ATM concepts roadmap - initial

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Abstract

The Engage 2 ATM concepts roadmap will provide an innovative set of concepts beyond the SESAR 3 timeframe. This deliverable provides initial reporting on the activities to date relating to the development of the roadmap. An AI-based trend analysis has been used to analyse over 500 documents, consisting of ATM conference papers, SESAR project deliverables and JU reference material. Results from the second iteration of the analysis are outlined. Planning of the on-line representation of the ATM concepts roadmap in the EngageWiki are outlined.

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[1] Representatives of all the beneficiaries involved in the project

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Engage 2

THE SESAR 3 KNOWLEDGE TRANSFER NETWORK

Engage 2

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1 Introduction

1.1 Background and context

A primary goal of the Engage 2 ATM concepts roadmap is to provide an innovative set of concepts beyond the SESAR 3 timeframe with emerging and distinct relevance to ATM. The development of the roadmap takes into consideration information on R&D topics, concepts, future priorities and challenges, existing research in the main SESAR programme, and links with other initiatives beyond ATM.

This work builds on the foundation work of the original Engage KTN (2018-2022) and recent work carried out within Task 4.1 to identify trends in the field of ATM. Mindful of the very fast development in generative artificial intelligence (GenAI), this technology was used for the first iteration of the trend analysis to explore ATM research literature – producing promising results in Task 4.1 of Engage 2. An AI based trend analysis has been retained for the second iteration, as reported in this interim deliverable which outlines the initial findings.

The ATM concepts roadmap will continue to be developed and is planned to be published on-line in 2026, hosted by the EngageWiki, and to be reported in D5.7. It is important to note that D5.1 is an interim deliverable, testing and developing the methodology to be finalised in D5.7, which will report on the final iteration of the AI-based trend analysis, taking into account shortcomings identified at this interim stage (such as the omission of any major new trend or technology). This is one of the main purposes of running the model for interim output evaluation (i.e. through this deliverable).

1.2 Scope and limitations

The time horizon for the trend analysis in this document was set to cover near- and mid-term perspectives. The AI based trend analysis covers trends with a horizon of 30 years. With a longer period to look at, more variables and unknowns come into play and factors outside technological advancements, such as economic cycles, political changes and societal shifts will have increased impact.

2 AI-based trend analysis

2.1 Generative AI: usage and limitations

In this report we use the so-called 'Generative AI' technology to automatically discover trends from articles and white papers. Following earlier favourable results using this technology in Task 4.1, this deliverable reports on the second iteration of the AI based trend analysis along with plans for the Engage 2 ATM concepts roadmap. The results of the final iteration of the AI based trend analysis and final schema of the roadmap to be published in the EngageWiki will be reported in D5.7 (due in 2026).

AI of different forms have been gaining more and more traction in the last 20 years, but the popularity of generative AI ('GenAI') grew rapidly in November 2022 when OpenAI released their new version of a chat AI called 'ChatGPT 3.0'. Its popularity immediately pushed other companies to release their own versions of a chat AI, in particular Google and Amazon. Although several concerns have been raised since then, in particular in terms of reliability, the datasets involved in training, etc., this technology has been flagged as the most promising path to general artificial intelligence, and has found many applications. Moreover, in just two and a half years, several new features have been added to the tools, including image recognition and generation, text and speech recognition, information retrieval, chain of thoughts etc.

By nature, these models are good at communicating in natural languages (and other types of languages, like programming languages), and are particularly suitable at synthesising text, extracting particular strands of information for the users. This makes them useful for many academic applications, in particular when researchers try to summarise information based on previously published academic papers, i.e. performing a literature review.

In this deliverable these models were used to extract knowledge and finding patterns within large sets of texts, to find trends in technological developments. Instead of relying on single prompts and high-level queries, several AI were fed sequentially or in parallel with the results of the previous one(s) (see Section 2.3.1 for more details). This setup allows us to have a much higher quality for the final results, avoiding common traps like hallucinations, over-focusing, missing important items, or putting all items on the same footing. On top of that, prompt engineering techniques were used at each step, allowing answers to be as relevant as possible, and to have proper formats for the next sequence of AIs.

Compared to deliverable D4.1 [2], we also slightly change the focus of the analysis. First, we focus on 'internal' documents only, meaning deliverables, white papers, and conference research papers. This is in contrast with the previous deliverable, where we also analysed papers found on-line thanks to the dedicated tool SciSpace (although this tool was not used with this deliverable).

Moreover, since we are still interested in trends in aviation, we are also interested in building a roadmap for European aviation technological deployment, which means trying also to capture approximate dates and interdependencies among trends.

2.2 Data sources

Along with formal Master Plan and Strategic Research and Innovation Agenda (SRIA) reference documents, published material from relevant conferences and SESAR projects has been sourced for the trend analysis. To avoid duplicating earlier work, material which was analysed by the original Engage KTN and by the first iteration of the Engage 2 trend analysis has not been reused. To recap, the Engage KTN conducted a gap analysis using material from the SESAR 1 and SESAR 2020 programmes (up to mid-2021) plus conference papers from the SESAR Innovation Days (SIDs, 2011-2020) and USA/Europe ATM Research and Development Seminar (ATM Seminar, 2011-2019). In the first iteration of the Engage 2 trend analysis [2], the intervening SIDs and ATM Seminar papers along with a sample of SESAR 2020 deliverables were fed into the AI pipeline for analysis (over 300 documents).

For the second iteration, 525 documents have been sourced:

- Papers from the latest SIDs (2024) and ATM Seminar (2021-2023) conferences have been supplemented with those from 2020-2024 International Conference on Research in Air Transportation (ICRAT);
- Final reporting and other potentially relevant deliverables from SESAR 2020 exploratory research (ER4) and industrial research (IR Wave 3) projects;
- Initial reporting from SESAR 3 exploratory research (ER1) and industrial research (IR1) projects;
- Reference documents: SESAR 3 JU (Master Plan 2025), Clean Aviation JU (SRIA 2024) and Shift2Rail/Europe's Rail JU (SRIA 2020, draft Master Plan 2022).

Table 1 and Table 2 provide breakdowns of the number of deliverables and conference papers sourced.

SESAR deliverables were sourced from CORDIS [4]. Potentially relevant public deliverables have been selected, such as the reporting of concept definitions and requirements, whereas dissemination and data management plans (for example) have been excluded. SESAR 2020 material includes final reporting, since these projects have all closed. In contrast, only initial material is currently available for the on-going SESAR 3 projects, e.g. by March 2025, ER1 projects had published 130 reports, of which 22 were considered potentially relevant for analysis. This explains why deliverables have only been sourced (to date) for 14 out of the 18 ER1 projects, and 13 of the 32 IR1 projects. However, material has been sourced for all nine SESAR 3 flagships, plus transversal activities.

Table 1: SESAR deliverables

SESAR programme	Calls	Project coverage	Deliverables
SESAR 2020	ER4	41/41	90
	IR Wave 3	5/5	46
SESAR 3	S3 ER1	14/18	22
	S3 IR1	13/32	45
Total	4	73/96	203

A total of 316 conference papers have been sourced. These are full papers, i.e. withdrawn papers and abstract- or video-only material have been excluded. ICRAT conference papers were not analysed in the first iteration (or by the Engage KTN), however it was decided to focus on the three most recent editions of this conference.

Table 2: Conference papers

Conference	Full papers
SIDs 2024	54
ATM Seminar 2021	54
ATM Seminar 2023	41
ICRAT 2020	55
ICRAT 2022	43
ICRAT 2024	69
Total	316

Links to SESAR deliverables (including reports not analysed as part of this task) and conference papers have been published in the EngageWiki [3].

2.3 Methodology for the AI-based trend analysis

2.3.1 Methodology – workflow

Our goal is the following: to produce a roadmap for the future development of the European air transportation system using an AI-based trend analysis, with minimal human intervention.

In order to do this, we selected two providers of general models: OpenAI and Mistral. OpenAI is the provider of the very well-known ChatGPT. We are using the API directly, in particular the models gpt4.1 and gpt4.1-mini. Mistral is another provider, which has the advantage of being cheaper and localised in Europe, which for security reasons may be better. We are using in particular models mistral-small-latest and mistral-medium-latest (which are always updated with the best available models, contrary to ChatGPT).

In the following we refer to ‘small models’ for gpt4.1-mini and mistral-small-latest and to ‘big models’ for gpt4.1-medium and mistral-medium-latest, which are respectively comparable in capabilities. Small and medium models are suited to different tasks. The former are best for performing ‘easy’ tasks like summaries or simple extraction. The latter, on the other hand, are good for making more complex decisions, taking into account more context and delving deeper into the meaning of the prompts.

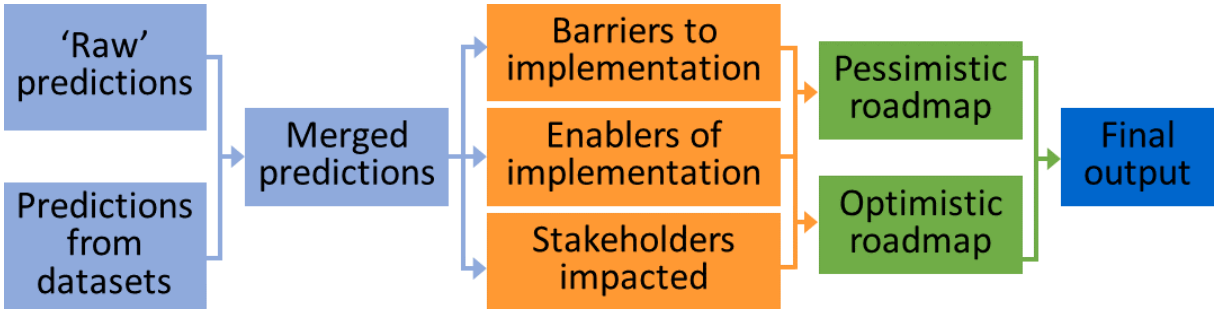

Figure 1:Workflow

Figure 1 shows the workflow used to prepare the final output for the second iteration (as prepared for this ***interim*** deliverable). At each step, an LLM takes as input the output of the previous step to produce the next one. For now, we consider the 'final' output as the document that contains all the relevant information to build the roadmap. The actual form of the roadmap and how it can be produced automatically is discussed in Section 4 and will be implemented in the next version of this deliverable (D5.7), which will report on the final iteration of the AI-based trend analysis, taking into account shortcomings identified at this interim stage (such as the omission of hydrogen as a major new technology) – which was indeed one of the main purposes of running the model for interim output evaluation (i.e. through this deliverable).

We define:

- 'raw' predictions as those made by the LLMs without the ATM (research) data
- predictions from datasets (see about datasets in Section 2.1) as those made using the ATM (research) data and the LLM background knowledge

The workflow starts by making these predictions independently. The raw predictions are used here to ensure that we capture 'obvious' trends that for some reasons were not captured through the datasets, thanks to the initial training of the LLM.

The merged predictions are then made also with a big model. The model is oblivious, at this stage, of the underlying data, and only has access to the two sets of predictions. The role of the model is then to decide which trends are the most important and consolidate them in 20 trends.

The next steps run in parallel. Each of them focuses on an important dimension of the roadmap: the barriers, the enablers and the impacts on stakeholders (including environment and society impacts). For this stage, the models have access again to the two datasets. They are tasked with making informed decisions and back them with citations from the sources.

The step after that comprises priming two independent models to be either pessimistic or optimistic, and to ask them to build roadmaps, including dates of implementation or development of the trends, taking into account the three previous dimensions. In the final version of the roadmap, we may allow the user to independently access both versions, or elements thereof (pessimistic and optimistic).

The final output is then consolidated through concatenation of the various steps.

This workflow allows us to have nuanced views of a complex system and to avoid typical hallucinations by reducing the dependency on a single model.

While this workflow uses different LLMs, it is still fairly simple in nature, because it is completely sequential. For the final deliverable (D5.7), we will include more complex feedback between agents, with consensus mechanisms (e.g. based on voting mechanisms), and verificatory agents (to check alignment with underlying data). We will also explore the possibility to weight trends by their perceived impact on the ATM system and/or society.

Modern LLMs are typically used with 'framework' libraries, that allow us to format and automatise their use, especially when they are used sequentially. For this deliverable, we used the LangChain framework. The final iteration may make use of even more modern approaches, like PydanticAI or LangGraph (particularly suited to agentic programming).

Note that in this iteration we do not need a RAG. Indeed, the information is sufficiently compressed to be included in the context window of the models.

2.3.2 Methodology – data

In this iteration, we focused on data that are more 'trusted' than on-line ones. While reviewing the results of the last iterations, it appeared that some sources provided by SciSpace were not as relevant as those from the ATM data. Hence, it was decided to focus on 'internal' sources for this iteration. It is planned, for the final iteration, to try to include external sources again, which may, sometimes, help in estimating the maturity of a trend. This however requires proper weights for sources or smart prompting for the different models involved. The external sources that we will consider will come directly from the results from SciSpace or other tools, as well as other documents from sources such as:

- Alliance for Zero-Emission Aviation (AZEA)[3]
- DESTINATION 2050 (industrial roadmap)[4]
- Association of European Research Establishments in Aeronautics (EREA) Vision studies (research establishments roadmaps)[5]

As introduced in Section 0, only new material was sourced for this iteration, i.e. documents which had already been used in the first iteration (reported in D4.1 [2]) or by the gap analysis conducted by the original Engage KTN were not re-analysed. The sources used in this iteration consist of three types:

- Conference papers – 316 items;
- Project deliverables – 203 items;
- JU reference and supporting material – 6 items.

The first step to process these sources is to convert pdfs in more machine-friendly formats (like markdown). This was done using the optical character recognition model from Mistral. This model,

[3] https://defence-industry-space.ec.europa.eu/eu-aeronautics-industry/alliance-zero-emission-aviation_en
[4] https://www.destination2050.eu/
[5] https://erea.org/erea-vision-studies/

cheap and very fast, is able to extract written characters from pdfs[6], and save all associated figures. Tags are automatically added for tables, sections, etc., so that subsequent models can treat them easily.

The second step is to produce summaries of the sources. Indeed, in the case of papers and deliverables, most of the relevant pieces of information can be extracted via 'focused' summaries, i.e. summaries that are produced by LLMs which already know what subsequent LLMs will be interested in. In most cases, at least for papers, it looks like these summaries coincide well with abstracts written by the authors themselves.

It was decided however to use the third source, the Master Plan [6].

[6] Even when the characters are part of an image.

3 Results from the AI-based trend analysis

This section presents the main results obtained from the method presented above. With each list or table, the AI also presents a more or less detailed account of the reasons why it chose these results. These justifications are not included in the present work.

3.1 Main trends discovered

The main trends selected by the AI are the following. As explained previously, they represent a blend of trends inferred from documents, and from the internal knowledge of the LLMs:

1. Electrification and Advanced Battery Technologies
2. Synthetic Fuels and Direct Air Capture Integration
3. Global Seamless Biometric Security and Identity
4. Digital Twin Airspace Simulation and Management
5. Biodegradable and Smart Aircraft Materials
6. Unmanned Freight and Cargo Drones
7. On-Demand, Personalized Air Travel
8. Integration of Remotely Piloted Aircraft Systems (RPAS)
9. Advanced U-Space and UAS Traffic Management
10. Space-based Multilateration and Satellite Surveillance
11. Collaborative Decision-Making (CDM) and Military-Civil ATM Integration
12. Trajectory-Based Operations and 4D Trajectory Management
13. AI and Machine Learning for Predictive Analytics in ATM
14. Urban Air Mobility (UAM) and Drone Integration
15. Cybersecurity Capabilities and Cyber-Resilience
16. Fully Autonomous Commercial Aircraft
17. Global Supersonic and Hypersonic Travel
18. Distributed Air Mobility Networks (Air Taxis and Urban VTOLs)
19. Quantum Computing-Optimized ATC (Air Traffic Control)
20. AI-Driven Predictive Maintenance and Self-Healing Systems

Note that many of these trends are common with the previous iteration (even though the previous one was more technically oriented). It is interesting to note also that self-healing systems (and sometimes self-healing materials) are now consistently present in the list. As noted in Section 2.3.1, hydrogen is omitted from the list of main trends. When running the models several times, most of the trends detected are common from one run to the next. However hydrogen technologies sometimes appear which raises the question of the stability of the results. There are ways of improving this in the final iteration, such as the batching of runs, and merging them with a system of scoring partly based on number of occurrences. We will explore these methods in the next deliverable, but it would be misleading to manually add it in this one.

3.2 Stakeholders impacted

The stakeholders impacted by each trend (numbered 1-20) are summarised in Table 3. As for other results, the list of stakeholders has not been provided to the model, but was inferred from the documents and the inner (latent) knowledge of the LLMs.

Note that in this table, R&D initiatives like the Clean Aviation JU or the SESAR 3 JU are not featured. We believe that the AI assumed implicitly that R&D is more an enabler than a stakeholder, which we agree with, since these entities exist to lead the improvement of the situation for the stakeholders themselves, not for themselves. Note that R&D is featured in the enablers in Table 4.

