Technische Hochschule Ingolstadt

Faculty of Computer Science

The Future of AI in Air Traffic Management: Coordinating Autonomous Airliners and UAM within Busy Airspaces using AI

Seminar Paper

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Affidavit

I certify that I have completed the work without outside help and without using sources other than those specified and that the work has not yet been submitted in the same or a similar form to any other examination authority and has been accepted by them as part of an examination. All statements that have been adopted literally or analogously are marked as such.

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Abstract

The rapid evolution of air transportation, driven by the emergence of Urban Air Mobility and autonomous airliners, necessitates significant advancements in current Air Traffic Management (ATM) systems. This report investigates the integration of Artificial Intelligence (AI) technologies into existing ATM infrastructure to address persistent challenges such as inefficient flight planning, constrained airspace capacity, and the escalating cognitive workload on air traffic controllers. Through analysis of AI-driven case studies, including the Metropolis projects and strategic airspace management models, the report demonstrates how AI can enhance dynamic airspace allocation, optimize traffic flow, and improve overall safety and efficiency. Furthermore, the report examines key challenges in AI integration, including maintaining interoperability with legacy systems, ensuring scalability to handle increasing traffic volumes, complying with regulatory frameworks, and guaranteeing system robustness and safety. These considerations are critical to realizing a resilient, adaptable, and future-ready ATM system capable of supporting the demands of next-generation aviation.

Acronyms

AG Attention Guidance. 8
AI Artificial Intelligence. 1–3, 5, 7–10
ANSP Air Navigation Service Providers. 9
ATC Air Traffic Control. 7
ATCO Air Traffic Controller. 1, 3, 7, 8, 10
ATM Air Traffic Management. 1–5, 7–10

BATMAN Boundary Arrival Task Manager. 8
Bi-LSTM Bidirectional Long Short-Term Memory. 5, 7

CoDiST Controller Display and Simulation Tool. 8
CONOPS Concepts of Operations. 9
CTU Chengdu Shuangliu International Airport. 2
CWP Controller Working Position. 7

DAS Dynamic Airspace Sectorisation. 5, 6
DASIM Data And Service Integration Module. 8
DBSCAN Density-Based Spatial Clustering of Applications with Noise. 5
DHM Dynamic HeatMap. 8
DIRC Digital Interactive Radar Controller. 8

EA Evolutionary Algorithm. 5
eVTOL electric vertical takeoff and landing. 1

FMC Flight Minimum Cost. 2
FMS Flight Minimum Shift. 2

HAT Human-Autonomy Teaming. 7, 8

IFR Instrument Flight Rule. 2

LUM Dehong Mangshi International Airport. 3

MTL Multi-Task Learning. 5
MUC Munich Airport. 3
MVP Modified Voltage Potential. 4, 5

TCC Trajectory Conflict Checker. 8
TCZ Tengchong Tuofeng Airport. 2, 3
TFT Temporal Fusion Transformer. 5

TraGAT Trajectory Generation and Advisory Tool. 8

UAM Urban Air Mobility. 1, 3

UAS Unmanned Aerial System. 1

UAV Unmanned Aerial Vehicle. 3, 4, 10

UTM Unmanned Traffic Management. 1

Contents

1 Introduction

The rapid advancement of aerospace technology and urban infrastructure is driving the emergence of Urban Air Mobility (UAM) and autonomous airliners, reshaping the future of air transportation. UAM refers to the use of electric vertical takeoff and landing (eVTOL) aircraft to provide efficient, low-emission air travel within and around cities, aiming to alleviate ground traffic congestion and reduce travel times [1]. Simultaneously, the development of autonomous airliners (capable of operating with minimal or no human intervention) is gaining momentum, promising increased safety, operational efficiency, and cost-effectiveness in commercial aviation [2]. Together, these innovations mark a significant shift toward smarter, more sustainable air transportation systems, supported by breakthroughs in Artificial Intelligence (AI), sensor technology, and regulatory evolution.

