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AI-Enabled Tactical FMP Hotspot Prediction and Resolution (ASTRA): A Solution for Traffic Complexity Management in En-Route Airspace †

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Abstract: The air traffic growth expected for future years will likely cause an imbalance between traffic demand and available capacity. This could lead to increased airspace congestion, heightened complexity, and a higher workload for controllers attempting to manage the situation. Nowadays, available tools can identify 4D Area of Relatively High Air Traffic Control Complexity (4DARHAC) events up to 20 min before they occur. Nonetheless, state-of-the-art Artificial Intelligence applications can significantly increase this prediction horizon. Powered by a combination of different Machine Learning models, the ASTRA solution aims to both detect and provide resolution strategies for 4DARHACs up to 1 h before onset. To validate ASTRA's operational concept, a series of workshops and interviews with Flow Management Position operators were conducted, focusing on assessing the initial concept and identifying end user needs. The feedback collected was validated by a board of Subject Matter Experts (SMEs) and transformed into a concrete set of functional and non-functional requirements. Overall, ASTRA's operational concept was endorsed as a promising solution for reducing airspace complexity while alleviating operator workload during the tactical phase of operations. Experts further highlighted the importance of integrating ASTRA with existing Flow Management Position software tools to maximize its operational impact and facilitate adoption.

Keywords: air traffic management; innovative concepts and scenarios; human factors

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1. Introduction

Air Traffic Management (ATM) involves the integrated management of air traffic and airspace, ensuring that efficiency and safety standards are maintained [1]. One of the domains of ATM is Air Traffic Flow and Capacity Management (ATFCM) [1], which intends to regulate the aircraft flow to prevent airspace sector congestion and balance air traffic demand with capacity (Demand–Capacity Balancing, DCB) [2,3].

In the near future, the growing demand for air transport could challenge ATM systems [4] and potentially impact aviation's strategic goals on sustainability and reduced environmental footprint [5,6]. When demand exceeds declared capacity, a sector overload occurs, and measures need to be taken to restore the balance [7,8]. Demand–capacity imbalances are more likely to create areas of high air traffic complexity [9]. Even in a sector that is operating within its declared capacity, traffic complexity can vary dynamically in time and space since it depends on many factors, beyond the number of aircraft that occupy the sector in a given period of time [10]. Within the project framework, complex traffic events are referred to as 4D Areas of Relatively High Air Traffic Control (ATC) Complexity (4DARHACs). A 4D area, which, depending on traffic type, may include variables like high traffic density, extensive required actions, and numerous ATC conflicts, significantly consuming ATC sector capacity. In ASTRA, this is defined as "4DARHAC", referring to ATC complexity within a tactical ATC timeline, distinct from an ATFCM hotspot. This definition includes a time element, the situation, the non-permanent nature of complexity, and a notion of relativity that emphasizes the need for contextualizing complexity. Complexity can be defined as a "measure of the difficulty that a particular traffic situation will present to an Air Traffic Controller (ATCO)" [11]. It directly impacts ATCO workload and depends on many factors, though there is no general agreement in the scientific community about which factors are the most important [12,13].

To prevent 4DARHACs, various ATFCM measures can be implemented, such as opening new sectors to accommodate increased demand, rerouting traffic flows through less congested areas, and rescheduling flights to balance traffic flows [14].

Currently, air traffic congestion or 4DARHACs are detected using flight plan data and are managed either at the pre-tactical or tactical phase of operation—i.e., shortly before or after the flight enters the airspace in consideration [14]. Advanced conventional solutions enable some Area Control Centers (ACCs) to predict such events with a horizon of approximately 20 min before their occurrence [15]. This relatively short prediction window limits the effectiveness of interventions, often necessitating last-minute tactical instructions from ATCOs and increasing workload at the Control Working Position (CWP) [16]. ASTRA's one-hour look-ahead capability could potentially enable earlier interventions, which may help reduce the complexity of such events or even prevent them altogether. A prediction horizon of one hour or more enables FMP operators to apply dissipation measures early, with minimal involvement from ATCOs, significantly reducing the workload at the CWP during the tactical phase. Early interventions also facilitate the planning of fuel-efficient and safer traffic flows by avoiding last-minute tactical maneuvers. Additionally, resolving 4DARHAC events earlier—using ASTRA's reinforcement learning agent optimized for airspace complexity reduction—can result in less complex and more predictable traffic patterns, potentially increasing airspace capacity.

