure 02 – Automation of Interactions Nowadays (2015) x Future of Automation of Interactions



Source: CONOPS 4D-TBO / FAA, 2015

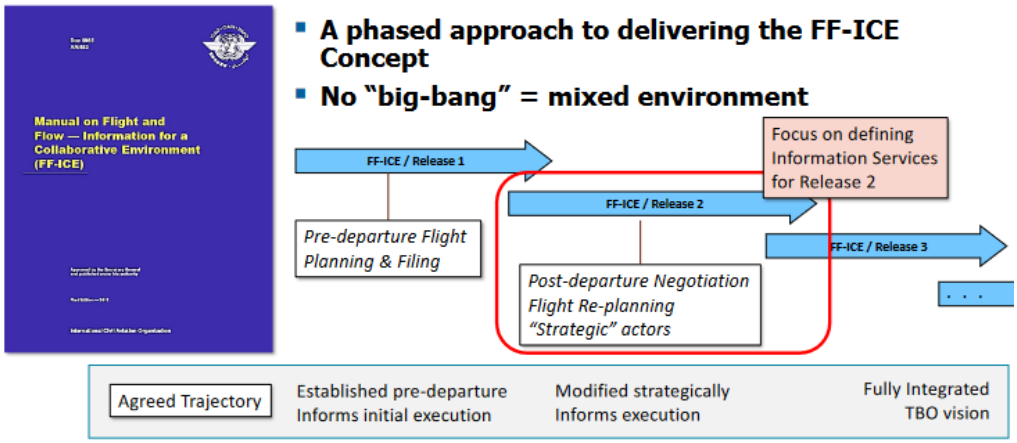
3.3 The Potential of Flight and Flow Information for a Collaborative Environment (FF-ICE) for UAM

FF-ICE, developed by ICAO, enables dynamic flight information sharing among ATM participants, replacing traditional flight plans (ICAO, 2012). This dynamic mechanism supports real-time information exchange, essential for implementing 4D-TBO (ICAO, 2016; DECEA, 2019).

FF-ICE organizes comprehensive flight data, fostering system compatibility and collaborative decision-making through standardized protocols (ICAO, 2012). Its benefits include optimized traffic flow, reduced delays, and increased efficiency through automation and integrated data management, which reduces the workload for controllers and pilots.

However, FF-ICE implementation demands advanced air-ground communication systems for real-time data exchange and models that ensure interoperability across systems. FF-ICE enhances situational awareness and operational safety, particularly for eVTOLs in UAM, by enabling real-time trajectory negotiation and optimizing flight profiles (ICAO, 2012).

Figure 03 – FF-ICE Interaction Framework (MITRE)



Source: FF-ICE Release Services Towards Trajectory-Based Operations (TBO) / MITRE, 2019

3.4 Considerations for Implementation

The successful integration of 4D-TBO, FF-ICE, and SWIM into SISCEAB for UAM operations requires careful planning across the aviation ecosystem. Strategic challenges include the development of a regulatory framework specific to UAM, ensuring safety, interoperability, and alignment with international standards.

Simultaneously, CNS infrastructure must be modernized to support low-altitude operations, ensuring safety and traffic flow in complex urban environments. Equally critical is the continuous training of technical staff, ensuring proficiency in managing integrated 4D-TBO, FF-ICE, and SWIM systems.

Cybersecurity also poses a significant challenge. The increased reliance on data exchange systems necessitates robust protection measures to safeguard data integrity and system resilience against cyber threats.

3.5 Preliminary analysis

4D-TBO, FF-ICE, and SWIM present promising technologies for the safe, efficient, and scalable integration of UAM into SISCEAB. Overcoming the implementation challenges will require a collaborative effort from DECEA, ANAC, aircraft operators, service providers, technology developers, and other stakeholders to position Brazil at the forefront of this new era in aviation.