As the skies grow increasingly crowded with traditional aircraft, drones, and emerging eVTOL vehicles, modernising Air Traffic Management (ATM) systems becomes essential. Traditional ATM frameworks, designed for conventional aviation, are not equipped to handle the complexity and volume introduced by UAM and autonomous operations [3]. To address this, the development of Unmanned Traffic Management (UTM) has emerged as a complementary solution, enabling the safe, scalable, and efficient integration of low-altitude, autonomous air traffic into national airspace systems [4]. UTM leverages digital communication, real-time data sharing, and dynamic airspace access. Together, ATM and UTM form the backbone of future-proofed aerial ecosystem, ensuring safety, reliability, and coordination across all types of airborne vehicles.

Integrating UTM into existing ATM infrastructure presents a range of technical, operational, and organisational challenges [4]. Traditional ATM systems are already under pressure, with many countries facing a critical shortage of Air Traffic Controllers (ATCOs): an issue that hampers the capacity to manage even current levels of air traffic safely and efficiently [5]. Adding to this challenge is the rapid growth of Unmanned Aerial System (UAS) and UAM operations, which introduces unpredictable flight patterns, higher traffic density in low-altitude airspace, and the need for real-time, automated coordination [6]. These factors demand that UTM systems be not only interoperable with legacy ATM systems, but also highly robust, adaptive, and capable of autonomous decision-making. Ensuring seamless integration while maintaining safety, reliability, and trust across both manned and unmanned aviation domains remains a core hurdle in realising the potential of next-generation air mobility.

2 Future of AI in ATM

This section explores how emerging AI technologies are being applied to address key challenges in ATM, including growing airspace complexity, increased controller workload, and staffing shortages. By enhancing decision-making, planning, and coordination processes, these technologies offer promising solutions to support both current and future airspace operations.

2.1 Efficient Flight Planning

Efficient flight planning is a cornerstone of modern ATM, particularly as global air traffic continues to grow and demands on limited airspace intensify. Civil aviation flight plans are developed under Instrument Flight Rules (IFRs) and must consider capacity constraints, aircraft performance limitations, and airline preferences. However, even though flight plans are typically filed about an hour before departure, they are often not executed as planned due to factors such as adverse weather, ground congestion, and delayed arrivals [7]. These disruptions reduce airport efficiency and propagate delays throughout the air traffic network, a phenomenon often referred to as the ripple effect [8].

Traditional ATM research has largely focused on tactical-level solutions such as flow management, but there is growing recognition that strategic-level flight planning also plays a crucial role. The works of Rosenow et al. [7] and Ye et al. [8] offer promising approaches to solving strategic flight planning challenges using optimisation and AI.

Rosenow et al. [7] identify that conventional flight planning still heavily relies on manual processes and heuristic methods that do not fully account for the dynamic and multi-objective nature of the airspace environment. As a result, suboptimal routes are often chosen, leading to excessive fuel consumption, extended flight times, and increased emissions. To address this, the authors propose a multi-objective optimisation model that balances multiple goals while maintaining logical route structures and time constraints. The results demonstrate significant potential for AI-driven models to improve operational efficiency and environmental sustainability.

Similarly, Ye et al. [8] propose a strategic flight planning framework tailored to high-demand, weather-sensitive regions in China. Their model optimises flight scheduling with two objectives: (1) minimising total departure and arrival time offsets (Flight Minimum Shift (FMS)), and (2) reducing strategic operational costs, including ground and airborne components (Flight Minimum Cost (FMC)). Using real-world data from rainy and foggy seasons at Chengdu Shuangliu International Airport (CTU), Tengchong Tuofeng Airport (TCZ), and Dehong Mangshi International Airport (LUM), the model showed that rerouting flights to less congested airports like LUM during capacity constraints at TCZ is both feasible and cost-effective. This effectively reduces the decision-making burden on ATCOs.

While these models highlight the effectiveness of optimisation in strategic planning, their real-world deployment faces challenges. Current models are often constrained by limited datasets and simplifications that fail to capture the full complexity of live airspace operations. As UAM begin to integrate into civilian airspace, such as those using vertiports (e.g., Munich Airport (MUC), Figure 1), the need for more robust, adaptive, and AI-powered optimisation frameworks becomes critical. Future systems must be capable of dynamically coordinating mixed traffic environments with both manned and unmanned aircraft, all while managing growing complexity and operational uncertainty.