For 4DARHACs resolution, Reinforcement Learning (RL) has been introduced, with two major types of resolution proposed. One involves proposing delayed take-offs to avoid congestion [17], while the other reroutes aircraft to resolve imbalances, jointly with human agents [18]. However, few Machine Learning (ML)-based solutions in the literature explicitly use eXplainable Artificial Intelligence (XAI) to support human agents in the understandability of ML solutions.

'AI-enabled tactical FMP hotspot prediction and resolution' (ASTRA) is a co-founded EU project supported by the Single European Sky ATM Research (SESAR) program, involving researchers from various organizations: Universita Ta Malta, Innovación y Gestión de Navegación Aérea (INGENAV), Deep Blue, Skysoft-ATM, and Skyguide. ASTRA aims to predict and resolve 4DARHAC events one hour before their occurrence. ASTRA will be able to detect and alert the Flow Management Position (FMP) when a potential 4DARHAC

event is predicted to occur (Figure 1). The developed interface will then suggest appropriate dissipation strategies ranked by complexity reduction and confidence level of success.

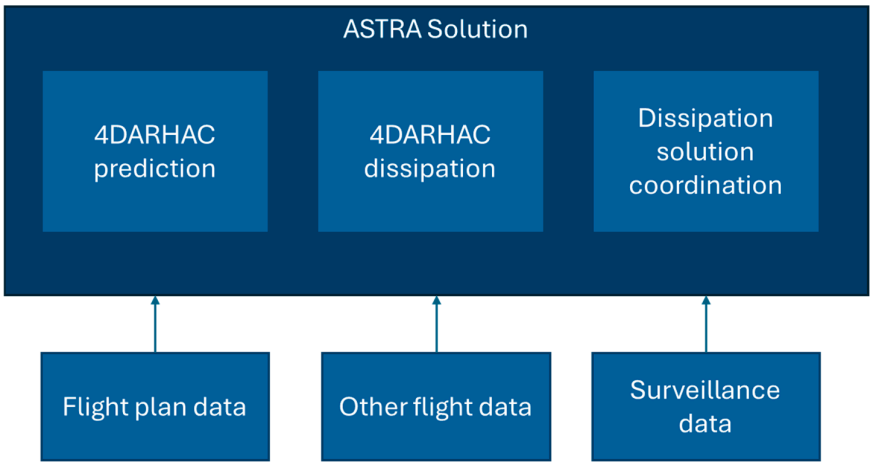


Figure 1. ASTRA concept.

To enhance comprehension of the dissipation strategies suggested by the RL agent and its underlying reasoning, ASTRA's Human Machine Interface (HMI) will incorporate XAI elements. While the exact design and layout of these features are still under discussion, the core philosophy revolves around the RL agent's complexity reduction principle. The HMI will explicitly illustrate the impact of each dissipation strategy on the overall complexity score and the individual factors contributing to it, enabling FMPs to understand each dissipation in quantifiable terms. In specific cases, ideas from ecological interface design may be utilized; for example, when suggesting flight level changes, the HMI could display the flight level occupancy by adjacent traffic and the corresponding timings, clarifying the constraints considered by the RL agent. Additionally, the HMI will feature a map, similar to the Plan View Display (radar map) used at the CWP, to show the projected traffic flow with and without dissipations applied, allowing FMPs to explore how traffic evolves under each scenario.

The implementation of a tool like ASTRA would bridge the gap between ATFCM and ATC, facilitating communication and enhancing collaboration between the FMP and the planner CWP [19]. By developing this kind of tool, it could be possible to predict congestions earlier than today, resulting in multiple benefits, including (i) reduction of strain on global ATM, (ii) reduction of ATCO workload, (iii) enhancement of ATC capacity without increasing complexity, (iv) enhancement of safety of operations, and (v) routes with lower environmental footprint.