Comparison Table 01: Current Air Traffic vs. Requirements for UAM in Brazil

Aspect	Current Air Traffic (Major Terminals)	Requirements for UAM (Aligned with GANP 2024)	Actions Required for UAM [2]
REGULATION			
Airspace Classification	Classes A to G (ICAO Annex 11)	New classification for UAM (**DECEA, 2024**)	**DECEA:** Define the new classification, rules and operating procedures
Flight Rule	IFR and VFR	DFR (Digital Flight Rules) (**DECEA, 2024**)	**DECEA:** Establish DFR, standards and operational requirements
Aircraft Certification	RBAC 23, RBAC 25 (**ANAC, 2023**)	Specific requirements for eVTOLs (under development)	**ANAC:** Define requirements and means of compliance for eVTOLs
AIR TRAFFIC MANAGEMENT (ATM)			
ATM System	SIGMA (Radar Systems, ADS-B, etc.)	System dedicated to UAM, integrated with SIGMA (**DECEA, 2024**)	**DECEA:** System dedicated to UAM, integrated with SIGMA
Traffic Separation	Primarily ATC, "See and Avoid" in Class G	Automated strategic and tactical deconfliction, potentially with cooperative separation (**DECEA, 2024**)	**DECEA:** Implement automated deconfliction technologies (e.g. ADS-B-based systems and 5G communication) and define standards for cooperative separation.
Flow Management	Centralized (CGNA)	Integrated with the UAM system, with real-time vertiport capacity and demand information	**DECEA:** Adapt the flow management system to include UAM and develop an interface with vertiports.
COMMUNICATION, NAVIGATION and SURVEILLANCE (CNS)			
Communication	VHF, datalink (limited)	Robust, low-latency VHF datalink for contingencies (**DECEA, 2024**)	**DECEA:** Implement robust and secure data communication infrastructure (e.g. 5G), ensure interoperability and develop communication protocols.
Navigation	GNSS, radio navigation aids	High-performance GNSS, potentially with augmentation systems (SBAS, GBAS)	**DECEA:** Evaluate and implement GNSS augmentation systems (SBAS/GBAS) in UAM areas.
Surveillance	Radar, ADS-B (limited)	ADS-B, MLAT (multilateration), cooperative surveillance systems (**DECEA, 2024**)	**DECEA:** Expand ADS-B coverage and implement MLAT. Develop and implement cooperative surveillance systems, including communication, navigation and performance requirements.
FLIGHT OPERATIONS [3]			
Piloting of aerial vehicles	Primarily manual	Initially with pilot on board, with potential for Remote PIC (RPIC) and autonomy in the future (**FAA, 2023**)	**ANAC e DECEA:** Regulate RPIC and autonomous operations when the technology is mature and safe.
Infrastructure	Airports, heliports	Network of vertiports and vertistops, integrated into the land transport system (**ANAC, 2023**)	**ANAC:** Define the technical and operational requirements for vertiports and regulate their construction and operation. **Operators:** Invest in the construction of private vertiports.
Cyber Security	Security measures in critical systems	Comprehensive cybersecurity system for the entire UAM infrastructure	**DECEA and ANAC:** Define and implement a cybersecurity and risk management system for UAM, including protocols, standards and procedures. **Operadores:** Implement cybersecurity programs, train staff and adopt best practices.

Source: The authors (2024).

Notes:
[1] Engagement and interoperability between DECEA, ANAC, aircraft operators, manufacturers, service providers and the national aeronautical community as a whole will be essential for the success of UAM in the country;
[2] Exemplary actions that may require complementary activities; and
[3] The implementation of UAM in Brazil must be gradual, aligned with the maturity of the technology and the evolution of the ecosystem.

4. DISCUSSION: CHALLENGES AND OPPORTUNITIES IN THE IMPLEMENTATION OF 4D-TBO, FF-ICE AND SWIM IN THE CONTEXT OF UAM FOR SISCEAB

The integration of 4D-TBO, supported by SWIM and FF-ICE, within the UAM framework for SISCEAB, presents numerous challenges and opportunities that necessitate detailed analysis and strategic planning. According to Yin's (2018) case study methodology, realizing the successful implementation of these technologies in Brazil requires concerted collaboration among DECEA, ANAC, aircraft operators, technology developers, and other key stakeholders. Addressing the technical and regulatory challenges effectively could position Brazil as a leader in this emerging field of aviation.