Table 3: Stakeholders impacted by trends

Trends	Aircraft Manufacturers	Airlines	Passengers	Airport Operators	Regulatory Authorities	Maintenance & Repair Orgs	Energy & Fuel Providers	Government & Policy Makers	Environmental Organizations	Technology & Software Providers	Air Traffic Management & Control	Security & Privacy & Cybersecurity	Investors & Financial Institutions	Local Communities	Logistics, Freight & Delivery	Pilots, Crew & Aircrew	Urban & City Planners & Local Gov	Insurance Companies	Military, Defense & Security Agencies
1	High (new designs, R&D)	High (ops cost, fleet changes)	Medium (lower noise/ emissions, ticket prices)	High (infrastructure upgrades)	High (new standards/ regulations)	High (skills & service changes)	High (electricity demand/ generation)	High (support & policy frameworks)	High (carbon footprint reduction)	Medium (battery tech & support systems)	Medium (coordination implications)	Medium (cyber risks & data protection)	Medium (investment & innovation)	Low (minimal direct impact)	Low (not main focus)	Low (limited operational impact)	Low (not directly)	Low (indirect)	Low (minor involvement)
2	Medium (engine/fuel system adaptation)	High (fuel sourcing, costs)	Medium (pricing travel choices)	Medium (fuel infrastructure)	High (policy, incentives, enforcement)	Low (minimal direct impact)	High (synthetic fuel production)	High (policy and economic support)	High (emissions reduction monitoring)	Low (supporting tech)	Low (minor impact)	Low (data & security limited)	Medium (funding and business risks)	High (near production sites)	Low (limited freight role)	Low (no direct pilot role)	Low (no direct urban planning role)	Low (not directly)	Low (minimal)
3	Low (limited impact)	Medium (operational efficiency)	High (faster processing, privacy concerns)	High (infrastructure, process upgrades)	High (standards, guidelines)	Low (no direct MRO role)	Low (no energy/fuel role)	Medium (policy & rights enforcement)	Low (privacy interest)	High (biometric tech demand)	Low (not ATM related)	High (privacy & security advocacy)	Low (limited investment)	Low (minimal local impact)	Low (no freight role)	Low (no direct pilot role)	Low (no urban planning role)	Low (no insurance role)	Medium (security agencies overlapping)
4	High (simulation & design applications)	High (planning, safety)	Medium (indirect safety & efficiency)	High (operations coordination)	High (informed policy development)	Low (no direct MRO role)	Low (not related to energy/fuel)	Medium (regulations)	Low (limited)	High (software & hardware support)	High (core ATM enhancement)	Low (security overlaps minor)	Low (investment phases)	Low (minor community effect)	Low (no freight)	Medium (decision support)	Low (not urban/ municipal)	Low (minor)	Low (limited defense role)
5	High (material integration, design)	Medium (fuel efficiency & maintenance)	Medium (safety & eco-friendly appeal)	Low (minimal infrastructure impact)	Medium (new materials certs & regs)	High (new repair skills needed)	Low (not energy related)	Medium (funding & regulations)	High (eco impact monitoring)	Low (supporting tech)	Low (not ATM focused)	Low (minor cyber-security role)	Medium (investment interest)	Low (minor community effect)	Low (freight irrelevant)	Low (no pilot role)	Low (not urban planning)	Low (no insurance outcome)	Low (minor/ none)
6	Low (not manufacturers directly)	Low (indirect via logistics)	Medium (faster deliveries)	Medium (infrastructure for drones)	High (integration rules)	Low (limited repair role)	Low (no energy focus)	Medium (policy & regulation)	Medium (emissions & noise concerns)	High (drone tech & comms)	Medium (airspace integration)	Medium (privacy & security concerns)	Medium (investment & risks)	Medium (urban noise, landing zones)	High (freight operational change)	Low (no pilot role)	Medium (urban planning & local gov)	Medium (risk models)	Low (minor defense use)
7	Medium (new aircraft, eVTOL design)	Medium (hybrid competition/ collaboration)	High (customization & convenience)	Medium (infrastructure & operations)	High (new safety & traffic regulations)	Low (limited repair role)	Low (no energy/fuel impact)	Medium (policy & regulations)	Low (minor environmental focus)	High (software/ platforms)	Low (limited ATM role)	Low (privacy/ security minor)	Medium (investment & growth)	Medium (noise & traffic)	Low (no freight)	Low (pilots for new vehicles)	Medium (urban planning & local gov)	Medium (new insurance models)	Low (minor defense)
8	Medium (tech development)	Low (indirect)	Medium (privacy & safety concerns)	Medium (airspace & alt ops)	High (regulatory & operational)	Low (minimal MRO)	Low (no fuel role)	Medium (policy & compliance)	Medium (noise, privacy concerns)	High (RPAS tech & systems)	High (integrated control)	Medium (privacy & security)	Medium (investment)	Medium (community impact)	Medium (delivery adaptation)	Medium (pilots operational challenges)	Medium (urban/local govt)	Medium (insurance changes)	Medium (defense use)

Trends	Aircraft Manufacturers	Airlines	Passengers	Airport Operators	Regulatory Authorities	Maintenance & Repair Orgs	Energy & Fuel Providers	Government & Policy Makers	Environmental Organizations	Technology & Software Providers	Air Traffic Management & Control	Security & Privacy & Cybersecurity	Investors & Financial Institutions	Local Communities	Logistics, Freight & Delivery	Pilots, Crew & Aircrew	Urban & City Planners & Local Gov	Insurance Companies	Military, Defense & Security Agencies
9	Low (not direct manufacturers)	Low (indirect)	Medium (operational guidelines)	Low (minor impact)	High (rules & standards)	Low (no MRO impact)	Low (no energy)	Medium (policy & enforcement)	Medium (noise & environment)	High (compatible tech)	High (air traffic control collaboration)	Medium (privacy/ security)	Low (limited investment)	Medium (local infrastructure)	Medium (delivery flow)	Low (no pilots)	Medium (urban planning & local gov)	Medium (risk models)	Low (not defense)
10	Medium (avionics integration)	Medium (routing & efficiency)	Medium (safety & scheduling)	Medium (airport flow)	Medium (policy & international standards)	Low (not MRO role)	Low (not energy related)	Medium (policy & cooperation)	Medium (emission & noise data)	Low (support tech)	High (ATC & global monitoring)	Low (security minor)	Low (investment minor)	Low (minimal local)	Low (minimal freight)	Low (pilot role small)	Low (urban planning minor)	Low (insurance minor)	High (defense surveillance)
11	Medium (systems integration)	Medium (routing changes)	Medium (fewer delays)	Medium (coordination needs)	High (framework & oversight)	Low (no MRO role)	Low (energy unrelated)	Medium (policy & coordination)	Low (minor environmental role)	High (systems & decision tools)	High (ATC complexity)	Medium (security & coordination)	Low (investment minor)	Low (limited community)	Low (minimal freight)	Low (minimal pilots)	Low (urban planning minor)	Low (insurance minor)	High (military/ security cooperation)
12	Medium (avionics & systems)	High (fuel efficiency & scheduling)	Medium (better reliability & times)	Medium (capacity & sequencing)	Medium (standards & procedures)	Low (no MRO role)	Low (no fuel focus)	Medium (policies)	Medium (emission reductions)	High (software & comms)	High (ANSP & controllers)	Low (security minor)	Low (investment minor)	Low (community minor)	Medium (logistics planning)	Low (no pilot effects)	Low (no urban planning role)	Low (insurance minor)	Low (defense minor)
13	Medium (connectivity integration)	High (scheduling & route optimization)	Medium (fewer disruptions)	Medium (ops & resource management)	Medium (policies & oversight)	Medium (maintenance optimization)	Low (energy indirect)	Low (regulatory adjustment)	Low (minor environment monitoring)	High (AI & ML tech)	High (ATM support)	Low (privacy/ security minor)	Low (investment minor)	Low (community minor)	Low (logistics minor)	Low (pilot enhanced decision support)	Low (not urban planning)	Low (insurance minor)	Low (defense minor)
14	Medium (urban-optimized designs)	Low (indirect)	Medium (new mobility & concerns)	Medium (new vertiport & facilities)	High (urban & flight regulations)	Low (limited MRO role)	Low (energy indirect)	Medium (urban policy)	Medium (noise & emissions)	High (navigation & comms)	Medium (ATM evolution)	Medium (privacy & security)	Low (investment minor)	High (city planning & noise)	Low (freight not main focus)	Low (no pilot role)	High (city gov & planners)	Medium (insurance development)	Low (minor defense role)
15	Medium (connected avionics)	High (digital ops & risk)	Medium (data security & trust)	High (critical infrastructure protection)	High (standards & enforcement)	Medium (digital maintenance systems)	Low (not energy)	High (national & sector security)	Low (minor environmental relevance)	High (security solutions)	Medium (ATC system security)	High (privacy & data security)	Medium (cyber-security investment)	Low (community impact minimal)	Low (freight minor)	Low (crew transition)	Low (urban planners not involved)	Medium (insurance for cyber risk)	Medium (national security role)
16	Medium (AI & sensors integration)	High (cost reduction, utilization)	Medium (safety & trust concerns)	Medium (infrastructure adapts)	High (certification & liability)	Medium (new maintenance expertise)	Low (energy unchanged)	Medium (policy & regulation)	Low (environment minor)	High (AI & autonomy tech)	Medium (new protocols)	Medium (cyber risks)	Medium (investment & development)	Low (community minimal)	Low (freight minimal)	Medium (pilot displacement/ retraining)	Low (urban planning minor)	Medium (insurance model changes)	Low (defense minor)
17	High (advanced tech/materials)	Medium (fleet & ops investment)	Medium (reduced travel time)	Medium (facility upgrades)	High (new safety & environmental regs)	Low (maintenance routine changes)	Low (fuel changes indirect)	Medium (policy & economic impact)	High (emissions & noise concerns)	Low (support tech)	Low (ATM minor)	Low (security minor)	Medium (investment risk & opportunity)	Low (local impact minimal)	Low (freight minor)	Low (pilot minor)	Low (urban planners minimal)	Medium (insurance & liability)	Low (government & security monitor)

Trends	Aircraft Manufacturers	Airlines	Passengers	Airport Operators	Regulatory Authorities	Maintenance & Repair Orgs	Energy & Fuel Providers	Government & Policy Makers	Environmental Organizations	Technology & Software Providers	Air Traffic Management & Control	Security & Privacy & Cybersecurity	Investors & Financial Institutions	Local Communities	Logistics, Freight & Delivery	Pilots, Crew & Aircrew	Urban & City Planners & Local Gov	Insurance Companies	Military, Defense & Security Agencies
18	Medium (urban VTOL manufacturing)	Low (indirect)	Medium (new urban mobility)	Medium (vertiport & infrastructure)	High (low-altitude traffic management)	Low (minor maintenance)	Low (energy indirect)	Medium (urban policy & planning)	Medium (noise & eco concerns)	High (navigation & booking tech)	Medium (ATM integration)	Medium (privacy & security)	Medium (investment & risk)	High (urban planning & community)	Low (freight minor)	Low (pilots for VTOL)	High (urban & local governments)	Medium (insurance adapts)	Low (minor defense impact)
19	Low (systems interface)	Medium (fuel & scheduling)	Medium (fewer delays)	Medium (traffic & gate management)	High (new standards & oversight)	Low (minor MRO impact)	Low (energy indirect)	Medium (regulatory adaptation)	Medium (fuel & noise monitoring)	High (quantum tech development)	High (ATC optimization)	Low (security minor)	Low (investment phase)	Medium (community noise/ traffic)	Low (freight minor)	Low (pilot minor)	Low (urban planning minor)	Low (insurance minor)	Medium (military/ surveillance benefit)
20	Medium (design integration)	High (cost & disruption reduction)	Medium (safety & punctuality)	Medium (ground ops efficiency)	Medium (safety regs adaptation)	High (shift to proactive maintenance)	Low (energy indirect)	Low (policy minor)	Low (minimal environment effect)	High (AI & sensor tech)	Low (ATM minor)	Low (security minor)	Medium (investment impact)	Low (community minor)	Low (logistics minor)	Medium (crew safety)	Low (urban planning minor)	Medium (insurance risk models)	Low (defense minor)

3.3 Enablers

The AI is also able to dig deeper into the implementation or evolution of the trends themselves, by selecting enablers and barriers to the trends. Table 4 presents different categories of enablers, and which enabler in particular will help the evolution of the trend. Note that 'Public and market acceptance' is listed as a category, but no enabler in particular is listed. We are not sure why this behaviour (which appeared several times) happens, but it appears to be linked to the fact that public acceptance may be an enabler in and of itself, not a category, and that little more information is needed in the cells themselves. The public acceptance is in any case more properly captured by the 'social impact' category, as shown in Section 3.6. Note that public acceptance is crucial and should not be underestimated. Without it, deployments of technological solutions are extremely difficult, at least in some cases.

Table 4: Enablers to trends

Trends \ Enabler	Technology & Infrastructure	Government & Regulatory Support	Investment & Collaboration	AI & Data Analytics	Security & Privacy	Public & Market Acceptance
Electrification and Advanced Battery Technologies	Advancements in battery tech, charging infra	Policy, emissions regulation	R&D investment, aerospace-battery collaboration	-	-	-
Synthetic Fuels and Direct Air Capture Integration	Electrolysis, renewable energy, carbon capture tech	Government policies, carbon pricing	Infrastructure & supply chain investment	-	-	-
Global Seamless Biometric Security and Identity	Advanced biometrics, cloud infra	Privacy & security frameworks	Stakeholder collaboration	-	Robust privacy & security frameworks	-
Digital Twin Airspace Simulation and Management	Sensor/IoT, HPC & cloud infra	Interoperability standards, data sharing	-	AI/ML algorithms, real-time analytics & visualization	-	-
Biodegradable and Smart Aircraft Materials	Advanced materials & nanotech, manufacturing	Regulatory support & certification	Cross-disciplinary research & collaboration	-	-	-
Unmanned Freight and Cargo Drones	Autonomous navigation, battery tech, comms	Regulatory frameworks, airspace integration	Cost-effective manufacturing & scalability	-	-	-
On-Demand, Personalized Air Travel	eVTOL tech, urban infrastructure	Regulatory framework, ATM integration	Booking platforms	Data-driven personalization, AI-driven customer experience	-	-
Integration of Remotely Piloted Aircraft Systems (RPAS)	Advanced ATM systems, sense-and-avoid, comms	Regulatory framework & standardization	Stakeholder collaboration & public acceptance	-	Public acceptance frameworks	-

Trends \ Enabler	Technology & Infrastructure	Government & Regulatory Support	Investment & Collaboration	AI & Data Analytics	Security & Privacy	Public & Market Acceptance
Advanced U-Space and UAS Traffic Management	Communication infrastructure, sense-and-avoid	Regulatory frameworks & standardization	Integration with ATM systems	Scalable automated traffic management platforms	-	-
Space-based Multilateration and Satellite Surveillance	Satellite tech, GNSS accuracy, data processing	Regulatory support & international collaboration	Cost reduction in launch & deployment	-	-	-
Collaborative Decision-Making (CDM) and Military-Civil ATM	Data sharing & communication	Harmonized regulatory frameworks	Joint training, interagency relationships	Integrated airspace management tools	Trust and interagency collaboration	-
Trajectory-Based Operations and 4D Management	Surveillance & communication systems	Regulatory harmonization & standards	Data sharing platforms	AI, enhanced ATM algorithms	-	-
AI and Machine Learning for Predictive Analytics in ATM	High-quality data, computing infra	Regulatory support & collaboration	Domain-specific AI models & algorithms	AI/ML for predictions	-	-
Urban Air Mobility (UAM) and Drone Integration	Advanced ATM, battery & propulsion technology	Regulatory framework & certification	Infrastructure development	-	Public acceptance & safety assurance	-
Cybersecurity Capabilities and Cyber-Resilience	Advanced threat intelligence sharing	Regulatory frameworks & standards	Cybersecurity workforce investment	AI/ML for threat detection	Incident response and recovery plans	-
Fully Autonomous Commercial Aircraft	AI & ML, robust sensors & comms	Regulatory framework & certification	-	Cybersecurity & data integrity	Public trust & acceptance	
Global Supersonic and Hypersonic Travel	Materials, aerodynamics, propulsion systems	Regulatory & environmental frameworks	Investment in R&D	-	-	-
Distributed Air Mobility Networks	Electric propulsion, urban infrastructure	Regulatory framework & ATM	Autonomous flight & AI	-	Public acceptance & market demand	
Quantum Computing-Optimized ATC	Quantum hardware, communication networks	Regulatory & standardization frameworks	Integration with classical ATC	Quantum algorithms for optimization	-	-
AI-Driven Predictive Maintenance and Self-Healing Systems	Advanced sensors, communication networks	Regulatory support & standardization	Big data analytics & cloud computing	AI/ML algorithms	-	-

3.4 Barriers

Similarly to enablers, the model can dive into the possible barriers, see Table 5. Here the table is organised slightly differently than the previous one (as chosen by the AI), with specific barriers as columns, and levels of severity in the cells.

Table 5: Barriers to trends

Trends \ Barriers	Regulatory & Certification	Technological & Performance Limitations	Infrastructure & Integration	Cost & Economic Factors	Safety, Security & Public Acceptance	Data, Privacy & Cybersecurity
Electrification and Advanced Battery Technologies	High	High	Medium	High	Medium	Low
Synthetic Fuels and Direct Air Capture Integration	High	High	High	High	Medium	Low
Global Seamless Biometric Security and Identity	Medium	Low	Low	High	High	High
Digital Twin Airspace Simulation and Management	Medium	High	High	Medium	Medium	High
Biodegradable and Smart Aircraft Materials	High	High	Medium	High	Medium	Low
Unmanned Freight and Cargo Drones	High	High	High	Medium	High	Medium
On-Demand, Personalized Air Travel	High	Medium	High	High	High	Low
Integration of Remotely Piloted Aircraft Systems (RPAS)	High	High	High	Medium	High	High
Advanced U-Space and UAS Traffic Management	High	High	High	Medium	High	High
Space-based Multilateration and Satellite Surveillance	High	High	High	High	Medium	High
Collaborative Decision-Making (CDM) and Military-Civil ATM Integration	High	High	High	Medium	Medium	Medium
Trajectory-Based Operations and 4D Trajectory Management	High	High	High	High	Medium	Medium
AI and Machine Learning for Predictive Analytics in ATM	High	High	High	Medium	Medium	High

Trends \ Barriers	Regulatory & Certification	Technological & Performance Limitations	Infrastructure & Integration	Cost & Economic Factors	Safety, Security & Public Acceptance	Data, Privacy & Cybersecurity
Urban Air Mobility (UAM) and Drone Integration	High	High	High	Medium	High	Medium
Cybersecurity Capabilities and Cyber-Resilience	Medium	Medium	Medium	High	Medium	High
Fully Autonomous Commercial Aircraft	High	High	High	Medium	High	High
Global Supersonic and Hypersonic Travel	High	High	High	High	Medium	Low
Distributed Air Mobility Networks (Air Taxis and Urban VTOLs)	High	High	High	Medium	High	Medium
Quantum Computing-Optimized ATC	High	High	High	High	Medium	Medium
AI-Driven Predictive Maintenance and Self-Healing Systems	High	High	High	High	Medium	High

3.5 Environmental impact

In Table 6 we show the raw output of the AI when asked about the likely impact of the trends on several environmental factors (also inferred by the model). As with other results, some detailed explanations are available, but the AI is able to put some small details in the table itself to help its comprehension.