The ASTRA solution is being validated through three exercises: (i) a workshop where the operational experts support the definition of the operational concept and requirements together with the researchers; (ii) a low fidelity simulation, where the HMI prototype is tested with end users; and (iii) a real-time simulation to test the final version of ASTRA, including its software and related algorithmic developments. End user feedback is collected at each stage to ensure alignment between the developed technologies and operator needs, effectively adhering to a Human-Centred Design (HCD) approach. HCD is an iterative system development method that prioritizes users' needs, tasks, and contexts to ensure usability and effectiveness. By applying ergonomic and usability principles, HCD creates solutions that align with user requirements while enhancing overall user experience and performance [20].

This paper focuses on the first validation exercise, which aimed to validate the operational concept and functional and non-functional requirements of the ASTRA solution.

This was achieved by involving SMEs in a workshop where they were asked to provide feedback and review the Operational Service and Environment Definition (OSED) and Functional Requirements Document (FRD) produced within the project framework.

The validation of ASTRA's operational concept and functional requirements aimed at exploring the SMEs' perceived enhancement of the ATM network performance, enabling the early detection and resolution of 4DARHAC events delivering benefits at the network level, as well as ASTRA's ability to increase capacity and efficiency of sectors, by reducing the workload of ATCOs and improving the operational efficiency of Air Navigation Services Providers (ANSPs).

2. Materials and Methods

The first validation exercise involved an online workshop with ASTRA's External Experts Advisory Board (EEAB), including representatives of different stakeholders (e.g., ANSPs, FMPs, and Network Managers (NMs)). SMEs assessed and provided feedback on the OSED and the FRD collected during earlier project phases.

The second validation exercise involved validating the ASTRA HMI through a low-fidelity simulation including interface prototype and questionnaires to gather feedback from end users. Furthermore, participants engaged in debriefing sessions to provide qualitative feedback.

The final validation exercise will consist of a human-in-the-loop Real-Time Simulation (RTS) of the ASTRA solution at Technology Readiness Level (TRL) 2, including its interface and algorithms for operational tasks. To test and assess the benefits and the implementation impact of the new tool, two types of experimental runs will be performed and compared: one with the ASTRA solution and one without it (to establish a baseline).

Since ASTRA is an exploratory research project, it started at TRL 1 (Basic Technology Research) and is expected to reach TRL 2 (Basic Technology Research/Research to Prove Feasibility) by its end, foreseen by early 2026. Given the low TRL, an implementation plan is not scheduled at this time, as further research will be required to deploy the solution in an operational environment. However, project partners might initiate a second phase of development to continue enhancing the solution after the project's conclusion.

As mentioned in Section 1, this paper focuses on the first validation exercise, part of a comprehensive process to identify, develop, and validate requirements, ensuring the ASTRA solution fulfills the needs of its users and stakeholders.

Prior to the EEAB workshop, the researchers held two sessions: a user needs workshop at INGENAV's facilities to identify the initial user requirements and high-level needs, and an HMI requirements definition workshop at Skyguide's facilities in Geneva. In these workshops, researchers gathered input from end users and other stakeholders who evaluated the ASTRA concept and scenarios to highlight specific needs and challenges from an operational and HMI perspective.

After these two stages, the EEAB workshop was conducted online via the Zoom platform. The involvement of SMEs ensured that the requirements were accurate, complete, and aligned with the project's scope and objectives, thanks to their expertise and knowledge.

2.1. Participants

A total of 11 participants attended the user needs workshop: 7 consortium members, 2 members of the EEAB representing policy makers and ANSP stakeholders, and 2 members from SESAR. A total of 8 participants attended the workshop in person, while 3 joined remotely.

For the HMI and user needs workshop, five participants attended. These participants included 2 in FMP roles, 2 ATC Supervisors, and 1 ATFCM Domain Manager.

All 4 EEAB members participated in the workshop either via Zoom or by providing feedback offline to the OSED and FRD documents, representing various stakeholders: 2 from policy makers and regulators organizations, 1 from an ANSP, and 1 ATCO and FMP expert.