4.1 Challenges

4.1.1 Regulation and Standardization

Updating Brazilian legislation for 4D-TBO, FF-ICE, and SWIM in the context of UAM is both urgent and indispensable. Current regulations lack the specific provisions needed for UAM operations using these technologies, underscoring the need for revisions to ensure safety, interoperability, and alignment with international standards. The urgency is compounded by the evolving nature of global UAM regulations, despite ICAO's ongoing efforts (DECEA, 2024).

DECEA has made significant strides with the UAM Concept of Operations (CONOPS), incorporating a new airspace classification and performance-based Digital Flight Rules (DFR), emphasizing the necessity for a robust regulatory foundation (DECEA, 2024). Aligning Brazilian regulations with international standards is critical to avoid fragmentation, ensure global interoperability, and facilitate project validation and UAM integration on a global scale (PINTO NETO et al., 2019).

4.1.2 Technological Infrastructure

The adaptation of Brazil's Communication, Navigation, and Surveillance (CNS) infrastructure is essential for the integration of 4D-TBO, FF-ICE, and SWIM technologies in SISCEAB. Urban environments present unique challenges due to the limitations of traditional CNS systems at low altitudes. Buildings and other obstacles hinder communication and surveillance systems, initially designed for higher altitudes (DECEA, 2024).

Therefore, the integration of reliable, low-latency air-to-ground communication systems capable of real-time trajectory sharing is vital to ensuring safe and efficient UAM operations (ICAO, 2019; DECEA, 2024). Aircraft navigation systems must also guarantee trajectory precision in densely populated areas. The successful integration of UAM depends on seamless interoperability between aeronautical systems and vertiport management systems, as evidenced by the successful application of SIGMA and DASA in SISCEAB (LAMB, 2024).

4.1.3 Cybersecurity

The implementation of SWIM and FF-ICE introduces new cybersecurity challenges. The critical nature of air operations and the increasing reliance on data exchange systems necessitate comprehensive cybersecurity strategies. The expanded attack surface resulting from new system

integrations demands robust protections to safeguard data integrity and system resilience against potential cyberattacks (ICAO, 2015; DECEA, 2019).

Close collaboration among DECEA, ANAC, aircraft manufacturers, and service providers is essential to ensure the implementation of effective cybersecurity measures, thus safeguarding the integrity and reliability of the UAM ecosystem (LAMB, 2024).

4.1.4 Change Management and Training

Implementing 4D-TBO, FF-ICE, and SWIM in SISCEAB involves more than technological upgrades; it represents a paradigm shift in air traffic management. SISCEAB professionals, particularly air traffic controllers, must transition from a reactive model to a dynamic, collaborative approach to airspace management, emphasizing proactive planning and real-time coordination of 4D trajectories (ICAO, 2019; DECEA, 2024).

Consequently, investment in comprehensive training is paramount to equip personnel with the skills needed for managing vast data volumes, negotiating trajectories, and monitoring 4D authorizations in real time (FAA, 2023). Similarly, pilot training is critical to ensure familiarity with the new systems and procedures essential for safe and efficient UAM operations (LAMB, 2024).

4.2 Opportunities

4.2.1 Airspace Efficiency and Optimization

The implementation of 4D-TBO, FF-ICE, and SWIM is essential for optimizing airspace use, particularly in urban settings. By incorporating time as the fourth dimension, 4D-TBO enables precise trajectory management, allowing for more direct routes that adapt in real time to weather conditions and aircraft performance. This enhances operational efficiency by reducing flight time and fuel consumption (ICAO, 2019; ICAO, 2016).