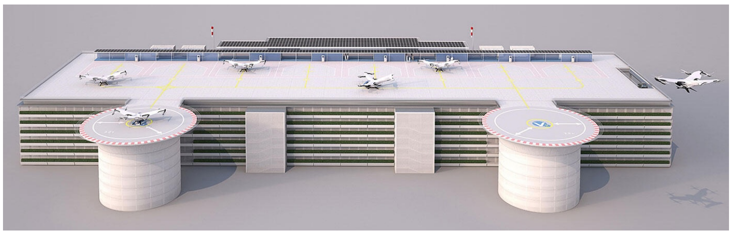


Figure 1: Development of vertiport on a parking garage at MUC [9].

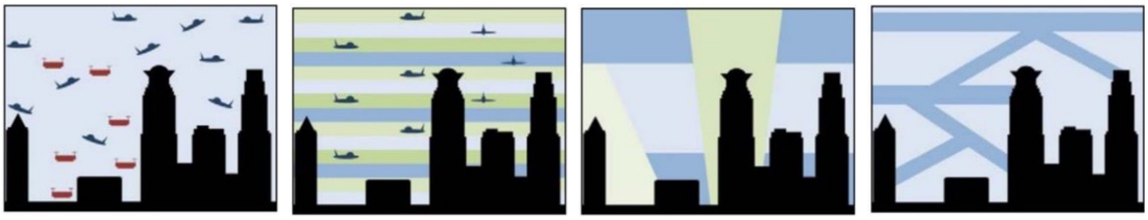
2.2 Maximised Airspace Utilisation

The increasing demand for UAM and the integration of Unmanned Aerial Vehicles (UAVs) into controlled airspace present major challenges for traditional ATM. To maximise the use of limited urban airspace while maintaining safety and efficiency, novel airspace design concepts and AI-driven separation management techniques are being explored.

The first Metropolis project investigated how different airspace structures affect capacity, complexity, safety, and efficiency in high-density urban environments. It introduced four airspace concepts: Full Mix, Layers, Zones, and Tubes, each offering varying levels of structure to manage UAV traffic (Figure 2):

- **Full Mix:** An unstructured airspace where aircraft navigate based only on physical constraints such as terrain and weather.
- **Layers:** Vertically segmented bands that restrict aircraft heading directions, providing horizontal deconfliction through altitude separation.
- **Zones:** Airspace is divided based on city layout, resembling current manned airspace practices.

- **Tubes:** Predefined, fixed aerial corridors that create conflict-free zones for structured traffic flow.



(a) Full-Mix (b) Layers (c) Zones (d) Tubes

Figure 2: Metropolis: Airspace concepts [3].

Simulations by Sunil et al. [10] showed that conflict resolution using the Modified Voltage Potential (MVP) and A* algorithms yielded better efficiency and fewer conflicts in less-structured airspace (Full Mix and Layers). Layers performed best overall, balancing throughput, safety, and flexibility.

Building on these findings, the Metropolis 2 project explored ATM concepts for mixed airspace environments, including both open and constrained regions. This second phase addressed practical constraints such as tall urban buildings and complex terrain, where vertically layered airspace may be impractical (e.g., in cities like New York). The project compared three separation management strategies with varying degrees of centralisation (Figure 3) [11]:

- **Centralised:** A single central authority handles pre-flight planning and strategic conflict resolution using global knowledge of all flights.
- **Decentralised:** Each UAV is responsible for its trajectory and separation, without access to other flight plans.
- **Hybrid:** Combines strategic central planning with tactical in-flight deconfliction by the agents themselves (a mix of both centralised and decentralised concepts).

Figure 3: Metropolis 2: Air traffic control concepts [12].

Badea [12] found that the centralised model was most efficient but limited in scalability, while the decentralised model promoted fairness but struggled with safety. The hybrid model delivered the best balance of safety, flexibility, and scalability, showcasing the benefits of combining proactive (strategic) and reactive (tactical) elements.

Overall, the Metropolis projects underscore the importance of AI in future ATM. Algorithms like A* and MVP support decentralised planning, while multi-agent reinforcement learning (MARL) and predictive models enhance conflict avoidance in real-time. Strategic AI tools are also vital for managing traffic flow, anticipating demand surges, and maintaining safety in uncertain environments.