2.2. Validation Objectives

The primary objectives of the validation exercise were to discuss the feasibility of the proposed solution, ensure its alignment with the project's goal, and gather feedback from stakeholders to assess ASTRA's concept and requirements. Specifically, the exercise aimed to assess the following key aspects crucial to the success of the project:

- The impact of the solution on workload;
- En-route capacity;
- Safety;
- Operational and cost efficiency;
- Fuel consumption.

2.3. Procedure

The first step of the requirement development process was the user needs workshop, conducted over two days in a hybrid mode, with most attendees present at INGENAV's facilities and three of them joining remotely.

The first day began with a welcome and introduction of the consortium partners, followed by an overview of ASTRA's background and its main objectives. Then, two different end user perspectives on ASTRA's concepts and future needs were presented. Afterwards, participants were given a presentation on related concepts that should be considered, such as hotspot definitions and solutions to capacity shortfalls, concluding with a question and answer (Q&A) session.

The second day featured two facilitated sessions focusing on how end users would use, and what they would need from, ASTRA. These sessions included brainstorming on ASTRA's potential field applications, uses, and functional needs, leading to clustering, prioritization, and discussion of these ideas.

The second step of the process was the HMI requirements workshop held in Geneva.

On the first day, participants signed informed consent forms and were assured that their data would remain confidential. Participation was voluntary, with the option to withdraw participation and data at any time. Later, each participant took part in a 1.5 h individual interview with project Human Factor (HF) experts to discuss their needs and requirements for the development of the ASTRA HMI.

The second day comprised presentations on the needs and challenges collected by the ASTRA project, followed by a presentation of the OSED and a plenary discussion. Before concluding, participants engaged in a discussion on HMI needs prioritization in order to rank requirements based on their implementation relevance.

For validation exercise #01, namely the EEAB workshop, the aim was to validate the operational concept and the functional and non-functional requirements of ASTRA, presenting the OSED—including the use cases envisioned for the project—and the FRD. After each presentation, members of the EEAB engaged in a discussion and Q&A session to provide their inputs and feedback on the solution's scope, objectives, techniques, expected benefits, and possible issues. This structure enabled a comprehensive understanding and specification of the context of use, as well as the identification of users and organizational requirements.

2.4. Data Collection and Analysis

The meetings were recorded, and notes were taken during the interviews and discussions. A qualitative analysis of the results was then performed to extract key discussion points per ASTRA validation objective.

3. Results and Discussion

Validation exercise #01 focused on gathering qualitative feedback from SMEs to meet the validation objectives at a conceptual level. Consequently, the results generated did not include quantitative data but rather focused on the project's alignment with Key Performance Areas (KPAs) and priorities for the next steps of development.

3.1. Workload

EEAB members agreed that the ASTRA solution has the potential to decrease ATCO workload levels by detecting and resolving 4DARHAC events before they occur, thereby leading to a reduction in traffic complexity. Nevertheless, FMPs indicated that using ASTRA would involve them in the pre-tactical ATC phase, leading to significant changes in their work domain. They also mentioned that ASTRA implementation would require extra coordination between the actors involved, although the communication workload could be balanced by reducing sector complexity. Nevertheless, the actual impact on FMP workload can only be reliably assessed in the RTS.

Furthermore, EEAB highlighted the need to fine-tune the algorithms that are going to be implemented in the ASTRA solution to ensure that they do not create new 4DARHAC events within the airspace when suggesting dissipation solutions. This phenomenon, referred to as the "domino effect", suggests that solutions proposed for one of the 4DARHAC events could trigger a new event in the same or another sector [21]. It is acknowledged that a dissipation solution will possibly lead to the use of capacity elsewhere [21], but in the ASTRA solution, this would be achieved without reaching unacceptable thresholds and without the generation of additional 4DARHAC events.

Another consideration for the workload is the explainability of AI. Participants agreed that explaining why a specific dissipation solution was suggested over another would enhance FMPs' trust in the ASTRA tool, reducing their workload by eliminating guesswork on how and why the dissipation solution was proposed. However, one EEAB member questioned whether ASTRA would be able to provide an understandable explanation of the proposed dissipations due to the slow progress of XAI.