Furthermore, dynamic trajectory control via FF-ICE fosters collaborative communication among stakeholders, increasing airspace capacity and minimizing delays (DECEA, 2024). SWIM's optimized infrastructure facilitates seamless data flow between systems, enabling effective coordination and maximizing low-altitude airspace utilization, where UAM operations will predominantly occur (PINTO NETO et al., 2019).

4.2.2 Operational Safety

The pursuit of enhanced operational safety in aviation is a driving force behind adopting technologies like 4D-TBO, FF-ICE, and SWIM. These technologies enable more efficient real-time information sharing, improving situational awareness for controllers, pilots, and other air traffic management participants (PINTO NETO et al., 2019).

FF-ICE supports collaborative decision-making, while 4D-TBO's automated conflict detection tools help identify and mitigate potential risks before they escalate, thereby improving operational safety (ICAO, 2012; ICAO, 2019). SWIM ensures secure and reliable communication between aircraft and control centers, bolstering system dependability and operational efficiency (DECEA, 2019; DECEA, 2024).

4.3 Inferences

The implementation of the 4D-TBO, FF-ICE and SWIM concepts in SISCEAB, aiming at the realization of UAM according to current projections and perspectives, presents challenges and opportunities that require a careful strategic approach in all spheres – strategic, operational and tactical. Collaboration between the various actors in the ecosystem will be essential, as well as continuous investments in research, development, professional training and infrastructure modernization.

The success of this initiative will depend on overcoming these challenges, maximizing opportunities and creating a regulatory, technological and operational environment conducive to innovation and growth in the sector.

5. CONCLUSIONS AND CONSIDERATIONS FOR THE FEASIBILITY OF UAM IN BRAZIL

UAM, driven by new aerial vehicles like eVTOL, has the potential to revolutionize urban transportation. However, safely integrating these aircraft into SISCEAB, in accordance with ICAO milestones, requires coordinated actions from all stakeholders in Brazil's aeronautical community. This analysis, grounded in documents from ICAO, FAA, DECEA, and ANAC, offers actionable recommendations for the safe implementation of UAM in Brazil. DECEA must prioritize adopting 4D-TBO, SWIM, and FF-ICE, recognizing 4D-TBO as a new air traffic management paradigm. These technologies, implemented gradually in line with ICAO's Aviation System Block Upgrades (ASBU) (ICAO, 2016; ICAO, 2019), will help SISCEAB manage increased low-altitude traffic, integrate UAM with conventional air traffic, and optimize airspace usage to avoid congestion and delays. Additionally, DECEA must swiftly define new airspace classifications and flight rules, such as Digital Flight Rules (DFR), considering the performance of eVTOLs and international standards.

A robust UAM traffic management system, integrated with existing ATM systems like SIGMA, must be developed to handle functions such as deconfliction, vertiport slot allocation, and contingency management. Upgrading the communication, navigation, and surveillance (CNS) infrastructure will be critical, with investments in ADS-B, MLAT (multilateration), and 5G/6G networks to support safe low-altitude operations in high-traffic areas. Furthermore, comprehensive cybersecurity measures must be adopted to protect data communication, aircraft systems, and vertiports from cyber threats.

ANAC will play a key role in regulating and certifying new UAM technologies and operators, focusing on clear certification requirements for eVTOLs, aligned with ICAO standards, FAA, and EASA. ANAC must also develop flexible regulations for UAM operations, covering certification of operators, pilot training, and vertiport integration with ground transportation systems.

UAM operators and the broader aviation community must engage in DECEA and ANAC-led working groups to shape a UAM model tailored to Brazil's needs. Investment in training for air traffic controllers, pilots, and ground staff is vital for safely operating in this evolving environment. Operators must also prioritize cybersecurity, implementing strong programs and best practices to protect systems and data, ensuring public trust.

UAM offers Brazil an opportunity to become a leader in future aviation, driving innovation and improving urban mobility. Achieving this will require strategic coordination among regulatory agencies, operators, and the aeronautical community. By adopting the technologies and concepts outlined in this analysis, supported by ongoing research and development, SISCEAB can lead airspace management into a new era of Brazilian aviation.

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