2.3 Dynamic Airspace Sectorisation

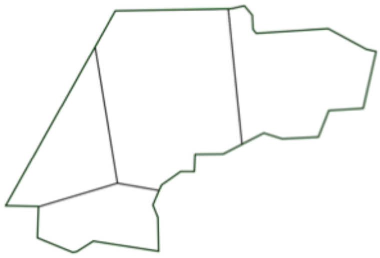
Dynamic Airspace Sectorisation (DAS) is a responsive approach to airspace management that adjusts sector boundaries according to real-time traffic demand and capacity constraints [13]. By clustering traffic patterns to identify high-density areas, DAS aims to support efficient planning and enhance controller operations [14].

Early research applied Evolutionary Algorithms (EAs) to optimise sector structures by balancing controller workload using metrics like task load distribution, geometric coherence, and flight path intersections. This method successfully replicated operational sector designs, such as those in the EDDYDUTA area (Figure 4), and adapted to daily traffic variations without expert input [14].

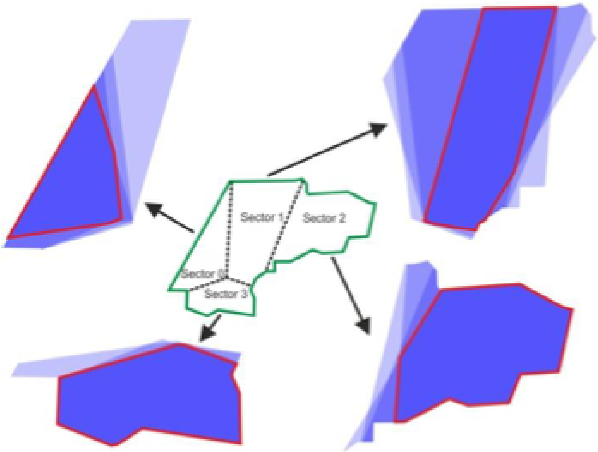
Recent advancements explore deep learning to improve DAS. Zhou et al. [15] introduced a Multi-Task Learning (MTL) model with Bidirectional Long Short-Term Memory (Bi-LSTM) networks to predict traffic flow and capacity, enabling proactive sector adjustments based on traffic-capacity imbalance forecasts across multiple time horizons. However, the model's black-box nature limits operational trust.

To improve interpretability, Zhou et al. [13] proposed AirFusion, a transparent AI framework using the Temporal Fusion Transformer (TFT) for time-series forecasting. It predicts demand and capacity up to four hours ahead, respects controller constraints, and uses Density-Based Spatial Clustering of Applications with Noise (DBSCAN) clustering and weighted graphs to guide sectorisation. AirFusion achieves high predictive accuracy (mean errors: 0.0234 for demand, 0.0291 for capacity) with strong R-squared values (0.9133 and 0.9605). Figure 5 illustrates the clustering and sector adaptation, where flight trajectories are colour-coded and major flows highlighted. When demand exceeds capacity, sectors are subdivided (purple dashed lines) to maintain workload balance.

(a) Original airspace structure



(b) Sectorisation after DAS optimisation



(c) Dynamic adaptation to traffic demand

Figure 4: Airspace EDDYDUTA [14]

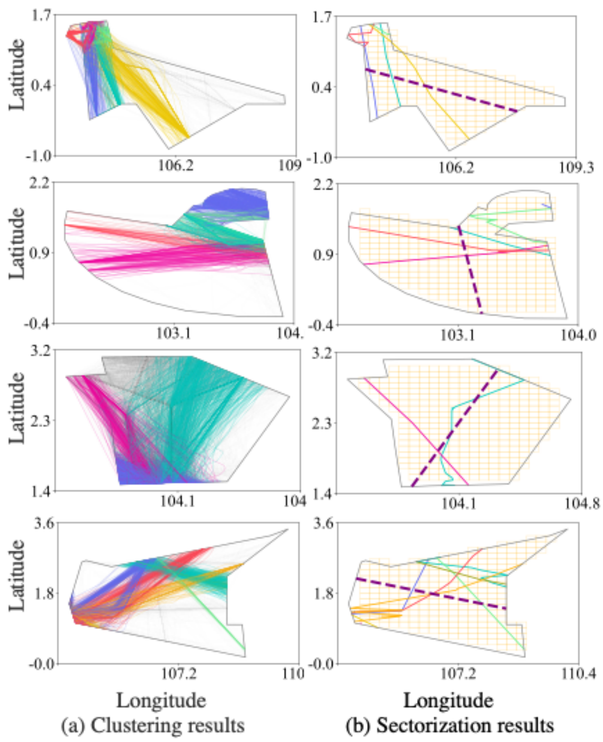


Figure 5: Clustering and sectorisation results for selected sectors [13].