One of the main objectives of the ASTRA project is to ensure the explainability of these strategies in the HMI development, where the tool will break down the complexity of 4DARHAC events and highlight contributing factors. Nonetheless, it is crucial to provide the right amount of information to end users to meet workload reduction criteria [22,23], as giving too much information could overwhelm their mental capacity, resulting in excessive information processing [24] and increasing workload.

Closely linked to workload is the complexity of the air traffic, which could be effectively managed using ASTRA's ability to predict and prevent a 4DARHAC event from occurring. This is consistent with the use of ML algorithms to detect and predict these events through trajectory prediction [25]. Trajectory prediction involves estimating the future states of the aircraft based on the current aircraft state, estimation of the pilot and controller intent, expected environmental conditions, and aircraft performance computer models and procedures [26]. Compared to direct congestion prediction, this method allows end users to observe which aircraft might be involved in the potential congestion [25]. Reliable trajectory predictions could theoretically lead to enhanced en-route capacity, miti-

gating airspace complexity, and positively affect operations, cost efficiency, and safety, as confirmed by experts.

3.2. En-Route Capacity

Participants also agreed that, by reliably detecting and resolving complex traffic situations, ASTRA could increase en-route capacity. According to some of the EEAB members, en-route capacity is highly influenced by traffic complexity. One of the participants highlighted that an increase in the complexity of airspace is often due to unexpected traffic appearing in a sector, such as aircraft deviating from their flight plans. This stresses the importance of focusing on the trajectory prediction tool of ASTRA to ensure reliable trajectory and event predictions, thus avoiding increased complexity.

3.3. Safety

EEAB members agreed that reducing complexity through ASTRA's implementation would also enhance safety by lowering excessive or unpredictable traffic risks and thereby improving ATCO situational awareness. They also noted that ASTRA's ability to detect 4DARHAC events early would enable proactive mitigation of traffic risks, preventing last-minute escalations of complex situations and traffic conflicts. Furthermore, EEAB members emphasized that dissipation solutions should prevent the creation of new 4DARHACs or conflicts in other parts of the airspace. Additionally, the solution's ability to provide FMPs with an appropriate list of actions to address issues and streamline flow management would also enhance safety by reducing human error.

3.4. Operational and Cost Efficiency

Regarding operational and cost efficiency, participants stated that ASTRA could positively impact these areas, as its dissipation system will execute re-routing decisions based on a cost/benefit analysis considering traffic flows, operator workload, and potential airspace disruptions. They also noted that ASTRA provides real-time monitoring to detect deviations from dissipation instructions earlier and offers post-operation analysis capabilities to examine historical decisions and identify best practices concerning prevailing traffic conditions, airspace configuration, and aircraft compliance. The feedback from participants suggested that economic benefits could also be achieved through gaining confidence in the ASTRA's ability to resolve typical 4DARHAC events, leading to sufficient trust in the tool for ACCs to roster ATCOs more efficiently compared to today.

3.5. Fuel Consumption

Given that ASTRA's dissipation solutions for 4DARHACs can reduce en-route delays by minimizing last-minute interventions at the tactical ATC level and prioritizing solutions with a lower environmental impact, participants agreed that ASTRA could reduce the overall fuel consumption. Moreover, they acknowledged that ASTRA's considerations of the environmental impact of dissipation solutions, which include functions that estimate fuel consumption for each aircraft per dissipation solution action, will identify dissipation strategies with lower fuel resource footprint and relay these estimates to FMPs for informed decision-making.

4. Conclusions

This first validation exercise of the ASTRA project aimed at collecting feedback and opinions on the concept of the project from SMEs who are EEAB members to validate the functional and non-functional requirements.

The overall feedback from the EEAB endorsed the initial concept of operations, which serves as a good basis for meeting the validation objectives envisioned for the next steps

of the project. However, it was highlighted that particular attention should be given to the development of algorithms to ensure that the proposed dissipation solutions do not generate 4DARHACs elsewhere in the airspace. The data gathered from the members will need further refinements for future versions of the OSED and the FRD, to be tested in subsequent validation exercises.

As this validation exercise was qualitative, it did not assess the actual impact of ASTRA on performance. Although a definitive assessment of system or human performance was not allowed, EEAB members recognized the potential benefits of the requirements.