Table 6: Environmental impact

Trends \ Impact	Greenhouse Gas Emissions	Air/Local Pollution (including NOx, particulates, air quality, ozone)	Noise Pollution	Plastic/Chemical/ Electronic/ Material Waste	Resource & Energy Consumption (inc. mining, rare earths, water)	Ecosystem/ Wildlife Disturbance/ Urban land use
Electrification and Advanced Battery Technologies	High positive	High positive	High positive	Medium negative	Medium to High negative	Low positive
Synthetic Fuels and Direct Air Capture Integration	High positive	Medium positive	Low	Low negative	Medium negative	Low to Medium negative or neutral

Trends \ Impact	Greenhouse Gas Emissions	Air/Local Pollution (including NOx, particulates, air quality, ozone)	Noise Pollution	Plastic/Chemical/ Electronic/ Material Waste	Resource & Energy Consumption (inc. mining, rare earths, water)	Ecosystem/ Wildlife Disturbance/ Urban land use
Global Seamless Biometric Security and Identity	Low to Medium negative	Low negative (energy/e-waste)	None	Low positive (plastic) / Low negative (e-waste)	Low negative	None
Digital Twin Airspace Simulation and Management	Medium positive	Low to Medium positive (air)	Low positive (noise)	Low positive	Low negative (e-waste/plastics)	Low to Medium negative
Biodegradable and Smart Aircraft Materials	Medium to High positive	Medium positive (via plastics/ chemicals)	Low positive	High positive (less plastic waste)	Medium positive (resource optimization)	Medium positive
Unmanned Freight and Cargo Drones	Medium positive	Low to Medium positive (road air quality) / Medium negative (noise)	Medium negative	Medium negative (waste)	Medium negative/ mixed (energy use)	Medium negative
On-Demand, Personalized Air Travel	High negative	Low to Medium negative (air quality, noise)	Medium negative	Medium negative	Low to Medium negative	Low to Medium negative
Integration of Remotely Piloted Aircraft Systems (RPAS)	Low to Medium mixed	Low to Medium negative (noise/air)	Low to Medium negative	Medium negative (waste)	Low to Medium negative	Medium negative
Advanced U-Space and UAS Traffic Management	Low to Medium mixed	Low positive (urban heat); Medium negative (noise, air)	Medium negative	Medium negative (plastic/e-waste)	Medium negative	Medium negative
Space-based Multilateration and Satellite Surveillance	Low to Medium negative	Medium positive (airline emission reduction)	Low	Low to Medium negative (waste, debris)	Low to Medium negative	Low negative (EM interference)
Collaborative Decision-Making (CDM) and Military-Civil ATM Integration	Medium positive	Medium positive (air pollution, moderate noise reduction)	Low to Medium positive	Low negative	Medium positive (resource efficiency)	Low positive
Trajectory-Based Operations and 4D Trajectory Management	Medium positive	Medium positive (air, noise)	Medium positive	Low negative	Medium positive	Low positive
AI and Machine Learning for Predictive Analytics in ATM	Medium positive	Low to Medium positive (air)	Low positive (noise)	Low positive	Low negative (plastic/e-waste)	Low to Medium negative
Urban Air Mobility (UAM) and Drone Integration	Medium mixed	Medium mixed (air)	Medium negative (noise)	Medium to High negative	Medium negative (plastic/e-waste)	Low to Medium negative (land/ resource use)
Cybersecurity Capabilities and Cyber-Resilience	Low negative	Low negative (air, if incident avoided)	Low negative	Medium negative (e-waste, plastic)	Medium negative	Low positive
Fully Autonomous Commercial Aircraft	Low to Medium positive	Low to Medium positive (noise, air quality)	Low to Medium positive	Medium negative (e-waste/plastic)	Medium negative	Low positive
Global Supersonic and Hypersonic Travel	High negative	Medium to High negative (stratosphere/ ozone, noise, particulates)	Medium negative	Low to Medium negative (plastic/ material)	Medium negative	Medium negative

Trends \ Impact	Greenhouse Gas Emissions	Air/Local Pollution (including NOx, particulates, air quality, ozone)	Noise Pollution	Plastic/Chemical/ Electronic/ Material Waste	Resource & Energy Consumption (inc. mining, rare earths, water)	Ecosystem/ Wildlife Disturbance/ Urban land use
Distributed Air Mobility Networks (Air Taxis/Urban VTOLs)	Medium mixed	Low to Medium mixed (air, noise, heat)	Medium to High negative	Low to Medium negative (plastic/ composite waste)	Medium negative (resource/energy use, urban use)	Low to Medium negative
Quantum Computing-Optimized ATC	Medium positive	Low positive (air, noise)	Low positive	Low negative (e-waste, plastic)	Low to Medium negative	Low positive
AI-Driven Predictive Maintenance and Self-Healing Systems	Medium positive	Medium positive (air/chemical)	Low to Medium positive (noise)	Low to Medium positive	Low negative (plastic/e-waste)	Medium negative (e-waste/ resources)

3.6 Social impact

Just like for the environment, the AI produces Table 7 that allows the user to have a direct view into the main issues expected. Note that, similarly to the environment, the different dimensions of the social impact have been chosen by the model itself, not the user prompt. Note that the AI is able to infer 'N/A' cases, which are sometimes hard for LLMs even when they are asked explicitly.

Table 7: Social impact

Trends \ Impact	Environ-mental Sustainability	Economic Opportunity & Efficiency	Social Equity & Gender Gap	Well-being & Public Health	Privacy & Surveillance	Employment Disruption & Skills Gap	Urban / Regional Development	Accessibility & Mobility	Safety & Security
Electrification & Advanced Battery	High Positive	Medium-High Positive	Medium Positive (with risk)	High Positive	N/A	Medium (Positive if reskilled)	Medium-High Positive	Medium Positive	High Positive
Synthetic Fuels & Direct Air Capture	High Positive	Medium-High Positive	Medium (Positive if inclusive)	Medium Positive	N/A	Medium (Requires transition)	Medium Positive	Medium Positive	High Positive
Biometric Security & Global ID	N/A	Medium (Mixed)	Medium (Mixed, possible exclusion/ gender bias)	High Positive	High Negative	Medium (Automation, mixed)	N/A	Medium (Mixed)	High Positive
Digital Twin Airspace Mgmt.	Medium Positive	High Positive	Low-Medium (risk of reinforcing gaps)	High Positive	Medium Negative	Medium (Need reskilling)	Medium Positive	Medium Positive	High Positive
Biodegradable & Smart Materials	High Positive	Medium-High Positive	Medium (Risk without intervention)	Medium Positive	N/A	Medium (Transition risk)	Medium-High Positive	Medium-High Positive	Medium Positive
Cargo Drones & Unmanned Freight	Medium-High Positive	High Positive	Medium (Shrink or widen gender gap)	Medium-High Positive	Medium Negative	High Negative (Disruption)	Medium Positive	Medium Positive	Medium Negative (new risks)

Trends \ Impact	Environ-mental Sustainability	Economic Opportunity & Efficiency	Social Equity & Gender Gap	Well-being & Public Health	Privacy & Surveillance	Employment Disruption & Skills Gap	Urban / Regional Development	Accessibility & Mobility	Safety & Security
On-Demand Personalized Travel	Medium Negative (unless green)	Medium Positive	High Negative (inequality risk)	Medium Positive	N/A	Medium (Job shifts possible)	Medium Mixed	Medium Positive	Medium Positive
RPAS (Remotely Piloted Aircraft)	Low-Medium Mixed	High Positive	Medium (Likely widen gap)	Medium-High Positive	High Negative	Medium-High (Skills gap)	Medium Positive	Medium-High Positive	Medium (Depends on reg.)
Advanced U-Space/UAS Mgmt	Medium Mixed	High Positive	Medium Negative (gender/job)	High Positive	Medium-High Negative	Medium (Job shifts)	Medium-High Positive	Medium-High Positive	High Positive
Satellite Surveillance & Multilateration	Low-Medium Mixed	Medium Positive	Low-Med Positive (inclusive policies)	High Positive	Medium Negative	Medium (Jobs shift)	N/A	Medium Positive	High Positive
CDM & Military-Civil ATM Integration	Medium Positive	Medium Positive	Low-Med Positive (diversity)	Medium Positive	Low-Med Negative	Medium (Shifts, new roles)	High Positive	Medium Positive	Medium Positive
4D Trajectory-Based Ops	High Positive	Medium-High Positive	Medium Negative (widen unless inclusive)	High Positive	N/A	Medium (Reskilling)	High Positive	High Positive	High Positive
AI / ML for Air Traffic Mgmt	High Positive	High Positive	Medium Negative (widen unless inclusive)	Medium Positive	Medium Negative	Medium Mixed	Medium Positive	High Positive	High Positive
Urban Air Mobility & Drone Integration	Medium Mixed	Medium Mixed	Medium Mixed (equity/gender risk)	Medium Mixed	Medium Negative	Medium Mixed (Job displacement)	High Positive	High Positive	High Mixed
Cybersecurity & Resilience	Medium-High Positive	High Positive	Medium Mixed (inclusive policy helps)	Medium Mixed	Medium Mixed	Medium Mixed	N/A	Medium Positive	High Positive
Fully Autonomous Aircraft	Medium Positive	High Positive	Medium Positive (lower pilot barriers)	High Positive	Medium Negative	High Negative (job loss risk)	Medium Positive	Medium Positive	Medium-High Positive (if trusted)
Supersonic/ Hypersonic Travel	Medium-High Negative	Medium Positive	High Negative (inequality risk)	Low-Medium Mixed	N/A	Medium (Access for few)	Medium Positive	Medium Positive	Medium Negative (noise, env)
Distributed Air Mobility Networks (VTOLs)	Medium Positive (if sustainable)	High Positive	High Negative (inequality risk)	Medium Positive	Medium Negative (noise/privacy)	Medium Negative (legacy jobs)	High Positive (urban change)	Medium Positive	Medium Positive
Quantum-Optimized ATC	Medium-High Positive	High Positive	Low-Med Positive (if inclusive)	Medium Positive	N/A	Medium-High (Shift, retrain)	Medium Positive	High Positive	High Positive
AI-Driven Predictive Maintenance & Self-Healing	Medium-High Positive	High Positive	Medium Positive (bias reduction possible)	High Positive	N/A	Medium (Job shifts)	Medium Positive	Medium Positive	High Positive

3.7 SDO mapping

Strategic deployment objectives (SDOs), as described by the Master Plan, can also be mapped to the trends, in terms of interaction between each other. Table 8 shows the results, where the AI is asked to flag whether a trend will impact, somehow, an SDO.

It is interesting to note that there seems to be fewer and fewer links for higher SDOs. It is unclear at this point why the models behave like this. In particular, the SDOs are fed **independently** to the model, and thus the latter cannot be biased by previous answers. The results seem also quite poor, especially compared to previous ones on the environmental and social impacts, with several links that seem spurious or dubious. One possibility is that the description of the SDOs are not long enough for the LLM to fully grasp their meaning and/or that the way we feed the LLM is somehow suboptimal. This point will be further explored in the final iteration of this work.

Table 8: Links between SDOs and trends

Trend \ SDO	SDO 1	SDO 2	SDO 3	SDO 4	SDO 5	SDO 6	SDO 7	SDO 8	SDO 9	SDO 10
Electrification and Advanced Battery Technologies	X	X								
Synthetic Fuels and Direct Air Capture Integration	X									
Global Seamless Biometric Security and Identity	X	X	X	X	X					
Digital Twin Airspace Simulation and Management	X	X	X	X	X	X	X	X		
Biodegradable and Smart Aircraft Materials	X	X								
Unmanned Freight and Cargo Drones	X	X	X	X	X	X	X	X	X	X
On-Demand, Personalized Air Travel	X	X	X	X	X	X	X	X	X	X
Integration of Remotely Piloted Aircraft Systems (RPAS)	X	X	X	X	X	X	X	X	X	X
Advanced U-Space and UAS Traffic Management	X	X	X	X	X	X	X	X	X	
Space-based Multilateration and Satellite Surveillance	X	X	X	X	X					
Collaborative Decision-Making (CDM) and Military-Civil ATM Integration	X	X	X	X	X					
Trajectory-Based Operations and 4D Trajectory Management	X	X	X	X	X	X				
AI and Machine Learning for Predictive Analytics in ATM	X	X	X	X	X	X	X	X		
Urban Air Mobility (UAM) and Drone Integration	X	X	X	X	X	X	X	X	X	X
Cybersecurity Capabilities and Cyber-Resilience	X	X	X	X	X	X	X	X	X	X
Fully Autonomous Commercial Aircraft	X	X	X	X	X	X	X	X	X	X
Global Supersonic and Hypersonic Travel	X	X	X	X	X	X	X	X		
Distributed Air Mobility Networks (Air Taxis and Urban VTOLs)	X	X	X	X	X	X	X	X	X	X
Quantum Computing-Optimized ATC	X	X	X	X	X	X				
AI-Driven Predictive Maintenance and Self-Healing Systems	X	X	X	X	X	X	X	X	X	X

3.8 Roadmaps

Finally, we present the prototypes of roadmaps that can be produced with this method. Here we present only the roadmaps in the form of years and short bullet points describing the milestones. More detailed explanations and links to stakeholders, barriers, and enablers have been produced and attached as an appendix to this report.

3.8.1 Optimistic roadmap

- 2025: Emergence of Electric Regional Aircraft and eVTOL Demonstrations: Electrification of short-haul aircraft and eVTOL (urban air mobility) demonstrators reach commercial pilots. Advancements in battery density, government subsidies, and aerospace-battery industry collaboration help overcome immediate technological and cost barriers, though flight range remains limited and regulatory frameworks are in rapid development.

- 2026: Global Rollout of Seamless Biometric Airport Security: Global airports implement interoperable, privacy-focused biometric security and seamless digital identity. Regulatory harmonization, strong data protection frameworks, and scalable cloud solutions drive adoption. Public trust initiatives and technical standards resolve privacy, cost, and interoperability challenges.

- 2027: Initial Widespread Deployment of Predictive Maintenance and AI-Enhanced ATM Analytics: AI-powered predictive analytics enhance air traffic management, and predictive maintenance is rolled out on new fleets, reducing delays and safety incidents. High-quality data sets, cloud computing, and big data analytics enable greater reliability, while certification hurdles are gradually being addressed through regulatory sandboxes.

- 2028: Early Urban and Distributed Air Mobility Pilots; Air Taxi Test Routes: Urban air taxi and distributed VTOL service pilots start in top-tier global cities. Batteries and autonomy tech cross key reliability thresholds, supported by targeted regulatory pilots and new digital booking infrastructure. Public skepticism and noise are mitigated via community engagement and fleet noise reduction mandates.

- 2029: First Synthetic Fuel Production Plants Supplying Major Airlines; Early dynamic airspace configuration (DAC) Integration: Facilities for sustainable synthetic fuel and direct air capture reach operational scale, supplying SAF to long-haul routes. Advances in electrolysis, carbon pricing, government incentives, and strategic investment result in viable pathways around high costs and initial infrastructure gaps.

- 2030: Advanced U-Space and Drone Traffic Management in Urban Centers: Advanced U-Space management, with automated drone deconfliction, becomes mandatory for urban drone delivery and air mobility. Key enablers include AI-driven sense-and-avoid, robust communication networks, and harmonized UTM regulations. Public and environmental concerns are addressed by real-time airspace and noise management tools.

- 2031: Large-Scale Integration of Unmanned Cargo Drones for Regional Logistics: Unmanned cargo drones scale in regional and logistics operations. Regulatory certainties, improved battery and autopilot systems, and cost-effective manufacturing outweigh early public acceptance and air traffic integration concerns, creating new opportunities for fast, low-emission last-mile delivery.

- 2032: Digital Twin Driven Airspace Management Goes Operational: Operational rollout of digital twin-based airspace management in several global regions allows real-time dynamic rerouting, predictive safety interventions, and optimized airport operations. High-performance computing, IoT/sensor maturity, and standards for data sharing overcome earlier cost, integration, and privacy hurdles.

- 2033: On-Demand, Personalized Air Travel Becomes a Multi-City Reality: Personalized, on-demand air travel (e.g., air taxis, small charter eVTOL) becomes available across multiple cities. Improved regulatory frameworks, urban infrastructure development (vertiports), and affordable digital scheduling platforms allow market growth. Concerns about emissions, inequality, and noise get mitigated by increasingly electrified fleets and tiered service models.

- 2034: Biodegradable and Smart Aircraft Materials Adopted in New Short-Haul Fleets: Biodegradable and smart materials are certified and adopted across next-gen regional and short-haul aircraft, reducing lifecycle impacts. Material science innovation, cross-industry partnerships, and responsive certification enable shift; new sustainable supply chains and advanced additive manufacturing overcome earlier production barriers.

- 2035: Fully Autonomous RPAS Broadly Integrated into Commercial Airspace: Remotely piloted aircraft systems (RPAS) get routine commercial airspace access. Advanced sense-and-avoid, robust communication, and effective collaboration among regulators and operators mitigate safety, privacy, and trust challenges, enabling safe integration with manned traffic.

- 2036: Collaborative Military-Civil ATM Fully Realized in Major Corridors: Real-time, collaborative military-civil air traffic management is deployed on major strategic routes, driven by joint training, data sharing, and harmonized regulatory guidelines. Security/confidentiality obstacles are addressed by secure, role-based protocols and common operational standards.

- 2037: Space-Based Multilateration Achieves Near-Global Aircraft Tracking: Near-global aircraft surveillance via space-based multilateration becomes operational, vastly enhancing situational awareness and search-and-rescue. Cost reductions in satellite launch and international regulatory cooperation resolve earlier integration and coverage limitations, while strong data security measures foster confidence.

- 2038: Trajectory-Based Operations and 4D Trajectory Management Standardized Worldwide: Trajectory-Based Operations (TBO) and 4D trajectory management become globally standardized for all commercial flights. Advanced ATM algorithms, surveillance/communication networks, and data-sharing standards accelerate implementation, while regulatory and integration barriers are harmonized under ICAO and regional oversight.

- 2039: AI-Driven, Self-Healing Aircraft in Mainstream Use: Mainstream fleets integrate AI-driven self-healing systems and predictive maintenance. High sensor density, big data, and certification frameworks enable predictive interventions and autonomous repairs, reducing downtime, resource use, and maintenance costs. Workforce retraining programs ensure transition for legacy maintenance roles.

- 2040: Cyber-Resilient, Quantum-Enhanced Air Traffic Control Pilots Begin: Quantum computing pilots for air traffic control optimization launch in advanced markets. Quantum-classical hybrid systems, robust communication, and regulatory frameworks mitigate risks related to hardware reliability and cost; demonstration projects validate safety and efficiency, paving the way for broader adoption.

- 2042: Commercial Launch of Supersonic Passenger Services with SAF Integration: First commercial supersonic passenger flights commence, powered by synthetic/SAFs and featuring radical noise and emission reduction technologies. Regulatory harmonization on noise, R&D in advanced materials, and global SAF supply chains help overcome lingering environmental and integration challenges.

- 2045: Large-Scale Distributed Air Mobility Networks Mature, Serving Most Major Cities: Distributed air mobility (urban air taxis, regional VTOL networks) expand to serve most global cities, providing on-demand access integrated with public transit. AI, battery advances, infrastructure build-out, and streamlined regulatory processes enable scale, while progressive policies address equity, noise, and energy sourcing.

- 2048: Fully Autonomous Commercial Passenger Flights Go Mainstream: Fully autonomous commercial passenger flights—without pilots on board—enter mainstream service for selected routes and city pairs. AI/ML reliability, robust sensors, cybersecurity, and finalized certification frameworks ensure safety and public trust. Airlines realize major efficiency gains, and transitions for dislocated personnel are managed via retraining.

- 2050: Net-Zero Carbon Growth Achieved by Global Aviation Sector: Through a combination of electrification, SAFs, DAC, advanced ATM, and smart fleet solutions, the aviation sector achieves net-zero carbon growth. Global policy alignment, technological breakthroughs, and full deployment multi-sectorally ensure operational growth is decoupled from emissions, with aviation positioned as an exemplar for sustainable high-mobility industries.

3.8.2 Pessimistic roadmap

- 2026: Slow Rollout of Battery-Electric Regional Aircraft: Due to persistent barriers around battery energy density, high cost, infrastructure limitations, and regulatory inertia, only a handful of short-range electric and hybrid commercial aircraft enter limited service. Airlines remain cautious due to uncertain economics, weak infrastructure, and incremental tech gains. Growth is subdued by slow advances in energy storage and lack of clear subsidy or carbon pricing signals.

- 2027: Increasing Barriers in Synthetic Fuel Scale-Up: Despite advances in electrolysis and government R&D, synthetic and direct air capture fuels face mounting cost and scalability obstacles. Renewable energy input is insufficient, and carbon capture scale lags. Regulatory and certification frameworks drag, preventing mass adoption. Jet fuel demand remains met by fossil sources, and investors hold back for clearer returns.

- 2028: Fragmented Biometric Security Adoption: Privacy laws diverge and cross-border harmonization of data standards stalls; biometric deployments appear only at some airports and are often locally limited. Public trust issues, lack of global interoperability, frequent cost overruns, and technical failures limit the actual realization of seamless global biometric processes. Airlines and airports abandon or delay full conversion amid compliance nightmares.

- 2029: Airspace Digital Twin Pilots Limited to Major Hubs: Major airports run digital twin airspace pilots, but full national or global rollouts are limited by huge computational/IT costs, data interoperability failures, and scarce collaborative buy-in from critical stakeholders. Local data silos, failure to standardize, and regulatory bottlenecks keep digital twin benefits limited to select, well-funded cities while broader adoption languishes.

- 2030: Biodegradable Materials in Prototype/Business Aircraft Only: Biodegradable and smart aircraft components are used on a handful of experimental or luxury business jets, but lack of regulatory clarity, durability issues in real operations, and high costs keep widebody or mainstream airline adoption at bay. Manufacturers prioritize conventional composites for reliability and certification ease.