Compared to the earlier Bi-LSTM model, AirFusion's integrated attention and feature selection mechanisms improve explainability, making it more suitable for real-world deployment where transparency is essential.

2.4 Digital ATCO Assistant

While AI has brought significant advancements to ATM, current Air Traffic Control (ATC) interfaces remain passive, primarily serving as information displays. Human ATCOs still manage critical decision-making and high-cognitive-load tasks. To meet growing air traffic demands, a shift toward higher automation is essential, requiring a redefined collaboration between human controllers and AI-based systems.

Jameel et al. [16] propose a digital ATCO architecture integrated with a Human-Autonomy Teaming (HAT) interface, forming the basis of a highly automated Controller Working Position (CWP) for en-route traffic. The digital ATCO handles routine tasks such as conflict detection, resolution planning, and pilot communication, allowing human controllers to assume a supervisory role and enabling potential single-operator sectors. The HAT interface supports flexible human-machine interaction across three modes: human, hybrid, and autonomous, ensuring oversight and adaptability.

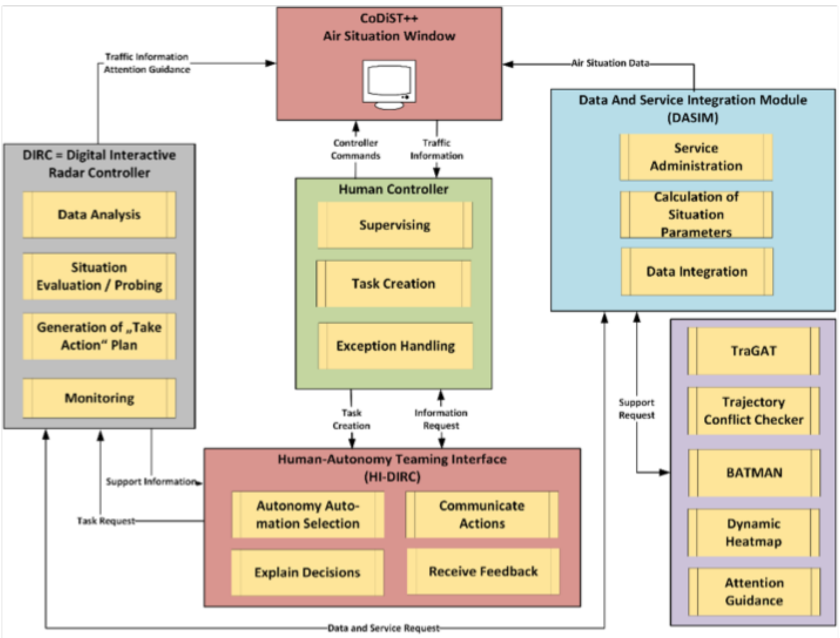


Figure 6: Overview of the system that enables single human ATCO assisted by a digital ATCO. [16]

As shown in Figure 6, the architecture includes:

1. **Controller Display and Simulation Tool (CoDiST)**: a radar display system supporting primary ATCO tasks.
2. **Digital Interactive Radar Controller (DIRC)**: the digital ATCO responsible for traffic control, action planning, and execution.
3. **HAT Interface (HI-DIRC)**: the HAT interface enabling communication between human and digital ATCOs.
4. **Data And Service Integration Module (DASIM)**: a data integration system ensuring seamless information access.
5. Various support tools including:
    - **Trajectory Generation and Advisory Tool (TraGAT)**: for generating optimised flight trajectories.
    - **Trajectory Conflict Checker (TCC)**: for continuous trajectory conflict checks.
    - **Boundary Arrival Task Manager (BATMAN)**: for coordination and handover readiness.
    - **Dynamic HeatMap (DHM)**: for detecting sector congestion and hotspots.
    - **Attention Guidance (AG)**: for highlighting critical flight events on the radar.

The system's proof-of-concept at Airspace World 2023 received positive feedback, with professional ATCOs' interests in contributing to further development.