Despite the results discussed, the study has certain inherent limitations. The methodology used, relying on SMEs, limits the breadth of the feedback due to its qualitative nature. Such feedback, while expertly informed, is non-generalizable and potentially subject to individual biases and personal perspectives.

Furthermore, the small number of SMEs involved in the workshop results in a lack of operational significance typically derived from a broader expert consensus. However, the well-positioned solution's requirement feedback gathered from participants could mitigate this effect.

Nevertheless, the outputs of this exercise have provided valuable inputs for the next validation activities of the ASTRA project. Future research and innovation activities could explore applying ASTRA network-wide, as this project assumes that the tool will operate at a local level within a single ACC. Furthermore, at higher technological maturity levels, it would be important to integrate the ASTRA HMI with existing FMP tools and to reduce the communication and coordination effort required to carry out dissipation actions (e.g., by automating coordination tasks).

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References

1. ICAO Doc 4444 ATM/501. 2007. Available online: https://www.icao.int/EURNAT/Other%20Meetings%20Seminars%20and%20Workshops/FPL%202012%20ICAO%20EUR%20Region%20Plan/Documentation%20related%20to%20FPL%202012%20Amendment/Amendment%201%20Doc4444.EN.pdf (accessed on 28 September 2024).
2. Air Traffic Management. Available online: https://skybrary.aero/articles/air-traffic-management-atm (accessed on 18 October 2024).
3. Niarchakou, S.; Sfyroeras, M. ATFCM OPERATIONS MANUAL: Network Manager. *Eurocontrol* **2024**. Available online: https://www.eurocontrol.int/sites/default/files/2020-05/eurocontrol-atfcm-operations-manual-22052020.pdf (accessed on 2 October 2024).
4. Icao.int. Future of Aviation. Available online: https://www.icao.int/Meetings/FutureOfAviation/Pages/default.aspx (accessed on 2 October 2024).
5. European Union. Aviation Safety Agency EASA's Sustainable Aviation Programme. Available online: https://www.easa.europa.eu/en/light/topics/easas-sustainable-aviation-programme (accessed on 2 October 2024).
6. EUROCONTROL. Aviation Outlook 2050: Air Traffic Forecast Shows Aviation Pathway to Net Zero CO_2 Emissions. Available online: https://www.eurocontrol.int/article/aviation-outlook-2050-air-traffic-forecast-shows-aviation-pathway-net-zero-co2-emissions (accessed on 2 October 2024).
7. EUROCONTROL. Experimental Centre Pessimistic Sector Capacity Estimation. *Eurocontrol* **2003**, *21*. Available online: https://www.eurocontrol.int/sites/default/files/library/026_Pessimistic_Sector_Capacity.pdf (accessed on 2 October 2024).
8. Wangnick, S. ACC Capacity, Cost and Overload Avoidance Trade-Offs. *SESAR Innov. Days* **2020**. Available online: https://www.sesarju.eu/sites/default/files/documents/sid/2020/papers/Paper%2046%20ACC%20Capacity,%20Cost%20and%20Overload%20Avoidance%20Trade-Offs.pdf (accessed on 2 October 2024).
9. Pejovic, T.; Natjasov, F.; Crnogorac, D. Relationship between Air Traffic Demand, Safety and Complexity in High Density Airspace in Europe. *MATEC Web Conf.* **2020**, *314*, 1004. [CrossRef]
10. Pérez Moreno, F.; Gómez Comendador, V.F.; Delgado-Aguilera Jurado, R.; Zamarreño Suárez, M.; Antulov-Fantulin, B.; Arnaldo Valdés, R.M. How Has the Concept of Air Traffic Complexity Evolved? Review and Analysis of the State of the Art of Air Traffic Complexity. *Appl. Sci.* **2024**, *14*, 3604. [CrossRef]