- 2031: Regulatory Stagnation Stalls Freight Drone Growth: Widespread drone freight delivery is sharply constrained by the lack of clear legal frameworks, poor integration with civil airspace, unresolved liability, security worries, and low public support. Major cities face local drone bans, stalling supply chain advances. Only small-scale, rural, or humanitarian UAV use persists.

- 2032: Air Taxi and VTOL Services Restricted to Niche Markets: Air taxi and VTOL services exist mainly as press events or ultra-premium offerings. Urban infrastructure, noise and safety worries, high operations costs, and unresolved traffic management challenges limit routes to isolated, well-controlled demonstration corridors in high-income regions. The promise of cheap mass mobility remains unfulfilled.

- 2033: Remotely Piloted Systems Face Regionally-Fragmented Integration: Remotely piloted aircraft are inconsistently incorporated into national airspace systems; major economies diverge on regulatory and security approaches. System reliability, cybersecurity scares, and public resistance limit cross-border or large-scale deployments. Stakeholders, lacking harmonization, keep integration regionally fragmented.

- 2034: First U-Space Corridors Stagnate, Hampered by Public and Safety Concerns: A handful of official urban U-Space corridors appear, but safety incidents, local privacy pushback, noise complaints, technological shortcomings, and regulatory resistance cap UAS traffic. Interoperability with manned aviation and ground authorities remains unsolved beyond demo projects, stalling full-scale rollouts.

- 2035: Space-Based Surveillance Systems Delayed by Funding, Political Tensions: The implementation of global space-based multilateration, critical for seamless air traffic surveillance, is bogged by multi-national disputes, budget shortfalls, satellite deployment delays, and cybersecurity/vulnerability fears. Gaps in coverage persist, especially over less-developed regions or remote oceanic/Polar areas.

- 2036: Slow Progress in Civil-Military ATM Integration: National security silos, chronic lack of transparency, cultural/organizational distrust, and incompatibility in civil-military ATM tech slow true integration. Data sharing lags behind rhetoric, and CDM remains theoretical or limited to crisis scenarios. Operational inefficiency from poor collaboration persists through the 2030s.

- 2037: Inconsistent 4D Trajectory Management Worldwide: Despite some regional progress in 4D trajectory-based operations, lack of global regulatory coordination, security concerns over data-sharing, legacy ATM limitations, and patchy infrastructure investment lead to persistent inconsistency. Airlines and pilots face a patchwork of regional standards and limited practical benefits.

- 2038: Predictive AI in ATM Stalemates due to Security, Legacy Tech: The promise of AI-driven predictive analytics for smarter ATM is mired in slow or uneven data quality improvement, integration woes with decades-old systems, certification hurdles, and mounting cybersecurity concerns. Localized, non-interoperable systems are the norm, with only incremental operational gains.

- 2039: Urban Air Mobility Limited by Noise/Regulatory Pushback: Urban air mobility projects continue to face local bans, NIMBY resistance, failed noise targets, and delayed regulatory clarity. Even as a few

cities promote high-profile air taxi pilots, wider deployment is blocked by operational incidents, disillusioned communities, and stagnating investment.

- 2040: Cybersecurity Shortcomings Exposed by Successful Attacks: As digitalization mounts, several high-profile cyberattacks or near-miss incidents in ATM or airliner systems underscore the inadequacy of current resilience. Talent shortages, high costs, legacy tech, and fragmented oversight leave many stakeholders exposed, prompting regulatory backlash and diverting resources to crisis response rather than proactive progress.

- 2041: Autonomous Commercial Aircraft Postponed after Public Setbacks: Negative public response after a spate of autonomous vehicle accidents, coupled with regulatory gridlock and ongoing technical limitations, stalls the launch of fully autonomous passenger jets. Fleets remain pilot-augmented, with autonomy capped at secondary functions. Investor retreats and strict liability regimes suppress launch plans.

- 2042: Supersonic/Hypersonic Travel Fails to Scale Beyond Limited Premium Routes: Despite technological demonstrations, supersonic and hypersonic transport stays confined to small, niche, ultra-premium routes for government and elite clients only. Environmental regulations, noise complaints, poor economics, and safety risks prevent commercial scaling. Few airports invest in required upgrades, and societal backlash intensifies.

- 2043: VTOL Distributed Air Mobility Remains Experimental: Distributed air taxi/VTOL networks remain experimental as urban airspace management, vertiport construction, and neighbour opposition continually delay citywide rollouts. Certification stasis, reliability shortfalls, and high cost-per-passenger conspire to keep deployments as high-profile, short-term pilots—not sustainable mobility infrastructure.

- 2045: Quantum-Optimized ATC Still in Research-Only Phase: Quantum computing remains largely confined to academic and industrial research. Quantum hardware lags in reliability and stability, fails to scale, and faces cost and skill bottlenecks. FAA and EASA (or equivalents) lack regulatory frameworks for quantum-enabled ATC, and risk-averse airlines and traffic managers delay any operational adoption.

- 2046: AI Predictive Maintenance Adoption Slowed by Certification Hurdles: Industry-wide AI predictive maintenance systems get delayed by regulatory uncertainty—regulators struggle to certify black-box AI models, airlines resist unproven fixes, and supply chains can't agree on uniform data protocols. High costs, cyber risk worries, and limited trust in automated decision-making hamper the technology's broader rollout.

3.8.3 Comparison between roadmaps

The previous roadmaps differ quite a lot in their scope and time, and it is interesting to note some recurrent pattern in their divergencies:

- Same dates, different stages: the pessimistic one usually has limited deployment of the same technology compared to the optimistic one by the same date. For example:
    - Biometric security, fragmented by 2028 in one case, seamless by 2026 on the other,
    - Military-Civil collaboration: Stalled in 2030s on one hand, fully realised in 2036 on the other.
- Widely different dates for implementation: sometimes the implementation is deemed likely, but at very different dates. For example:
    - Predictive maintenance, implemented after 2046 on one hand, and by 2027 on the other hand.
- Different outlook on the same technology, by the same date. For example:
    - Cybersecurity: by 2040, quantum-enhanced procedures allow high-profile breaches in one case, and help preventing attacks on the other hand.

The overall conclusion is that these roadmaps may not provide any important insight without going deeper into why and how each milestone is set by the model. To go further, one may need to develop automonous agents, which recursively go into the justifications for each milestone.

4 Future representation of the ATM concepts roadmap

This section sets out the planning for work beyond deliverable D5.1. It begins with a sampling of industry roadmaps, to be used for inspiration regarding best practice in the formulation of the final roadmap to be published in the EngageWiki, more specific planning for hosting the roadmap therein, and key next steps for this activity, split over two periods (medium term and longer term).

4.1 Industry roadmaps

As background for the future representation of the ATM concepts roadmap, various roadmaps published by Europe's JUs and Agencies have been reviewed, along with a sample of roadmaps from national bodies. Note that not all roadmaps are depicted visually – in some cases a descriptive roadmap has been published.

The following examples show a range of roadmaps. Some are visually complex, others are less so, in many cases reflecting the intended purpose of the roadmap.

Figure 2 shows detailed planning by Clean Aviation JU for one of three new generation of aircraft (ultra-efficient regional aircraft in this case). A phased timeline is given, showing challenges, targets and TRLs.

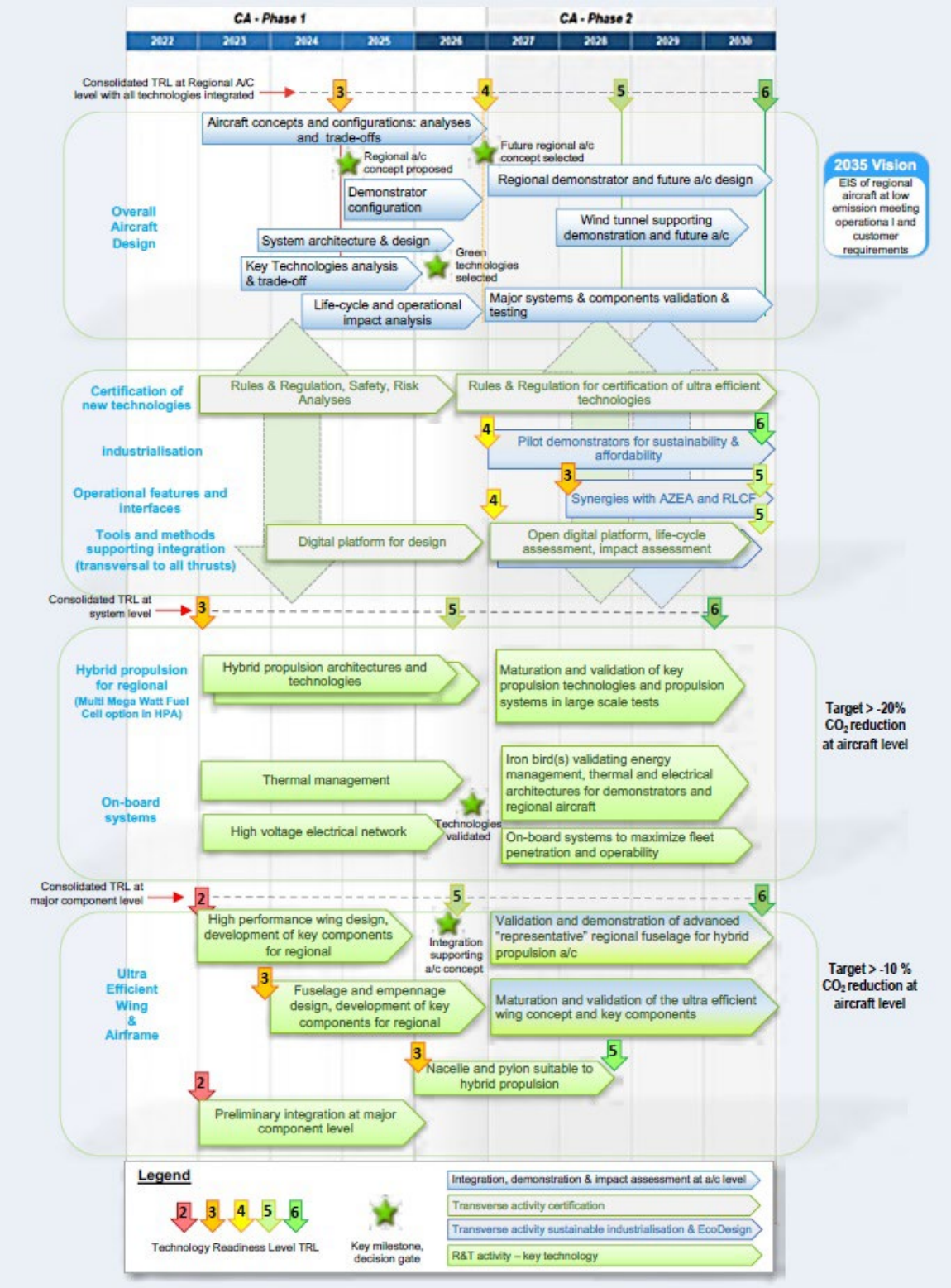

Figure 2:Example roadmap – Clean Aviation JU Ultra-Efficient Regional Aircraft

(source: [1])

Roadmaps in the ATM Master Plan [6] provide timelines for the development and deployment of technologies towards the 2045 vision. Figure 3 identifies elements and their impact on the environment for each technology (e.g. trajectory optimisation), whilst Figure 4 provides a timeline for the development and deployment activities of one of the key technologies (TBO) for the network, air traffic control and intra-regional trajectory-based operations.

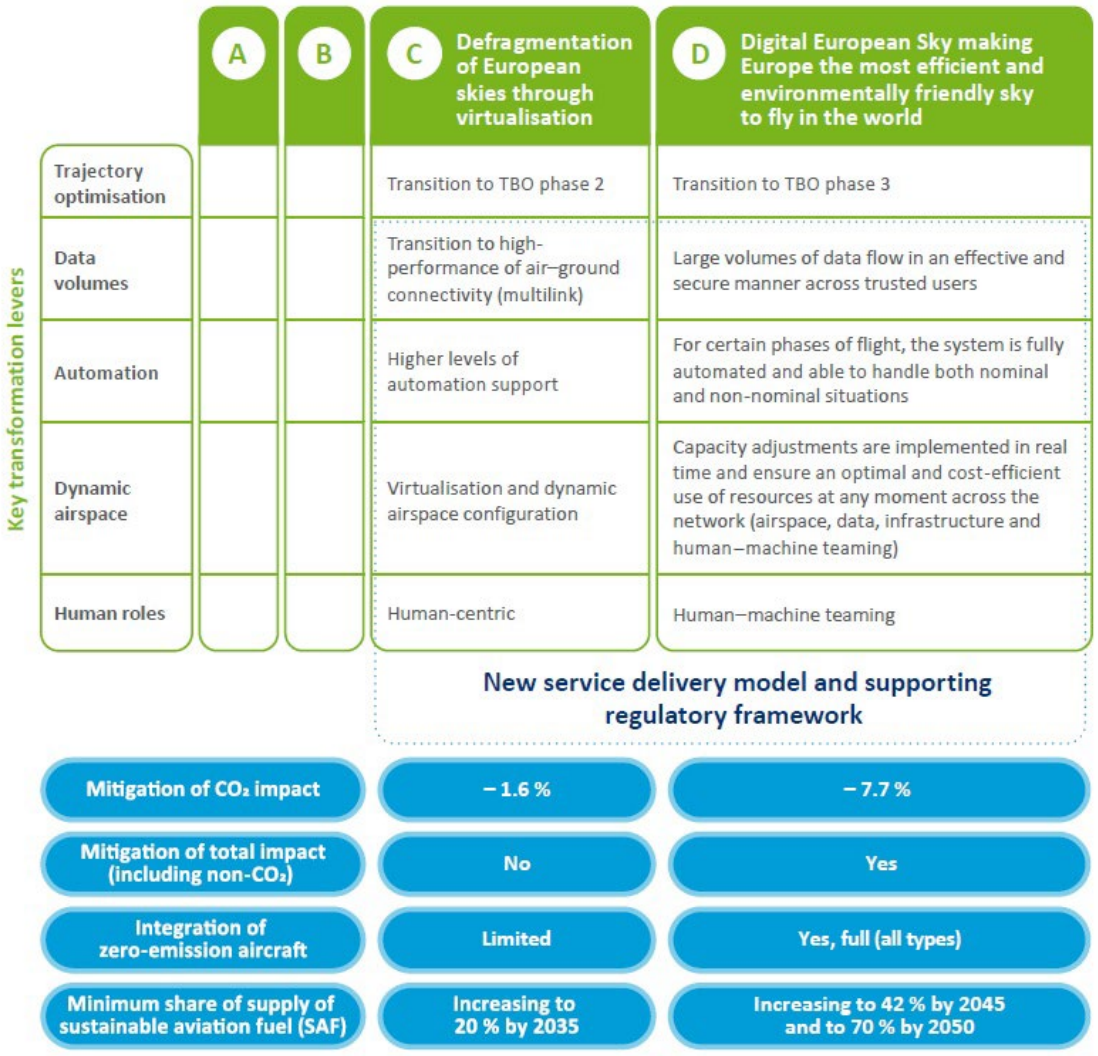

Figure 3:Example roadmap – SESAR 3 JU critical path for roll out by 2045

(source: [6])

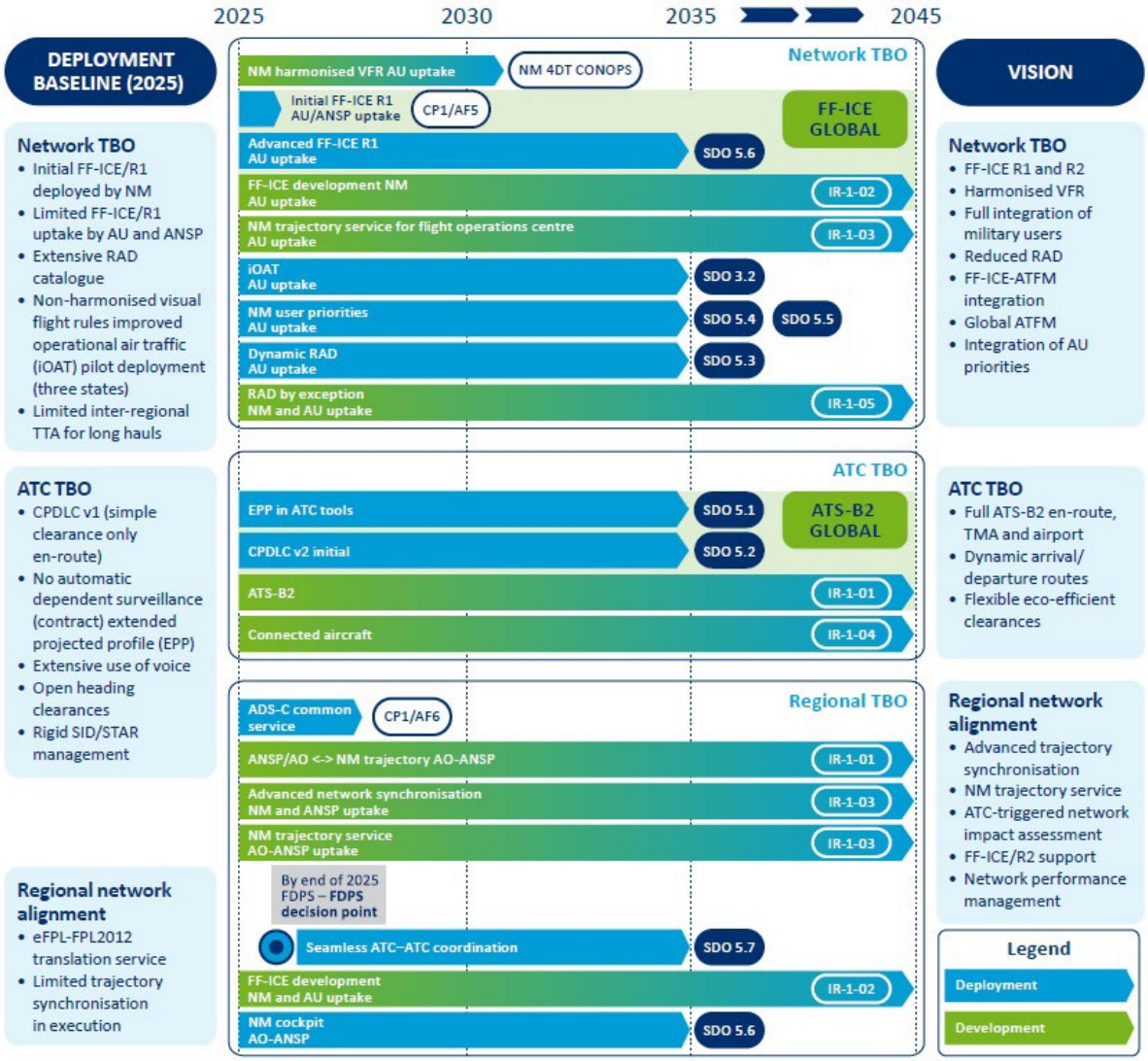

Figure 4:Example roadmap – SESAR 3 JU integrated TBO roadmap

(source: [6])

Not all roadmaps provide timelines. The National Quantum Computing Centre's technology roadmap (Figure 5) sets out a pathway for the development of general-purpose quantum computing across the UK. Critical milestones have been identified, such as the demonstration of an early quantum advantage.