Future research will explore optimal task distribution strategies, robust human-in-the-loop designs, and mechanisms for seamless task reallocation in uncertain conditions. Emphasis will also be placed on enhancing AI transparency and explainability to foster trust and support certification.

3 Challenges of Integrating AI in ATM

Despite the significant progress in enhancing ATM systems through the integration of AI, numerous challenges remain that hinder its seamless implementation. Malakis et al. [17] provide a comprehensive overview of these challenges, highlighting the complexities involved in technical, operational, organizational, and regulatory domains.

3.1 Political / Regulatory

The political and regulatory challenges in integrating AI into ATM include the persistent fragmentation of the European ATM sector and state sovereignty issues, which complicate coordinated reform. The certification processes for AI-related technologies remain complex due to their novelty, while outdated development assurance frameworks require adaptation, exemplified by the emergence of the Learning Assurance Concept. Legal ambiguity persists regarding the roles of Air Traffic Services Providers versus ATM Data Service Providers. Moreover, harmonizing ethics policies, ensuring geographical redundancy of data centers, resolving cross-border risk-sharing agreements, and maintaining public trust through transparency and social acceptability pose additional hurdles.

3.2 ANSP / Business

From the perspective of Air Navigation Service Providerss (ANSPs) and business stakeholders, challenges revolve around managing organizational transformation, legal and insurance uncertainties, and the risks associated with early adoption of emerging technologies. The unclear cost-benefit profile of AI solutions, combined with complexities in defining service scopes and boundaries, further complicates investment decisions. There are also high costs for upgraded cybersecurity, and the transition disrupts established knowledge-sharing and training practices. Effective change management strategies, including robust simulation and feedback loops involving operators, are critical to facilitating this technological shift.

3.3 Technical

Technically, the implementation of AI in ATM systems is impeded by issues such as the difficulty of sharing AI infrastructure across national boundaries and the inherent dependence of machine learning models on high-quality, representative datasets. Challenges like the curse of dimensionality, lack of generalizability across operational contexts, and the need for tailored AI solutions hinder scalability. Additionally, ensuring data integrity, developing resilient backup systems, and designing AI capable of interpreting weak signals for decision-making are essential to maintaining safety and operational reliability.

3.4 Operational

Operational challenges include managing the increased complexity and interdependencies introduced by AI, and synchronizing procedures between Air Traffic Services Units and the Network Manager. Current Concepts of Operations (CONOPS) often fail to accommodate AI capabilities, necessitating new operational models. Issues with the explainability of AI outputs and poorly defined function allocation can leave controllers vulnerable when automation fails. A cohesive strategy is needed to harmonize AI integration across all stakeholders, including controllers, pilots, and airport operators, while mitigating the disruption to established communication and authority structures.

3.5 ATCOs

For ATCOs, AI integration presents challenges in maintaining situational awareness and adapting to changing roles. It disrupts long-standing coordination patterns among ATCOs and between ATCOs and flight crews, potentially undermining resilience. Increasing automation introduces unexpected behaviors and error types, requiring new cognitive skills and mental models to understand and manage AI systems. Acceptance of new responsibilities, resistance due to job security concerns, de-skilling, attention management difficulties, and social impacts such as mobility and relocation further complicate human factors integration into AI-enhanced ATM environments.

4 Conclusion and Outlook

The integration of AI into ATM is transforming aviation through innovations like linear optimisation for flight planning, dynamic airspace sectorisation, and digital ATCO assistants. These technologies aim to enhance operational efficiency, optimise airspace use, and reduce controller workload by supporting decision-making and automating routine tasks.

Despite this progress, significant challenges remain. Regulatory fragmentation, complex certification processes, data privacy concerns, and the need for explainable AI all hinder seamless implementation. Operational models must adapt to AI capabilities, while human factors such as ATCO role changes, training, and trust in automation require careful consideration to ensure safety and acceptance.

Looking forward, the concept of fully autonomous, unmanned ATM systems remains a distant but plausible goal. Ongoing research explores AI-driven airspace management and autonomous coordination of UAVs. Although technical, ethical, and regulatory hurdles persist, the potential for such systems highlights the importance of sustained innovation, collaboration, and a measured approach to future AI adoption in ATM.

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