11. Cano, M.; Degrémont, S.; Terzioski, P. *Step1 V3 Final Complexity Management OSED*; SESAR: Bruxelles, Belgium, 2016. Available online: https://www.sesarju.eu/sites/default/files/documents/solution/Sol17%2004%20OSED%20Solution%2017%20P04%2007%2001_D68_STEP1%20V3%20Final%20Complexity%20Management%20OSED.pdf (accessed on 4 October 2024).
12. Edwards, T.; Gabets, C.; Mercer, J.; Bienert, N. *Task Demand Variation in Air Traffic Control: Implications for Workload, Fatigue, and Performance*; Springer: Cham, Switzerland, 2016; Volume 484, ISBN 9783319416816. [CrossRef]
13. Hilburn, B. Cognitive Complexity in Air Traffic Control a Literature Review. *Eurocontrol* **2004**, *12*, 21.
14. EUROCONTROL. *ATFCM Operating Procedures for Flow Management Position*; EUROCONTROL: Bruxelles, Belgium, 2014; Volume 18.1.1. Available online: https://www.eurocontrol.int/sites/default/files/content/documents/nm/network-operations/HANDBOOK/atfcm-ops-procedures-fmp-current.pdf (accessed on 5 October 2024).
15. Ayhan, S.; De Oliveira, I.R.; Balvedi, G.; Costas, P.; Leite, A.; De Azevedo, F.C.F. Big Data-Driven Prediction of Airspace Congestion. In Proceedings of the AIAA/IEEE Digital Avionics Systems Conference—Proceedings, Barcelona, Spain, 1–5 October 2023. [CrossRef]
16. Dhief, I.; Wang, Z.; Liang, M.; Alam, S.; Schultz, M.; Delahaye, D. Predicting Aircraft Landing Time in Extended-Tma Using Machine Learning Methods. In Proceedings of the ICRAT 2020 Conference, Tampa, FL, USA, 15 September 2020.
17. Crespo, A.M.F.; Weigang, L.; de Barros, A.G. Reinforcement Learning Agents to Tactical Air Traffic Flow Management. *Int. J. Aviat. Manag.* **2012**, *1*, 145–161. [CrossRef]
18. Kravaris, T.; Lentzos, K.; Santipantakis, G.; Vouros, G.A.; Andrienko, G.; Andrienko, N.; Crook, I.; Garcia, J.M.C.; Martinez, E.I. Explaining Deep Reinforcement Learning Decisions in Complex Multiagent Settings: Towards Enabling Automation in Air Traffic Flow Management. *Appl. Intell.* **2023**, *53*, 4063–4098. [CrossRef] [PubMed]
19. *ASTRA D2.9*; Operational Services and Environment Description (OSED)—Intermediate. SESAR JU: Bruxelles, Belgium, 2024.
20. *ISO 9241-210*; Ergonomics of Human–System Interaction—Human-Centred Design for Interactive Systems. ISO: Geneva, Switzerland, 2010.
21. ASTRA Functional Requirements document (FRD)—Intermediate. SESAR JU: Bruxelles, Belgium. 2024. Available online: https://cordis.europa.eu/project/id/101114787/results (accessed on 17 October 2024).
22. Chakraborti, T.; Sreedharan, S.; Kambhampati, S. Balancing Explicability and Explanations for Human-Aware Planning. In Proceedings of the 28th International Joint Conference on Artificial Intelligence, Macao, China, 10–16 August 2019; AAAI Press: Macao, China, 2019; pp. 1335–1343. [CrossRef]

23. Chakraborti, T.; Sreedharan, S.; Grover, S.; Kambhampati, S. Plan Explanations as Model Reconciliation—An Empirical Study. In Proceedings of the 2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI), Daegu, Republic of Korea, 11–14 March 2019; pp. 258–266. [CrossRef]
24. Sanneman, L.; Shah, J.A. The Situation Awareness Framework for Explainable AI (SAFE-AI) and Human Factors Considerations for XAI Systems. *Int. J. Hum.–Comput. Interact.* **2022**, *38*, 1772–1788. [CrossRef]
25. Zeng, W.; Chu, X.; Xu, Z.; Liu, Y.; Quan, Z. Aircraft 4D Trajectory Prediction in Civil Aviation: A Review. *Aerospace* **2022**, *9*, 91. [CrossRef]
26. Garcia-Chico, J.; Vivona, R.; Cate, K. Characterizing Intent Maneuvers from Operational Data: Step Towards Trajectory Prediction Uncertainty Estimation. In Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit, Honolulu, HI, USA, 18–21 August 2008. [CrossRef]

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