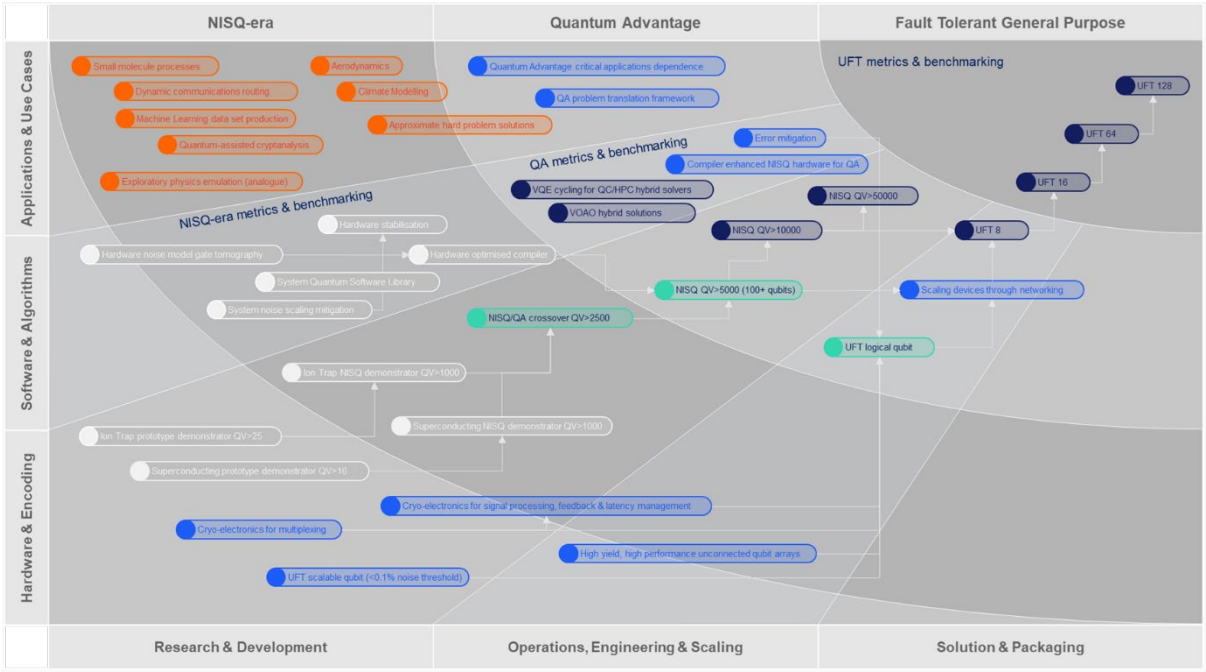

Figure 5:Example roadmap – NQCC technology roadmap

(source: [5])

Considering some of these design features as inspiration for the Engage 2 roadmap, as per the version to be hosted in the wiki, current planning elements are reviewed in the next section. It is to be noted that we propose primarily an enabler-based approach, rather than using a timeline, as per the example of Figure 5.

4.2 Plans for the ATM concepts roadmap

A Sankey diagram visualisation was used to represent the ATM concepts roadmap published by the original Engage KTN (see Figure 6). Experience of the lengthy development process of the previous roadmap suggests that Engage 2 should develop a rather simpler roadmap schema. The planned, simpler visualisation will include a high-level roadmap with which users can easily interact, which links to more detailed information such as technological trends. Note such a simplification relates only to the visual representation of the roadmap and not the AI-based trend analysis underpinning the results (second iteration now completed).

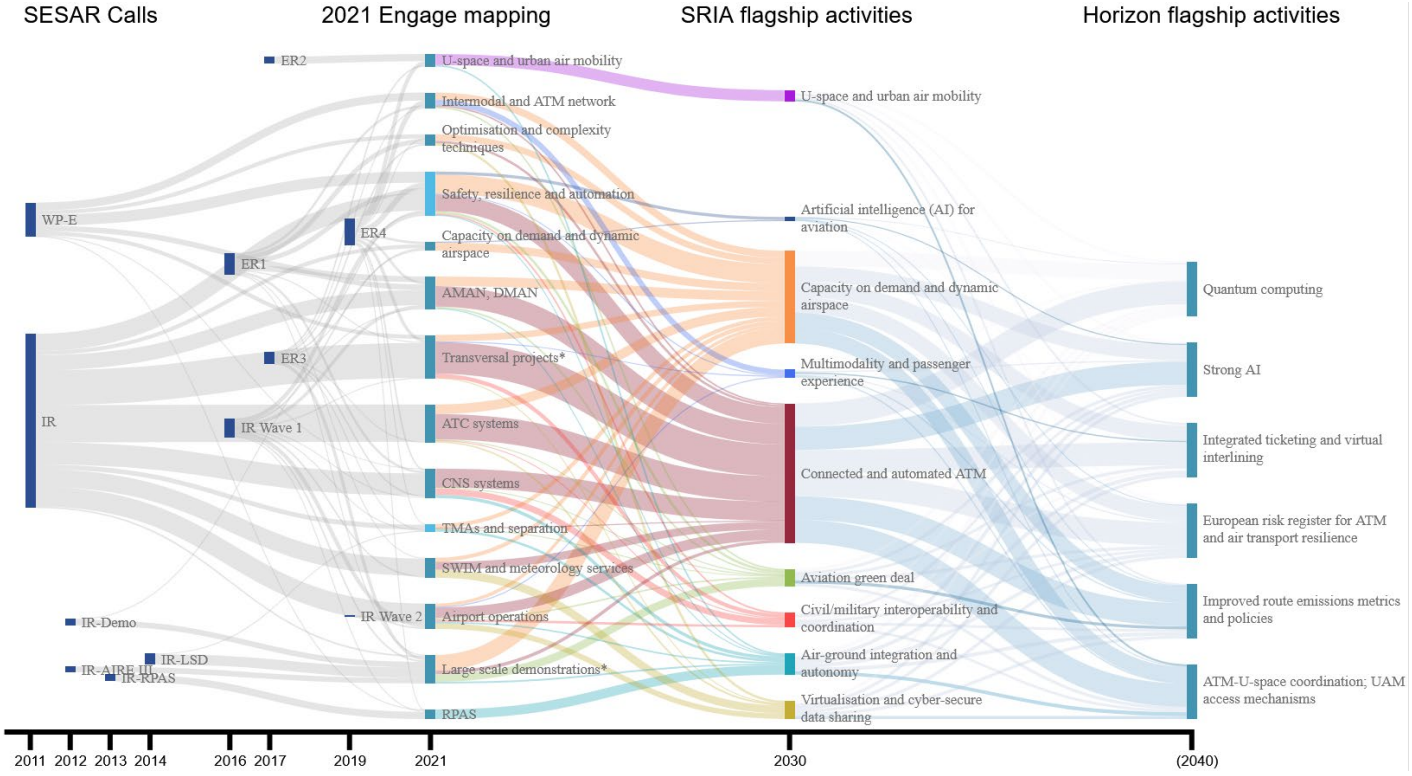

Figure 6:ATM concepts roadmap published by the original Engage KTN

In liaison with the EngageWiki task leader, initial parameters for representing the ATM concepts roadmap on-line have been considered. Whilst the limits have not been finalised, it is likely that no more than 20 technologies will be included visually.

Table 9: Initial scoping of ATM concepts roadmap parameters

Feature	Realistic parameter*
How to represent the likelihood of the enablers	4 likelihood categories • *e.g. 'traffic light'-type of colour scheme or a different colour per technology (subject to the number of technologies shown); depth of colour and level of transparency are also feasible*
Number of technologies to include	up to 20 • *a high number of technologies may present challenges to differentiate by colour*
Enablers per technology	5 • *roadmap enablers could be linked to files or wiki pages*
How to represent impacted stakeholders (approximate number)	20+ • *further information could be via a drop-down list for each technology, to contain the grid size*

* Realistic parameters, though not finalised.

Another roadmap feature under consideration is the inclusion of an interactive chatbot, to offer additional functionality to the user. Whilst expertise exists for a custom chatbot to be developed in-house, it might prove to be less challenging to integrate an 'off-the-shelf' chatbot such as Google NotebookLM in the wiki.

In the interim, the wiki roadmap page will include a list of the new technologies (with a link to this deliverable) along with a survey inviting comments on the selected technologies and the wider deliverable content.

4.3 Next steps

The key next steps for this activity may be split over two periods.

4.3.1 Medium term (July-October 2025)

- A potential link between the ATM concepts roadmap and the skill transformation map (being developed within Task 4.2) was noted at a recent Engage 2- SESAR 3 JU coordination meeting; a dedicated meeting will be arranged between the task leaders to discuss this further.
- Interim wiki content will be produced (and remain until the final roadmap version is launched): a simple list of the new technologies; a link to D5.1 (once the deliverable has been accepted), and; a link to a survey (which the University of Westminster will prepare) inviting comments on the technologies and wider deliverable content.

4.3.2 Longer term (October 2025 onwards)

- Further material will be sourced for the next iteration, including conference papers from the 2025 editions of the SIDs and ATRD Symposium (successor to ATM Seminar and ICRAT conferences). In addition to recently published SESAR 3 ER/IR project deliverables, any remaining SESAR 2020 deliverables will also be considered. Material from other non-SESAR Horizon projects will be scoped, for example deliverables relating to mobility, information and communication technology, space and transportation topics.
- The final iteration of the AI based trend analysis will be carried out, with final reporting on the ATM concepts roadmap due in 2026 (D5.7 ATM concepts roadmap - final).
- The final schema of the ATM concepts roadmap (reported in D5.7) will be published in the EngageWiki (replacing the interim wiki content).

5 References

[1] Clean Aviation Joint Undertaking, 2024. Strategic Research and Innovation Agenda – 2024 edition (2nd revision), September 2024, https://www.clean-aviation.eu/about-us/reference-documents.

[2] Engage 2 project, 2024. D4.1 ATM sector changes, Edition 01.00, October 2024.

[3] Engage 2 project, 2025. EngageWiki (SESAR projects and ATM conference papers pages), https://wikiengagektn.com/projects/ and https://wikiengagektn.com/papers/.

[4] European Commission, 2025. CORDIS website, https://cordis.europa.eu/.

[5] National Quantum Computing Centre, 2023. Technology roadmap, https://www.nqcc.ac.uk/technology-and-research/technology-roadmap/.

[6] SESAR 3 Joint Undertaking, 2024. European ATM Master Plan – 2025 edition, December 2024, https://www.sesarju.eu/MasterPlan2025_SupportingDocuments.

6 List of acronyms

Acronym	Description
AI	Artificial intelligence
ANSP	Air navigation service provider
API	Application programming interface
ATC	Air traffic control
ATM	Air traffic management
ATM Seminar	USA/Europe ATM Research and Development Seminar
ATRD Symposium	US-Europe Air Transportation Research & Development Symposium
AZEA	Alliance for Zero-Emission Aviation
CDM	Collaborative decision-making
DAC	Dynamic airspace configuration
ER	Exploratory research
EREA	Association of European Research Establishments in Aeronautics
eVTOL	Electric vertical take-off and landing
GenAI	Generative AI
GNSS	Global navigation satellite system
HPC	High-performance computing
ICRAT	International Conference on Research in Air Transportation
IoT	Internet of things
IR	Industrial research
JU	Joint Undertaking
KTN	Knowledge transfer network
LLM	Large language model
ML	Machine learning
NQCC	National Quantum Computing Centre
R&D	Research and development
RAG	Retrieval-augmented generation
RPAS	Remotely piloted aircraft systems
SAF	Sustainable aviation fuel
SDO	Strategic deployment objective
SESAR	Single European Sky ATM Research Programme

Acronym	Description
SIDs	SESAR Innovation Days
SRIA	Strategic Research and Innovation Agenda
TBO	Trajectory-based operations
TRL	Technical readiness level
UAM	Urban air mobility
UAS	Unmanned/uncrewed aerial system
VTOL	Vertical take-off and landing

7 Appendix: AI ‘final’ output

The AI ‘final’ output ***from the second iteration*** is attached. Please note that this appendix was generated automatically, with no control over the formatting or layout. Moreover, please be reminded that this is only the ‘final’ output of this ***interim*** phase of the work, which will be taken forward in Deliverable 5.7, as explained in Section 2.3.1.

AI 'final' output (second iteration)

1. Overview

1.1 List of trends

Most relevant trends:

- Electrification and Advanced Battery Technologies
- Synthetic Fuels and Direct Air Capture Integration
- Global Seamless Biometric Security and Identity
- Digital Twin Airspace Simulation and Management
- Biodegradable and Smart Aircraft Materials
- Unmanned Freight and Cargo Drones
- On-Demand, Personalized Air Travel
- Integration of Remotely Piloted Aircraft Systems (RPAS)
- Advanced U-Space and UAS Traffic Management
- Space-based Multilateration and Satellite Surveillance
- Collaborative Decision-Making (CDM) and Military-Civil ATM Integration
- Trajectory-Based Operations and 4D Trajectory Management
- AI and Machine Learning for Predictive Analytics in ATM
- Urban Air Mobility (UAM) and Drone Integration
- Cybersecurity Capabilities and Cyber-Resilience
- Fully Autonomous Commercial Aircraft
- Global Supersonic and Hypersonic Travel
- Distributed Air Mobility Networks (Air Taxis and Urban VTOLs)
- Quantum Computing-Optimized ATC (Air Traffic Control)
- AI-Driven Predictive Maintenance and Self-Healing Systems

1.2 Stakeholder impacted

Stakeholders impacted by trends:

1.3 Enablers

Enablers by trends:

1.4 Barriers

Barriers by trend:

1.5 Environmental impacts

Impact by trend:

Trends Impact	Greenhouse Gas Emissions	Air/Local Pollution (including NOx, particulates, air quality, ozone)	Noise Pollution	Plastic/Chemical/Electronic Waste	Resource & Energy Consumption (inc. mining, raw materials, water)	Ecosystem/Wildlife Disturbance/Habitat/Urban land use
Electrification and Advanced Battery Technologies	High positive	High positive	High positive	Medium negative	Medium to High negative	Low positive
Synthetic Fuels and Direct Air Capture Integration	High positive	Medium positive	Low	Low negative	Medium negative	Low to Medium negative or neutral
Global Seamless Biometric Security and Identity	Low to Medium negative	Low negative (energy/e-waste)		Low positive (plastic) / Low negative (e-waste)	Low negative	
Digital Twin Airspace Simulation and Management	Medium positive	Low to Medium positive (air); Low positive (noise)	Low positive	Low negative (e-waste/plastics)	Low to Medium negative	Low positive
Biodegradable and Smart Aircraft Materials	Medium to High positive	Medium positive (via plastics/chemicals)	Low positive	High positive (less plastic waste)	Medium positive (resource optimization)	Medium positive

Trends Impact	Greenhouse Gas Emissions	Air/Local Pollution (including NOx, particulates, air quality, ozone)	Noise Pollution	Plastic/Chemical/Electronic Waste	Resource & Energy Consumption (inc. mining, raw materials, water)	Ecosystem/Wildlife Disturbance/Habitat/Urban land use
Unmanned Freight and Cargo Drones	Medium positive	Low to Medium positive (road air quality) / Medium negative (noise)	Medium negative	Medium negative (waste)	Medium negative/mixed (energy use)	Medium negative
On-Demand, Personalized Air Travel	High negative	Low to Medium negative (air quality, noise)	Medium negative	Medium negative	Low to Medium negative	Low to Medium negative
Integration of Remotely Piloted Aircraft Systems (RPAS)	Low to Medium mixed	Low to Medium negative (noise/air)	Low to Medium negative	Medium negative (waste)	Low to Medium negative	Medium negative
Advanced U-Space and UAS Traffic Management	Low to Medium mixed	Low positive (urban heat); Medium negative (noise, air)	Medium negative	Medium negative (plastic/e-waste)	Medium negative	Medium negative
Space-based Multilateration and Satellite Surveillance	Low to Medium negative	Medium positive (airline emission reduction)	Low	Low to Medium negative (waste, debris)	Low to Medium negative	Low negative (EM interference)
Collaborative Decision-Making (CDM) and Military-Civil ATM Integration	Medium positive	Medium positive (air pollution, moderate noise reduction)	Low to Medium positive	Low negative	Medium positive (resource efficiency)	Low positive

Trends Impact	Greenhouse Gas Emissions	Air/Local Pollution (including NOx, particulates, air quality, ozone)	Noise Pollution	Plastic/Chemical/Electronic Waste	Resource & Energy Consumption (inc. mining, material, water)	Ecosystem/Wildlife Disturbance/Habitat & Urban land use
Trajectory-Based Operations and 4D Trajectory Management	Medium positive	Medium positive (air, noise)	Medium positive	Low negative	Medium positive	Low positive
AI and Machine Learning for Predictive Analytics in ATM	Medium positive	Low to Medium positive (air); Low positive (noise)	Low positive	Low negative (plastic/e-waste)	Low to Medium negative	Low positive
Urban Air Mobility (UAM) and Drone Integration	Medium mixed	Medium mixed (air); Medium negative (noise)	Medium to High negative	Medium negative (plastic/e-waste)	Low to Medium negative (land/resource use)	Low to Medium negative
Cybersecurity Capabilities and Cyber-Resilience	Low negative	Low negative (air, if incident avoided)	Low negative	Medium negative (e-waste, plastic)	Medium negative	Low positive
Fully Autonomous Commercial Aircraft	Low to Medium positive	Low to Medium positive (noise, air quality)	Low to Medium positive	Medium negative (e-waste/plastic)	Medium negative	Low positive
Global Supersonic and Hypersonic Travel	High negative	Medium to High negative (stratosphere/ozone, noise, particulates)	Medium negative	Low to Medium negative (plastic/material)	Medium negative	Medium negative

Trends Impact	Greenhouse Gas Emissions	Air/Local Pollution (including NOx, particulates, air quality, ozone)	Noise Pollution	Plastic/Chemical Waste	Resource & Energy Consumption (inc. mining, rare earths, water)	Ecosystem/Wildlife Disturbance/Habitat Loss/Material land use
Distributed Air Mobility Networks (Air Taxis/Urban VTOLs)	Medium mixed	Low to Medium mixed (air, noise, heat)	Medium to High negative	Low to Medium negative (plastic/composite waste)	Medium negative (resource/energy use, urban use)	Low to Medium negative
Quantum Computing-Optimized ATC	Medium positive	Low positive (air, noise)	Low positive	Low negative (e-waste, plastic)	Low to Medium negative	Low positive
AI-Driven Predictive Maintece and Self-Healing Systems	Medium positive	Medium positive (air/chemical); Low to Medium positive (noise)	Low to Medium positive	Low negative (plastic/e-waste)	Medium negative (e-waste/resources)	Low positive

1.6 Societal impacts

Impact by trend:

Trends Impact	Environmental Sustainability	Economic Opportunity & Efficiency	Social Equity & Gender Gap	Well-being & Public Health	Privacy & Surveillance	Employment Disruption & Skills Gap	Urban / Regional Development	Accessibility & Mobility	Safety & Security
Electrification & Advanced Battery	High Positive	Medium-High Positive	Medium-Positive (with risk)	High Positive		Medium (Positive if reskilled)	Medium-High Positive	Medium-Positive	High Positive

Trends Impact	Environmental Sustainability	Economic Opportunity & Efficiency	Social Equity & Gender Gap	Well-being & Public Health	Privacy & Surveillance	Employment Disruption & Skills Gap	Urban / Regional Development	Accessibility & Mobility	Safety & Security
Synthetic Fuels & Direct Air Capture	High Positive	Medium-High Positive	Medium (Positive if inclusive)	Medium Positive		Medium (Requires transition)	Medium Positive	Medium Positive	High Positive
Biometric Security & Global ID		Medium (Mixed)	Medium (Mixed, possible exclusion/gender bias)	High Positive	High Negative	Medium (Automation, mixed)		Medium (Mixed)	High Positive
Digital Twin Airspace Mgmt.	Medium Positive	High Positive	Low-Medium (risk of reinforcing gaps)	High Positive	Medium Negative	Medium (Need reskilling)	Medium Positive	Medium Positive	High Positive
Biodegradable & Smart Materials	High Positive	Medium-High Positive	Medium (Risk without intervention)	Medium Positive		Medium (Transition risk)	Medium-High Positive	Medium-High Positive	Medium Positive
Cargo Drones & Unmanned Freight	Medium-High Positive	High Positive	Medium (Shrink or widen gender gap)	Medium-High Positive	Medium Negative	High Negative (Disruption)	Medium Positive	Medium Positive	Medium Negative (new risks)
On-Demand Personalized Travel	Medium Negative (unless green)	Medium Positive	High Negative (inequality risk)	Medium Positive		Medium (Job shifts possible)	Medium Mixed	Medium Positive	Medium Positive
RPAS (Remotely Piloted Aircraft)	Low-Medium Mixed	High Positive	Medium (Likely widen gap)	Medium-High Positive	High Negative	Medium-High (Skills gap)	Medium Positive	Medium-High Positive	Medium (Depends on reg.)

Trends Impact	Environmental Sustainability	Economic Opportunity & Efficiency	Social Equity & Gender Gap	Well-being & Public Health	Privacy & Surveillance	Employment Disruption & Skills Gap	Urban / Regional Development	Accessibility & Mobility	Safety & Security
Advanced U-Space/UAS Mgmt	Medium Mixed	High Positive	Medium Negative (gender/job)	High Positive	Medium-High Negative	Medium (Job shifts)	Medium High Positive	Medium High Positive	High Positive
Satellite Surveillance & Multilateration	Low-Medium Mixed	Medium Positive	Low-Med Positive (inclusive policies)	High Positive	Medium Negative	Medium (Jobs shift)		Medium Positive	High Positive
CDM & Military-Civil ATM Integration	Medium Positive	Medium Positive	Low-Med Positive (diversity)	Medium Positive	Low-Med Negative	Medium (Shifts, new roles)	High Positive	Medium Positive	Medium Positive
4D Trajectory-Based Ops	High Positive	Medium-High Positive	Medium Negative (widen unless inclusive)	High Positive		Medium (Reskilling)	High Positive	High Positive	High Positive
AI / ML for Air Traffic Mgmt	High Positive	High Positive	Medium Negative (widen unless inclusive)	Medium Positive	Medium Negative	Medium Mixed	Medium Positive	High Positive	High Positive
Urban Air Mobility & Drone Integration	Medium Mixed	Medium Mixed	Medium Mixed (equity/gender risk)	Medium Mixed	Medium Negative	Medium Mixed (Job displacement)	High Positive	High Positive	High Mixed
Cybersecurity & Resilience	Medium-High Positive	High Positive	Medium Mixed (inclusive policy helps)	Medium Mixed	Medium Mixed	Medium Mixed		Medium Positive	High Positive

Trends Impact	Environmental Sustainability	Economic Opportunity & Efficiency	Social Equity & Gender Gap	Well-being & Public Health	Privacy & Surveillance	Employment Disruption & Skills Gap	Urban / Regional Development	Accessibility & Mobility	Safety & Security
Fully Autonomous Aircraft	Medium Positive	High Positive	Medium Positive (lower pilot barriers)	High Positive	Medium Negative	High Negative (job loss risk)	Medium Positive	Medium Positive	Medium-High Positive (if trusted)
Supersonic/Hypersonic Travel	High Negative	Medium Positive	High Negative (inequality risk)	Low-Medium Mixed		Medium (Access for few)	Medium Positive	Medium Positive	Medium Negative (noise, env)
Distributed Air Mobility Networks (VTOLs)	Medium Positive (if sustainable)	High Positive	High Negative (inequality risk)	Medium Positive	Medium Negative (noise/privacy)	Medium Negative (legacy jobs)	High Positive (urban change)	Medium Positive	Medium Positive
Quantum-Optimized ATC	Medium-High Positive	High Positive	Low-Med Positive (if inclusive)	Medium Positive		Medium-High (Shift, retrain)	Medium Positive	High Positive	High Positive
AI-Driven Predictive Maintece & Self-Healing	Medium-High Positive	High Positive	Medium Positive (bias reduction possible)	High Positive		Medium (Job shifts)	Medium Positive	Medium Positive	High Positive

1.7 SDO mapping

SDO influenced by trend:

Trend SDO	SDO 1	SDO 2	SDO 3	SDO 4	SDO 5	SDO 6	SDO 7	SDO 8	SDO 9	SDO 10
Electrification and Advanced Battery Technologies	X	X								
Synthetic Fuels and Direct Air Capture Integration	X									
Global Seamless Biometric Security and Identity	X	X	X	X	X					
Digital Twin Airspace Simulation and Management	X	X	X	X	X	X	X	X		
Biodegradable and Smart Aircraft Materials	X	X								
Unmanned Freight and Cargo Drones	X	X	X	X	X	X	X	X	X	X
On-Demand, Personalized Air Travel	X	X	X	X	X	X	X	X	X	X
Integration of Remotely Piloted Aircraft Systems (RPAS)	X	X	X	X	X	X	X	X	X	X
Advanced U-Space and UAS Traffic Management	X	X	X	X	X	X	X	X	X	
Space-based Multilateration and Satellite Surveillance	X	X	X	X	X					
Collaborative Decision-Making (CDM) and Military-Civil ATM Integration	X	X	X	X	X					
Trajectory-Based Operations and 4D Trajectory Management	X	X	X	X	X	X				
AI and Machine Learning for Predictive Analytics in ATM	X	X	X	X	X	X	X	X		
Urban Air Mobility (UAM) and Drone Integration	X	X	X	X	X	X	X	X	X	X
Cybersecurity Capabilities and Cyber-Resilience	X	X	X	X	X	X	X	X	X	X

Trend SDO	SDO 1	SDO 2	SDO 3	SDO 4	SDO 5	SDO 6	SDO 7	SDO 8	SDO 9	SDO 10
Fully Autonomous Commercial Aircraft	X	X	X	X	X	X	X	X	X	X
Global Supersonic and Hypersonic Travel	X	X	X	X	X	X	X	X		
Distributed Air Mobility Networks (Air Taxis and Urban VTOLs)	X	X	X	X	X	X	X	X	X	X
Quantum Computing-Optimized ATC	X	X	X	X	X	X				
AI-Driven Predictive Maintece and Self-Healing Systems	X	X	X	X	X	X	X	X	X	X

1.8. Roadmaps

Pessimistic roadmap:

- 2025: Emergence of Electric Regional Aircraft and eVTOL Demonstrations: Electrification of short-haul aircraft and eVTOL (urban air mobility) demonstrators reach commercial pilots. Advancements in battery density, government subsidies, and aerospace-battery industry collaboration help overcome immediate technological and cost barriers, though flight range remains limited and regulatory frameworks are in rapid development.
- 2026: Global Rollout of Seamless Biometric Airport Security: Global airports implement interoperable, privacy-focused biometric security and seamless digital identity. Regulatory harmonization, strong data protection frameworks, and scalable cloud solutions drive adoption. Public trust initiatives and technical standards resolve privacy, cost, and interoperability challenges.
- 2027: Initial Widespread Deployment of Predictive Maintenance and AI-Enhanced ATM Analytics: AI-powered predictive analytics enhance air traffic management, and predictive maintenance is rolled out on new fleets, reducing delays and safety incidents. High-quality data sets, cloud computing, and big data analytics enable greater reliability, while certification hurdles are gradually being addressed through regulatory sandboxes.
- 2028: Early Urban and Distributed Air Mobility Pilots; Air Taxi Test Routes: Urban air taxi and distributed VTOL service pilots start in top-tier global cities. Batteries and autonomy tech cross key reliability thresholds, supported by targeted regulatory pilots and new digital booking infrastructure. Public skepticism and noise are mitigated via community engagement and fleet noise reduction mandates.
- 2029: First Synthetic Fuel Production Plants Supplying Major Airlines;

Early DAC Integration: Facilities for sustainable synthetic fuel and direct air capture reach operational scale, supplying SAF to long-haul routes. Advances in electrolysis, carbon pricing, government incentives, and strategic investment result in viable pathways around high costs and initial infrastructure gaps.

- 2030: Advanced U-Space and Drone Traffic Management in Urban Centers: Advanced U-Space management, with automated drone deconfliction, becomes mandatory for urban drone delivery and air mobility. Key enablers include AI-driven sense-and-avoid, robust communication networks, and harmonized UTM regulations. Public and environmental concerns are addressed by real-time airspace and noise management tools.
- 2031: Large-Scale Integration of Unmanned Cargo Drones for Regional Logistics: Unmanned cargo drones scale in regional and logistics operations. Regulatory certainties, improved battery and autopilot systems, and cost-effective manufacturing outweigh early public acceptance and air traffic integration concerns, creating new opportunities for fast, low-emission last-mile delivery.
- 2032: Digital Twin Driven Airspace Management Goes Operational: Operational rollout of digital twin-based airspace management in several global regions allows real-time dynamic rerouting, predictive safety interventions, and optimized airport operations. High-performance computing, IoT/sensor maturity, and standards for data sharing overcome earlier cost, integration, and privacy hurdles.
- 2033: On-Demand, Personalized Air Travel Becomes a Multi-City Reality: Personalized, on-demand air travel (e.g., air taxis, small charter eVTOL) becomes available across multiple cities. Improved regulatory frameworks, urban infrastructure development (vertiports), and affordable digital scheduling platforms allow market growth. Concerns about emissions, inequality, and noise get mitigated by increasingly electrified fleets and tiered service models.
- 2034: Biodegradable and Smart Aircraft Materials Adopted in New Short-Haul Fleets: Biodegradable and smart materials are certified and adopted across next-gen regional and short-haul aircraft, reducing lifecycle impacts. Material science innovation, cross-industry partnerships, and responsive certification enable shift; new sustainable supply chains and advanced additive manufacturing overcome earlier production barriers.
- 2035: Fully Autonomous RPAS Broadly Integrated into Commercial Airspace: Remotely piloted aircraft systems (RPAS) get routine commercial airspace access. Advanced sense-and-avoid, robust communication, and effective collaboration among regulators and operators mitigate safety, privacy, and trust challenges, enabling safe integration with manned traffic.
- 2036: Collaborative Military-Civil ATM Fully Realized in Major Corridors: Real-time, collaborative military-civil air traffic management is deployed on major strategic routes, driven by joint training, data sharing, and harmonized regulatory guidelines. Security/confidentiality obstacles are addressed by secure, role-based protocols and common operational

standards.

- 2037: Space-Based Multilateration Achieves Near-Global Aircraft Tracking: Near-global aircraft surveillance via space-based multilateration becomes operational, vastly enhancing situational awareness and search-and-rescue. Cost reductions in satellite launch and international regulatory cooperation resolve earlier integration and coverage limitations, while strong data security measures foster confidence.
- 2038: Trajectory-Based Operations and 4D Trajectory Management Standardized Worldwide: Trajectory-Based Operations (TBO) and 4D trajectory management become globally standardized for all commercial flights. Advanced ATM algorithms, surveillance/communication networks, and data-sharing standards accelerate implementation, while regulatory and integration barriers are harmonized under ICAO and regional oversight.
- 2039: AI-Driven, Self-Healing Aircraft in Mainstream Use: Mainstream fleets integrate AI-driven self-healing systems and predictive maintenance. High sensor density, big data, and certification frameworks enable predictive interventions and autonomous repairs, reducing downtime, resource use, and maintenance costs. Workforce retraining programs ensure transition for legacy maintenance roles.
- 2040: Cyber-Resilient, Quantum-Enhanced Air Traffic Control Pilots Begin: Quantum computing pilots for air traffic control optimization launch in advanced markets. Quantum-classical hybrid systems, robust communication, and regulatory frameworks mitigate risks related to hardware reliability and cost; demonstration projects validate safety and efficiency, paving the way for broader adoption.
- 2042: Commercial Launch of Supersonic Passenger Services with SAF Integration: First commercial supersonic passenger flights commence, powered by synthetic/SAFs and featuring radical noise and emission reduction technologies. Regulatory harmonization on noise, R&D in advanced materials, and global SAF supply chains help overcome lingering environmental and integration challenges.
- 2045: Large-Scale Distributed Air Mobility Networks Mature, Serving Most Major Cities: Distributed air mobility (urban air taxis, regional VTOL networks) expand to serve most global cities, providing on-demand access integrated with public transit. AI, battery advances, infrastructure buildout, and streamlined regulatory processes enable scale, while progressive policies address equity, noise, and energy sourcing.
- 2048: Fully Autonomous Commercial Passenger Flights Go Mainstream: Fully autonomous commercial passenger flights—without pilots on board—enter mainstream service for selected routes and city pairs. AI/ML reliability, robust sensors, cybersecurity, and finalized certification frameworks ensure safety and public trust. Airlines realize major efficiency gains, and transitions for dislocated personnel are managed via retraining.
- 2050: Net-Zero Carbon Growth Achieved by Global Aviation Sector: Through a combination of electrification, SAFs, DAC, advanced ATM, and smart fleet solutions, the aviation sector achieves net-zero carbon growth.

Global policy alignment, technological breakthroughs, and full deployment multi-sectorally ensure operational growth is decoupled from emissions, with aviation positioned as an exemplar for sustainable high-mobility industries.

Optimistic roadmap:

- 2026: Slow Rollout of Battery-Electric Regional Aircraft: Due to persistent barriers around battery energy density, high cost, infrastructure limitations, and regulatory inertia, only a handful of short-range electric and hybrid commercial aircraft enter limited service. Airlines remain cautious due to uncertain economics, weak infrastructure, and incremental tech gains. Growth is subdued by slow advances in energy storage and lack of clear subsidy or carbon pricing signals.
- 2027: Increasing Barriers in Synthetic Fuel Scale-Up: Despite advances in electrolysis and government R&D, synthetic and direct air capture fuels face mounting cost and scalability obstacles. Renewable energy input is insufficient, and carbon capture scale lags. Regulatory and certification frameworks drag, preventing mass adoption. Jet fuel demand remains met by fossil sources, and investors hold back for clearer returns.
- 2028: Fragmented Biometric Security Adoption: Privacy laws diverge and cross-border harmonization of data standards stalls; biometric deployments appear only at some airports and are often locally limited. Public trust issues, lack of global interoperability, frequent cost overruns, and technical failures limit the actual realization of seamless global biometric processes. Airlines and airports abandon or delay full conversion amid compliance nightmares.
- 2029: Airspace Digital Twin Pilots Limited to Major Hubs: Major airports run digital twin airspace pilots, but full national or global rollouts are limited by huge computational/IT costs, data interoperability failures, and scarce collaborative buy-in from critical stakeholders. Local data silos, failure to standardize, and regulatory bottlenecks keep digital twin benefits limited to select, well-funded cities while broader adoption languishes.
- 2030: Biodegradable Materials in Prototype/Business Aircraft Only: Biodegradable and smart aircraft components are used on a handful of experimental or luxury business jets, but lack of regulatory clarity, durability issues in real operations, and high costs keep widebody or mainstream airline adoption at bay. Manufacturers prioritize conventional composites for reliability and certification ease.
- 2031: Regulatory Stagnation Stalls Freight Drone Growth: Widespread drone freight delivery is sharply constrained by the lack of clear legal frameworks, poor integration with civil airspace, unresolved liability, security worries, and low public support. Major cities face local drone bans, stalling supply chain advances. Only small-scale, rural, or humanitarian UAV use persists.
- 2032: Air Taxi and VTOL Services Restricted to Niche Markets: Air taxi and VTOL services exist mainly as press events or ultra-premium offerings.

Urban infrastructure, noise and safety worries, high operations costs, and unresolved traffic management challenges limit routes to isolated, well-controlled demonstration corridors in high-income regions. The promise of cheap mass mobility remains unfulfilled.

- 2033: Remotely Piloted Systems Face Regionally-Fragmented Integration: Remotely piloted aircraft are inconsistently incorporated into national airspace systems; major economies diverge on regulatory and security approaches. System reliability, cybersecurity scares, and public resistance limit cross-border or large-scale deployments. Stakeholders, lacking harmonization, keep integration regionally fragmented.
- 2034: First U-Space Corridors Stagnate, Hampered by Public and Safety Concerns: A handful of official urban U-Space corridors appear, but safety incidents, local privacy pushback, noise complaints, technological shortcomings, and regulatory resistance cap UAS traffic. Interoperability with manned aviation and ground authorities remains unsolved beyond demo projects, stalling full-scale rollouts.
- 2035: Space-Based Surveillance Systems Delayed by Funding, Political Tensions: The implementation of global space-based multilateration, critical for seamless air traffic surveillance, is bogged by multi-national disputes, budget shortfalls, satellite deployment delays, and cybersecurity/vulnerability fears. Gaps in coverage persist, especially over less-developed regions or remote oceanic/Polar areas.
- 2036: Slow Progress in Civil-Military ATM Integration: National security silos, chronic lack of transparency, cultural/organizational distrust, and incompatibility in civil-military ATM tech slow true integration. Data sharing lags behind rhetoric, and CDM remains theoretical or limited to crisis scenarios. Operational inefficiency from poor collaboration persists through the 2030s.
- 2037: Inconsistent 4D Trajectory Management Worldwide: Despite some regional progress in 4D trajectory-based operations, lack of global regulatory coordination, security concerns over data-sharing, legacy ATM limitations, and patchy infrastructure investment lead to persistent inconsistency. Airlines and pilots face a patchwork of regional standards and limited practical benefits.
- 2038: Predictive AI in ATM Stalemates due to Security, Legacy Tech: The promise of AI-driven predictive analytics for smarter ATM is mired in slow or uneven data quality improvement, integration woes with decades-old systems, certification hurdles, and mounting cybersecurity concerns. Localized, non-interoperable systems are the norm, with only incremental operational gains.
- 2039: Urban Air Mobility Limited by Noise/Regulatory Pushback: Urban air mobility projects continue to face local bans, NIMBY resistance, failed noise targets, and delayed regulatory clarity. Even as a few cities promote high-profile air taxi pilots, wider deployment is blocked by operational incidents, disillusioned communities, and stagnating investment.
- 2040: Cybersecurity Shortcomings Exposed by Successful Attacks: As dig-

italization mounts, several high-profile cyberattacks or near-miss incidents in ATM or airliner systems underscore the inadequacy of current resilience. Talent shortages, high costs, legacy tech, and fragmented oversight leave many stakeholders exposed, prompting regulatory backlash and diverting resources to crisis response rather than proactive progress.

- 2041: Autonomous Commercial Aircraft Postponed after Public Setbacks: Negative public response after a spate of autonomous vehicle accidents, coupled with regulatory gridlock and ongoing technical limitations, stalls the launch of fully autonomous passenger jets. Fleets remain pilot-augmented, with autonomy capped at secondary functions. Investor retreats and strict liability regimes suppress launch plans.
- 2042: Supersonic/Hypersonic Travel Fails to Scale Beyond Limited Premium Routes: Despite technological demonstrations, supersonic and hypersonic transport stays confined to small, niche, ultra-premium routes for government and elite clients only. Environmental regulations, noise complaints, poor economics, and safety risks prevent commercial scaling. Few airports invest in required upgrades, and societal backlash intensifies.
- 2043: VTOL Distributed Air Mobility Remains Experimental: Distributed air taxi/VTOL networks remain experimental as urban airspace management, vertiport construction, and neighbor opposition continually delay citywide rollouts. Certification stasis, reliability shortfalls, and high cost-per-passenger conspire to keep deployments as high-profile, short-term pilots—not sustainable mobility infrastructure.
- 2045: Quantum-Optimized ATC Still in Research-Only Phase: Quantum computing remains largely confined to academic and industrial research. Quantum hardware lags in reliability and stability, fails to scale, and faces cost and skill bottlenecks. FAA and EASA (or equivalents) lack regulatory frameworks for quantum-enabled ATC, and risk-averse airlines and traffic managers delay any operational adoption.
- 2046: AI Predictive Maintenance Adoption Slowed by Certification Hurdles: Industry-wide AI predictive maintenance systems get delayed by regulatory uncertainty—regulators struggle to certify black-box AI models, airlines resist unproven fixes, and supply chains can't agree on uniform data protocols. High costs, cyber risk worries, and limited trust in automated decision-making hamper the technology's broader rollout.

2. Details and explanations

2.1 Electrification and Advanced Battery Technologies

The move toward electric and hybrid-electric propulsion systems powered by advanced batteries is set to revolutionize short- to medium-haul aviation, cutting emissions, operating costs, and noise, while enabling new aircraft designs.

2.1.1 Barriers:

- Energy Density Limitations: Current battery technologies have significantly lower energy density compared to conventional aviation fuels, which limits flight range and payload capacity. This constraint restricts the applicability of electrification primarily to short- and medium-haul routes, slowing broader adoption in air transportation.
- Battery Weight and Volume: Batteries are heavier and bulkier than traditional fuel systems for the same energy output, which negatively impacts aircraft design, efficiency, and payload capabilities. The additional weight reduces overall aircraft performance and necessitates novel engineering solutions, delaying development timelines.
- High Development and Production Costs: Advanced battery technologies require substantial investment in research, development, and manufacturing infrastructure. High costs associated with raw materials, such as lithium and cobalt, as well as complex manufacturing processes, challenge the economic viability and scalability of electric aircraft.
- Charging Infrastructure and Turnaround Times: Efficient operation of electric aircraft depends on rapid charging or battery swapping capabilities. Currently, charging infrastructure at airports is underdeveloped, and battery recharge times are long compared to refueling conventional aircraft. This creates operational and scheduling challenges that hinder commercial deployment.
- Regulatory and Certification Challenges: Electric and hybrid-electric aircraft must meet rigorous safety and performance certification standards. Regulatory frameworks specific to these novel propulsion systems are still evolving, leading to uncertainties and delays in approval processes. This slows down market entry and investor confidence.

2.1.2 Enablers:

- Advancements in Battery Energy Density: Higher battery energy density allows aircraft to store more power with less weight, directly improving flight range and payload capacity. This makes electric and hybrid-electric propulsion feasible for short- to medium-haul flights, addressing one of the key constraints in electrifying air transportation.
- Government Policy and Regulatory Support: Government policies such as subsidies, emissions regulations, and mandates for cleaner aviation technologies incentivize airlines and manufacturers to adopt electrification and invest in advanced batteries. Regulatory certainty accelerates market adoption and funds safety certification processes.
- Investment in Research and Development: Robust R&D investment drives technological breakthroughs in battery chemistry, thermal management,

and electric propulsion integration. This accelerates innovation cycles to produce batteries that are safer, lighter, longer-lasting, and more efficient, enabling practical electrification solutions.

- Development of Charging and Energy Infrastructure: The development of a reliable and widespread electric charging infrastructure at airports, including fast-charging capabilities, supports operations and turnaround times for electric aircraft. Integration with renewable energy sources further enhances sustainability and operational cost reductions.
- Collaboration between Aerospace and Battery Industries: Partnerships between aerospace companies and battery technology firms foster cross-industry innovation, allowing for the tailoring of batteries specifically optimized for aviation needs. This collaboration accelerates development timelines and ensures compatibility with aircraft design and certification requirements.

2.1.3 Stakeholders impacted:

- Aircraft Manufacturers: Aircraft manufacturers will be impacted as they need to design and produce new electric and hybrid aircraft models that integrate advanced battery technologies, requiring new engineering approaches and R&D investments.
- Airlines: Airlines will experience changes in operational costs and maintenance procedures due to more efficient, quieter, and environmentally friendly aircraft, potentially altering route structures and fleet management strategies.
- Battery Manufacturers: Battery manufacturers will see increased demand for high-performance, lightweight, and safe batteries tailored specifically for aviation, driving innovation and scaling in battery technology.
- Regulatory Authorities: Regulatory authorities must develop new certifications, safety standards, and regulations to address the unique challenges of electrified propulsion systems and battery safety in aviation.
- Passengers: Passengers may benefit from reduced noise and emissions during flights, as well as potentially lower ticket prices due to decreased operating costs, influencing travel preferences and expectations.
- Airport Operators: Airport operators will need to upgrade infrastructure to support electric aircraft charging and maintenance facilities, as well as adapt to altered ground operations and energy requirements.
- Environmental Organizations: Environmental organizations will be stakeholders as this technological shift contributes to reducing aviation's carbon footprint and environmental impact, aligning with global sustainability goals.

- Maintenance and Repair Organizations (MROs): Maintenance and Repair Organizations (MROs) will need to develop new skills and capabilities to service electric propulsion systems and battery technologies, transforming workforce training and service offerings.
- Energy Providers: Energy providers will be affected as the demand for electricity at airports rises, requiring enhanced grid capacity and potentially new business models related to renewable energy integration.
- Government and Policy Makers: Government and policy makers will need to support research, infrastructure development, and regulatory frameworks to facilitate the adoption of electrification and advanced batteries in aviation, influencing economic and environmental policies.

2.1.4 Environmental impact:

- Greenhouse Gas Emissions: Electrification of aviation using advanced batteries is expected to result in significantly lower direct greenhouse gas emissions during operation compared to traditional fossil-fueled aircraft, especially for short- to medium-haul flights. This has a HIGH positive impact on reducing climate change drivers. However, overall impact depends on the carbon intensity of the electricity generation mix and battery manufacturing processes.
- Air Pollution: Electric propulsion produces negligible operational air pollutants (such as NOx and particulate matter), resulting in a HIGH positive impact as local air quality around airports improves, benefiting both humans and ecosystems.
- Plastic and Chemical Pollution: Batteries are largely composed of plastics, polymers, and chemicals which, if improperly managed, could lead to medium levels of plastic and chemical pollution. However, with robust recycling and waste management strategies, the negative impact can be mitigated.
- Resource Extraction and Mining Impacts: The demand for minerals such as lithium, cobalt, and nickel for advanced batteries can drive increased mining activities, resulting in MEDIUM to HIGH negative environmental impacts such as habitat destruction, water pollution, and increased energy use. Sustainable sourcing and recycling practices can reduce some of these effects.
- End-of-Life Battery Waste: If batteries are not properly recycled or disposed of, there is potential for a MEDIUM negative impact due to toxic battery waste and accumulation of non-biodegradable components, which can persist in landfills or the natural environment.
- Noise Pollution: Electric aircraft produce much less noise during operation compared to conventional aircraft, causing a HIGH positive impact on

reducing noise pollution for communities near airports.

2.1.5 Societal impacts:

- Environmental Sustainability: Electrification and advanced battery technologies can significantly reduce greenhouse gas emissions and noise pollution in air transportation, enabling a more sustainable aviation industry. This positive, high-level impact tackles climate change and helps preserve ecological balance.
- Economic Opportunity: The transition to electric aviation can create new industries, jobs, and entrepreneurship opportunities, especially in battery manufacturing, maintenance, and infrastructure. However, it may disrupt traditional sectors, leading to job displacement. The overall economic impact is positive and medium to high, provided adequate reskilling is in place.
- Gender Gap: If not managed inclusively, the expansion of electrification and battery-related jobs and education could replicate or even exacerbate current gender imbalances in STEM fields. Proactive policies can translate this trend into a positive, medium-level impact on narrowing the gender gap by promoting women's participation in the new green and tech-based workforce.
- Public Health and Well-being: Reduced emissions and noise translate to improved public health and community well-being, especially for people living near airports. This high, positive impact can lower respiratory illnesses and stress-related conditions, and contribute to higher quality of life.
- Urban Development: Electrification supports innovations like urban air mobility (eVTOLs), which could reshape city layouts and commuting patterns. If implementation is equitable, this medium-to-high impact can enhance urban accessibility and reduce congestion. Otherwise, it risks reinforcing existing inequalities.
- Access and Mobility: Cheaper, quieter, and cleaner electric aircraft could make air travel more accessible to remote or underserved populations, improving connectivity. The impact is positive and medium, depending on regulatory considerations and infrastructure rollout.
- Energy Infrastructure Shift: A large-scale shift to electric aviation will require rethinking energy generation, distribution, and airport infrastructure—potentially spurring investments in renewables. This high, positive impact depends on sustainable sourcing of battery materials, grid upgrades, and global coordination.

2.2 Synthetic Fuels and Direct Air Capture Integration

Development and deployment of sustainable aviation fuels (SAF), synthetic fuels, and direct air capture to reduce the carbon footprint of aviation, aiming for a future of net-zero-emission flight operations.

2.2.1 Barriers:

- High Production Costs: The synthesis of synthetic fuels and operation of direct air capture (DAC) technologies require significant financial investment and expensive raw materials. High production costs make these fuels less competitive against conventional jet fuels, slowing adoption and scale-up in the aviation industry.
- Energy Intensity and Infrastructure Requirements: Both synthetic fuel production and DAC are highly energy-intensive processes that demand robust, often renewable, energy infrastructure. Inadequate renewable energy availability and lack of upgraded infrastructure restrict the efficiency and sustainability of these solutions, impeding widespread deployment.
- Limited Carbon Capture Scalability: Scaling direct air capture technology to the levels required for meaningful CO2 removal from the atmosphere remains a significant technical and logistical challenge. Limited scalability impairs integration potential with synthetic fuel production, limiting the impact on reducing aviation's net carbon emissions.
- Regulatory and Certification Challenges: Synthetic fuels and DAC integration require comprehensive regulatory approvals and aviation fuel certifications to ensure safety, reliability, and compatibility with existing aircraft engines. Regulatory delays or strict certification processes can slow the introduction of these technologies into commercial flight operations.
- Market Demand and Investment Uncertainty: Market demand for sustainable aviation fuels remains uncertain due to higher costs and competition with other green technologies. This uncertainty deters private and public investment, limiting funding for research, development, and commercialization necessary for scaling synthetic fuel and DAC integration.

2.2.2 Enablers:

- Advancements in Electrolysis and Renewable Energy: Improvements in electrolysis technology and the availability of abundant renewable energy are critical to producing green hydrogen and capturing CO2 sustainably. This reduces costs and increases the feasibility of producing synthetic fuels at scale, directly supporting cleaner aviation fuels.
- Government Policies and Incentives: Supportive government policies, subsidies, and mandates accelerate research, development, and adoption of synthetic fuels and direct air capture. Regulatory certainty encourages

private sector investment and innovation in these technologies, enabling faster integration into air transportation.

- Carbon Pricing and Emission Regulations: Implementation of carbon pricing mechanisms and strict emission regulations makes fossil fuel-based aviation less economically attractive. This drives airlines and fuel producers to transition towards synthetic fuels and incentivizes development of DAC to offset emissions, fostering market demand.
- Scaling of Carbon Capture Technologies: Effective scaling of direct air capture technology is essential to provide a sustainable source of carbon dioxide for synthetic fuel synthesis. Advances in DAC efficiency and cost reductions will enable large-scale integration with fuel production, helping to close the carbon loop for aviation.
- Investment in Infrastructure and Supply Chains: Developing the necessary infrastructure, including production facilities, distribution networks, and airport fueling systems, ensures reliable supply chains for synthetic fuels. Investment in these areas enables practical deployment and widespread use within the aviation sector.

2.2.3 Stakeholders impacted:

- Airlines: Airlines will be impacted as they will need to adopt synthetic fuels and integrate direct air capture solutions to meet sustainability goals, potentially altering fuel sourcing, operational costs, and carbon emissions reporting.
- Synthetic Fuel Producers: Synthetic Fuel Producers stand to benefit from new market demand but must invest in scaling production technologies and infrastructure to supply aviation with sustainable fuels at competitive prices.
- Direct Air Capture Technology Providers: Direct Air Capture Technology Providers will see increased demand for carbon capture solutions integrated with fuel production, promoting innovation and commercialization of their technologies.
- Government and Regulatory Bodies: Government and Regulatory Bodies will be affected as they will need to develop and enforce policies, incentives, and regulations to support sustainable fuels and carbon capture integration while ensuring compliance with climate targets.
- Passengers: Passengers may experience changes in ticket pricing and travel choices as airlines incorporate sustainable fuels, but ultimately benefit from reduced aviation-related environmental impacts.
- Airport Operators: Airport Operators will need to adapt infrastructure to support storage, handling, and distribution of synthetic fuels and potentially host direct air capture facilities or related equipment.

- Environmental Organizations: Environmental Organizations will be closely monitoring and influencing the development and deployment of synthetic fuels and direct air capture to ensure they deliver genuine emissions reductions and protection of natural resources.
- Investors and Financial Institutions: Investors and Financial Institutions will be impacted as new opportunities and risks emerge in funding companies involved in synthetic fuel production and carbon capture technologies, influencing portfolio strategies.
- Aircraft Manufacturers: Aircraft Manufacturers will need to adapt engine and fuel system designs to optimize performance with synthetic fuels and comply with stricter emissions standards, potentially redesigning aircraft components.
- Local Communities: Local Communities near production or capture facilities may be affected by new industrial activities, requiring engagement to address social, economic, and environmental concerns related to the deployment of these technologies.

2.2.4 Environmental impact:

- Greenhouse Gas Emissions: Synthetic fuels, when produced using renewable energy and integrated with direct air capture (DAC), can significantly reduce net greenhouse gas emissions compared to conventional fossil fuels. DAC removes CO2 directly from the atmosphere, which can be reused or sequestered, resulting in a high positive impact on mitigating climate change and the greenhouse effect.
- Energy Consumption: The production of synthetic fuels and operation of DAC systems require substantial amounts of energy. If this energy comes from renewable sources, the impact is positive or neutral; if from fossil sources, it could offset emission reductions. The impact level depends on the energy mix, but is generally moderate to high.
- Resource Use: Synthesizing fuels and building DAC infrastructure uses raw materials (e.g., metals, chemicals). Large-scale deployment could increase mining and resource extraction, with a medium impact if not managed sustainably.
- Air Quality: Unlike traditional aviation fuels, synthetic fuels can be engineered for cleaner combustion, reducing emissions of particulates and NOx, which improves air quality and offers a moderate positive impact.
- Plastic Pollution: Synthetic fuels are generally less associated with plastic pollution, but the production infrastructure may entail some plastic use for equipment or chemical feedstocks. Overall, impact is low and can be managed with current waste controls.

- Water Use: Process water is needed in fuel synthesis and DAC (cooling, chemical reactions). If not managed well, this can strain local water resources. The impact is low to medium depending on location and scale.
- Ecosystem Impact: Construction and operation of DAC and synthetic fuel plants can disturb local habitats and ecosystems, especially at large scale. Impact is generally low to medium if careful siting and mitigation measures are adopted.

2.2.5 Societal impacts:

- Environmental Sustainability: The integration of synthetic fuels and direct air capture significantly reduces greenhouse gas emissions from air transportation, advancing efforts toward environmental sustainability. This positive impact is high, as it can help mitigate climate change on a global scale.
- Economic Opportunity and Transition: The development of these technologies will create new jobs in engineering, manufacturing, and clean energy sectors, but may also disrupt traditional fossil fuel industries. The impact is medium to high, as it enables economic transition but requires retraining workers.
- Social Well-being: Cleaner air and reduction in pollutants will improve public health and overall well-being, especially in urban and airport-adjacent communities. The impact is positive and medium, contributing to better respiratory and cardiovascular health.
- Gender Gap and Workforce Diversity: The emerging sectors may present opportunities to close the gender gap in STEM and clean energy jobs if proactive steps are taken. However, there is a risk that existing disparities persist if access to education and employment is not equitably distributed. The impact is moderate and can be positive if managed deliberately.
- Global Equity: Availability of affordable synthetic fuels could narrow the gap between developed and developing countries in participating in sustainable aviation, but access and cost barriers may perpetuate global inequalities if not addressed. The impact is medium, with potential for both positive and negative outcomes.
- Technological Advancement: Pursuit of advanced synthetic fuel and capture technologies drives innovation and cross-sector collaboration, leading to spillover benefits in other industries. The impact is positive and high, accelerating technological progress.

2.3 Global Seamless Biometric Security and Identity

Worldwide adoption of seamless biometric authentication for passengers and crew, improving security, streamlining check-in and border processes, and enhancing

the passenger experience.

2.3.1 Barriers:

- Data Privacy and Protection Concerns: Data privacy regulations vary significantly across countries, making it difficult to uniformly collect, store, and share biometric data. This barrier impacts development by creating legal and compliance risks, slowing down the adoption of seamless biometric solutions on a global scale.
- Lack of Global Standardization: Without universally accepted standards for biometric systems and data formats, different countries and airports implement incompatible systems. This fragmentation hinders the seamless integration necessary for global biometric identity verification, limiting its effectiveness across international air transportation.
- High Implementation and Maintenance Costs: Deploying and maintaining advanced biometric infrastructure requires substantial financial investment. Airports and airlines, especially in developing regions, may face budget constraints, delaying adoption. This cost barrier restricts widespread implementation and can lead to uneven availability of biometric security benefits.
- Interoperability Challenges: Technical challenges arise when integrating biometric systems from multiple vendors and linking them with existing legacy infrastructure. Interoperability issues impede smooth data exchange and verification processes, negatively impacting the user experience and the efficiency gains expected from global seamless biometric identification.
- Public Acceptance and Trust Issues: Passengers and crew may have concerns about how their biometric data is collected, used, and protected, possibly leading to resistance. Without public trust and acceptance, the deployment of biometric solutions can face societal pushback, affecting usage rates and ultimately undermining the trend's success.

2.3.2 Enablers:

- Advanced Biometric Technology: Advanced biometric technologies such as facial recognition, fingerprint scanning, and iris recognition provide high accuracy and speed. These innovations enable more reliable identity verification, reducing manual checks and enhancing security while expediting passenger processing at airports.
- Global Data Interoperability Standards: Global data interoperability standards ensure that biometric information and identity credentials can be shared securely and efficiently between countries, airlines, and border control agencies. This facilitates seamless passenger experiences across international boundaries, enabling end-to-end identity verification.

- Robust Privacy and Security Frameworks: Robust privacy and security frameworks are critical to protect sensitive biometric data against breaches and misuse. Establishing clear regulations and trust mechanisms encourages passenger acceptance and compliance by ensuring their data is handled transparently and securely.
- Integrated Stakeholder Collaboration: Integrated collaboration among airlines, airports, governments, technology providers, and regulatory bodies drives unified deployment of biometric systems. This stakeholder alignment enables harmonized processes and technology adoption, eliminating fragmentation that would impede seamless global implementation.
- Scalable Cloud Infrastructure: Scalable cloud infrastructure supports the large-scale processing and storage of biometric data in real-time. Cloud platforms enable rapid access to identity information with high availability and resilience, essential for managing peak travel volumes and supporting global operations.

2.3.3 Stakeholders impacted:

- Passengers: Passengers will benefit from faster and more seamless identity verification processes, reducing wait times and improving their overall travel experience, while also having concerns about data privacy and security.
- Airline Companies: Airline Companies will experience improved operational efficiency through faster boarding and reduced instances of identity fraud, leading to cost savings and enhanced customer satisfaction.
- Airport Authorities: Airport Authorities will be impacted by the need to upgrade infrastructure and processes to incorporate biometric systems, improving security and passenger flow management.
- Border Control and Immigration Agencies: Border Control and Immigration Agencies will gain enhanced tools to verify traveler identities more accurately and quickly, strengthening security while facilitating legitimate travel.
- Biometric Technology Providers: Biometric Technology Providers will see increased demand for their products and services as global air transportation adopts seamless biometric systems, driving innovation and market growth.
- Privacy Advocacy Groups: Privacy Advocacy Groups will be critical stakeholders concerned with ensuring that biometric data is collected, stored, and used ethically and securely, advocating for robust privacy protections.
- Regulatory Bodies: Regulatory Bodies will need to establish and enforce standards and guidelines for biometric data usage, interoperability, and privacy to ensure compliance and protect traveler rights.

- Airport Retailers and Service Providers: Airport Retailers and Service Providers will benefit indirectly from smoother passenger flows, leading to increased dwell times and sales opportunities within airport terminals.
- Government Security Agencies: Government Security Agencies will be affected as biometric systems enhance national security capabilities by providing stronger identity verification and tracking of individuals in transit.
- Aircrew and Airport Staff: Aircrew and Airport Staff will experience changes in operational procedures due to streamlined identity checks, potentially reducing manual workload and improving security protocols.

2.3.4 Environmental impact:

- Reduction in plastic pollution: Positive, low-to-medium impact: As biometric security replaces physical ID cards, boarding passes, and paper documentation, there may be a reduction in the production and disposal of plastics and other materials, helping decrease plastic pollution.
- Energy consumption and greenhouse gas emissions: Negative, low-to-medium impact: The deployment and operation of large-scale biometric systems (servers, data centers, networks, and sensors) will require significant energy resources. Unless powered by renewable sources, this could increase greenhouse gas emissions.
- Electronic waste (e-waste) generation: Negative, low impact: Advanced biometric devices (scanners, cameras, terminals) have limited lifespans and may contribute to the accumulation of electronic waste, though the scale is relatively small compared to other electronics industries.
- Resource extraction for digital infrastructure: Negative, low impact: The need for new hardware and IT infrastructure to support biometric systems may require increased extraction of metals and rare earth elements, leading to limited but measurable environmental strain in those sectors.

2.3.5 Societal impacts:

- privacy and surveillance: High impact (negative): Global seamless biometric security increases the risk of mass surveillance, loss of anonymity, and potential abuse of personal data by state and private actors. Constant tracking may erode privacy for all segments of society.
- security and fraud prevention: High impact (positive): Enhanced biometric identity systems dramatically reduce identity theft and improve fraud prevention across sectors such as air travel, banking, and government services, increasing trust and safety.
- accessibility and inclusivity: Medium impact (mixed): While biometric systems can streamline processes and improve accessibility for many, they

may exclude those whose biometric characteristics are difficult to capture or who lack official documentation (such as marginalized or disabled individuals), potentially deepening exclusion.

- gender and demographic disparities: Medium impact (mixed): Biometric systems may exhibit gender and ethnic bias due to underlying training data or design choices, leading to more frequent errors for women, transgender individuals, and ethnic minorities. This could both widen and expose existing social gaps if not addressed.
- well-being and convenience: High impact (positive): Increased convenience and reduced friction in travel, transactions, and border controls improve overall well-being and daily life satisfaction for most users, enabling faster access to services.
- economic and employment shifts: Medium impact (mixed): Automation of identity verification may reduce employment in traditional security, customs, or administration roles, requiring economic adaptation and reskilling but also opening new opportunities in tech, analysis, and oversight.

2.4 Digital Twin Airspace Simulation and Management

Use of high-fidelity digital twins—virtual replicas of airspace, assets, and operations—for real-time monitoring, simulation, and decision support, leading to smarter and safer airspace management.

2.4.1 Barriers:

- Data Integration and Interoperability: Digital Twin Airspace Simulation requires integrating diverse data sources from multiple systems and organizations. Lack of standardized data formats and protocols hinders seamless data exchange, leading to incomplete or inconsistent representations that impair simulation accuracy and decision support.
- High Computational and Infrastructure Requirements: Creating and running high-fidelity digital twins in real-time demands substantial computational power and advanced infrastructure. These requirements can limit scalability and increase costs, slowing down development and deployment for widespread airspace management applications.
- Regulatory and Privacy Concerns: Air transportation involves sensitive operational data, and the use of digital twins raises concerns about data privacy, security, and compliance with aviation regulations. Navigating complex regulatory landscapes can delay development and restrict data availability necessary for accurate simulations.
- Complexity of Modeling Real-World Airspace Dynamics: Accurately modeling the dynamic, stochastic nature of airspace with numerous interacting

entities (aircraft, weather, human controllers) is highly complex. Simplifying assumptions reduce fidelity, while complexity increases computational demands, challenging the creation of reliable and actionable digital twins.

- Stakeholder Collaboration and Adoption Challenges: The development and effective use of digital twin airspace systems require close cooperation among airlines, air traffic control, regulators, and technology providers. Divergent priorities, resistance to change, and lack of shared incentives can impede collaboration, slowing down innovation and adoption.

2.4.2 Enablers:

- Advanced Sensor and IoT Integration: Advanced Sensor and IoT Integration enables continuous and precise data collection from physical airspace elements, aircraft, and infrastructure. This real-time data is essential for creating accurate and dynamic digital twins, allowing simulations to closely mirror actual conditions and improve situational awareness and predictive capabilities.
- High-Performance Computing and Cloud Infrastructure: High-Performance Computing and Cloud Infrastructure provide the necessary computational power and scalability to process massive volumes of data and run complex simulations in real time. This ensures that digital twin environments can update instantly and support decision-making under high traffic and dynamic airspace conditions.
- Artificial Intelligence and Machine Learning Algorithms: Artificial Intelligence and Machine Learning Algorithms empower digital twins to analyze patterns, predict system behaviors, and optimize airspace management strategies autonomously. These technologies enable proactive risk management and smarter decision support, enhancing safety and efficiency in air transportation.
- Interoperability Standards and Data Sharing Protocols: Interoperability Standards and Data Sharing Protocols facilitate seamless integration and communication between diverse systems, stakeholders, and technologies within the air transportation ecosystem. These standards ensure that digital twins can aggregate and harmonize data from multiple sources, enabling cohesive and collaborative airspace management.
- Real-time Data Analytics and Visualization Tools: Real-time Data Analytics and Visualization Tools allow operators and decision-makers to intuitively access, interpret, and interact with the digital twin simulations. Effective visualization and analytical capabilities improve understanding of complex airspace dynamics and enhance timely, informed responses to emerging situations.

2.4.3 Stakeholders impacted:

- Air Traffic Controllers: Air Traffic Controllers will have access to real-time, high-fidelity data and simulations that enhance their situational awareness, enabling more precise and safer management of airspace traffic flows.
- Airlines: Airlines will benefit from improved operational efficiency and safety by utilizing predictive simulations for flight planning, avoiding congestion, and reducing delays and fuel consumption.
- Airport Authorities: Airport Authorities will be impacted by optimized airspace and ground operations coordination, leading to smoother arrivals and departures, better resource allocation, and enhanced safety.
- Regulatory Bodies: Regulatory Bodies will use digital twin data to develop more informed and adaptive policies and regulations that ensure the safety and efficiency of increasingly complex airspace environments.
- Aircraft Manufacturers: Aircraft Manufacturers can leverage digital twin simulations to test aircraft performance and integration within airspace scenarios, improving design and compliance with future operational requirements.
- Pilots: Pilots will experience enhanced decision-support through predictive modeling and real-time updates, improving safety and operational efficiency during flights.
- Airspace Management Organizations: Airspace Management Organizations will be able to optimize airspace design and utilization dynamically, improving capacity and reducing conflicts using continuous feedback from digital twins.
- Passengers: Passengers will indirectly benefit from safer, more efficient flights with fewer delays and smoother travel experiences due to better airspace and traffic management.
- Technology Providers: Technology Providers will be key enablers by developing and maintaining the software and hardware infrastructure needed for digital twin environments, driving innovation and new business opportunities.
- Emergency Services: Emergency Services will benefit from better situational awareness and coordinated response capabilities in the event of airborne emergencies or disruptions informed by real-time simulations.

2.4.4 Environmental impact:

- Greenhouse Gas Emissions: Digital Twin Airspace Simulation and Management can optimize aircraft flight paths and airspace operations, potentially reducing unnecessary fuel burn and improving efficiency. This can lead to a medium positive impact on greenhouse gas emissions by enabling lower

CO2 output per flight and reducing the total energy usage of the aviation sector.

- Resource Consumption and E-Waste: Developing and operating high-fidelity digital twin systems requires computing hardware, sensors, and data centers. While this increases energy and raw material consumption, the overall impact is low to medium—additional resource use is typically offset by improved operational efficiency and minimal compared to broader aviation impacts. However, increased reliance on digital systems will contribute to long-term e-waste unless responsibly managed.
- Plastic Pollution: The direct impact of digital twin technologies on plastic pollution is very low. Their operation does not involve significant plastic consumption or disposal, although there is a minor indirect impact related to the production and disposal of electronic devices and sensors.
- Air Quality: By enabling more efficient and predictable airspace management, digital twin systems can decrease congestion and traffic bottlenecks, reducing localized spikes in air pollution (NOx, particulates) around airports. The impact is positive and likely low to medium, depending on implementation scale.
- Noise Pollution: Optimized routing and traffic management can lead to more consistent and possibly slightly reduced noise footprints near airports and populated areas. While not a major shift, the impact is positive and low.
- Ecosystem Disturbance: With better real-time awareness and scenario simulation, flight paths can be adjusted to avoid sensitive habitats and protected areas more effectively. This can mitigate some ecosystem disturbance from noise and air traffic, representing a low but positive impact.

2.4.5 Societal impacts:

- Safety and Security: High positive impact: Digital twin airspace simulations enable real-time risk assessment and predictive analytics, resulting in safer skies by reducing accidents and optimizing responses to emergencies.
- Environmental Sustainability: Medium positive impact: Digital twins facilitate optimized flight paths and airspace management, decreasing fuel consumption and emissions, which helps combat climate change and improves air quality.
- Economic Opportunity: High positive impact: Advanced airspace management creates new jobs in data science, software engineering, simulation, and analytics, fostering economic growth, though it may also disrupt certain traditional roles in air navigation.
- Workforce and Skills: Medium impact (positive and negative): The shift toward digital-centric roles enhances demand for tech-savvy workers but

may increase skill gaps and require substantial retraining for those in conventional aviation jobs.

- Gender Gap: Low to medium impact (potentially positive): While the trend itself is gender-neutral, there is a risk that without intentional efforts, the underrepresentation of women and minorities in tech fields could persist, reinforcing existing disparities if access to upskilling and employment isn't made equitable.
- Well-being and Quality of Life: High positive impact: Improved efficiency, fewer delays, greater reliability, and safer skies enhance overall passenger experience and quality of life for professionals and travelers alike.
- Privacy and Data Concerns: Medium negative impact: Increased reliance on digital data and simulation tools raises concerns about data privacy, potential surveillance, and the risk of cyber-attacks affecting critical infrastructures.

2.5 Biodegradable and Smart Aircraft Materials

Implementation of advanced biodegradable and smart materials in aircraft manufacturing that self-heal, adapt to environmental conditions, and reduce overall environmental impact.

2.5.1 Barriers:

- Material Performance and Durability: Biodegradable and smart materials must meet stringent performance and durability standards under extreme aerospace conditions, such as variations in temperature, pressure, and mechanical stress. Failure to achieve consistent reliability limits their adoption in safety-critical air transportation systems.
- High Development and Certification Costs: Developing new biodegradable and smart materials requires significant investment in research, prototyping, and certification, which increases costs. This financial barrier restricts innovation and delays integration into mainstream aircraft manufacturing.
- Lack of Established Manufacturing Processes: Current manufacturing processes are optimized for traditional aerospace materials like aluminum and composites. The introduction of biodegradable and smart materials demands the creation of new, often complex manufacturing techniques that are not yet mature, slowing down production scalability.
- Limited Availability of Suitable Biodegradable Components: Biodegradable materials suitable for aerospace use must balance environmental benefits with mechanical and thermal properties. However, sourcing raw materials that provide this balance at scale is challenging, restricting the consistent supply chain needed for large-scale air transportation applications.

- Regulatory and Safety Certification Challenges: Aircraft materials must undergo rigorous regulatory and safety certifications before implementation. Existing certification frameworks are not yet fully adapted for biodegradable and smart materials, creating lengthy and uncertain approval processes that hinder their timely development and deployment.

2.5.2 Enablers:

- Advanced Material Science and Nanotechnology: Advances in material science and nanotechnology enable the creation of biodegradable polymers and smart composites that possess self-healing, adaptive, and environmentally friendly properties, directly impacting the effectiveness and feasibility of these materials in aircraft applications.
- Sustainable Supply Chain and Raw Materials: Developing a sustainable supply chain for bio-based raw materials ensures consistent, eco-friendly sourcing that reduces reliance on fossil fuels and supports the large-scale production of biodegradable and smart materials needed for aircraft manufacturing.
- Innovative Manufacturing Techniques: Innovative manufacturing techniques, such as additive manufacturing and advanced molding processes, allow precise fabrication and integration of smart materials into complex aircraft structures while maintaining performance and sustainability standards.
- Regulatory Support and Certification Framework: Supportive regulatory frameworks and streamlined certification processes encourage the adoption of novel biodegradable and smart materials by ensuring safety, reliability, and environmental compliance within the stringent aviation industry requirements.
- Cross-disciplinary Research and Industry Collaboration: Cross-disciplinary collaboration between academia, industry, and government enables knowledge sharing, accelerates innovation cycles, and pools resources to overcome technical challenges, thereby fostering the development and implementation of these advanced materials in air transportation.

2.5.3 Stakeholders impacted:

- Aircraft Manufacturers: Aircraft manufacturers will need to innovate their design and production processes to integrate biodegradable and smart materials, affecting manufacturing costs, supply chains, and aircraft performance.
- Airlines: Airlines will benefit from reduced aircraft weight and fuel consumption, potentially lowering operational costs and emissions, but will also face new maintenance protocols related to smart materials.

- Passengers: Passengers may experience safer, more reliable flights with environmentally friendly aircraft options, and could also influence demand for greener travel solutions.
- Regulatory Authorities: Regulatory authorities must update and enforce aviation safety and environmental regulations to accommodate new material certifications and usage standards.
- Material Suppliers: Material suppliers will be impacted through the development and supply of new biodegradable and smart material technologies, requiring investments in advanced manufacturing capabilities.
- Maintenance and Repair Organizations: Maintenance and repair organizations will need to develop new expertise and tools to repair and maintain smart materials that can self-heal or adapt, changing traditional maintenance workflows.
- Environmental Organizations: Environmental organizations will have a stake in promoting and monitoring the reduction of aerospace environmental impacts enabled by biodegradable and adaptive aircraft materials.
- Research and Development Institutions: Research and development institutions will be heavily involved in advancing material science, testing new materials, and innovating applications within the aerospace sector.
- Government and Policy Makers: Government and policy makers will influence funding, incentives, and regulations that can accelerate or slow adoption of these new materials in aviation to meet sustainability goals.
- Investors and Shareholders: Investors and shareholders will be impacted by the economic potential and risks associated with the adoption of emerging biodegradable and smart materials technologies in air transportation.

2.5.4 Environmental impact:

- Greenhouse Gas Emissions: The use of biodegradable and smart materials may reduce greenhouse gas emissions associated with manufacturing, maintenance, and end-of-life disposal. Self-healing materials can decrease the need for frequent repairs and replacements, leading to lower emissions over time. This impact is positive and potentially medium to high, depending on adoption scale and degree of lifecycle emissions reductions.
- Plastic Pollution: Traditional aircraft materials, especially composites and plastics, contribute to persistent plastic pollution upon disposal. Biodegradable materials break down more easily and are less likely to contribute to long-term environmental contamination. This impact is positive and of high significance, as it addresses one of the main sources of plastic waste in aviation.

- Resource Consumption: Smart materials can optimize resource consumption by reducing material needs (through self-healing and adaptive properties) and prolonging component lifespans. Biodegradable inputs can also decrease dependency on petroleum-based plastics and toxic chemicals. Positive impact, with medium level if widely adopted.
- Aircraft Lifespan and Waste: Shorter aircraft lifespans can create significant waste. Smart, self-healing, and robust biodegradable materials may extend the usable lifespans of aircraft components, decreasing waste production and improving the sustainability of end-of-life processes. This is a positive impact, with medium significance.
- Operational Efficiency: Lightweight smart materials may improve fuel efficiency through reduced aircraft weight, thereby lessening operational environmental impacts, such as fuel use and emissions. This has a positive impact of medium magnitude, depending on the degree of weight reduction achieved and the corresponding fuel savings.

2.5.5 Societal impacts:

- Environmental Sustainability: The use of biodegradable and smart aircraft materials will significantly reduce the environmental footprint of the aviation industry by minimizing waste and lowering emissions. This has a high positive impact, supporting global climate goals.
- Economic Impact and Job Creation: Advancements in aircraft materials are likely to stimulate new industries and job roles, especially in material science and maintenance of smart materials. The economic impact is medium to high and mostly positive, with possible short-term transitional challenges for traditional manufacturing workers.
- Well-being and Public Health: Reduced pollution and safer, self-healing aircraft will improve the health and well-being of passengers, crew, and populations near major airports. This impact is medium and positive.
- Gender Gap in STEM and Manufacturing: The push for new skills in engineering and materials science may widen the gender gap unless deliberate efforts are made to encourage women and underrepresented groups in STEM and advanced manufacturing fields. This is a medium, mixed impact, with the risk of negative outcomes without intervention.
- Accessibility and Air Mobility: More sustainable aircraft could lead to expanded air mobility options, increasing accessibility for remote regions and populations, thereby promoting social and economic inclusion. This is a medium to high, positive impact.
- Long-term Societal Trust in Technology: The successful adoption of smart, self-healing materials in aviation may increase societal trust in advanced

technologies and automation, reducing fear of flying and fostering acceptance of further innovations. This is a medium, positive impact.

2.6 Unmanned Freight and Cargo Drones

Large-scale introduction of unmanned drones for freight and cargo, enhancing logistics efficiency, especially for last-mile delivery and remote area supply, while reducing road congestion.

2.6.1 Barriers:

- Regulatory and Legal Challenges: Regulatory and Legal Challenges: The lack of clear, harmonized regulations governing unmanned freight drones restricts their widespread adoption. Governments need to establish airspace rules, certification processes, and liability frameworks, which impacts the deployment speed and operational scalability.
- Technology and Reliability Limitations: Technology and Reliability Limitations: Current drone technology still faces limitations in battery life, payload capacity, and autonomous navigation under varying weather conditions. These technical constraints hinder the ability to operate large-scale, reliable freight delivery services, affecting efficiency and cost-effectiveness.
- Air Traffic Management Integration: Air Traffic Management Integration: Integrating unmanned drones safely into existing air traffic systems poses significant challenges. Without robust systems for drone traffic management and collision avoidance, the risk of airspace congestion and accidents increases, slowing regulatory approval and operational expansion.
- Safety and Security Concerns: Safety and Security Concerns: Ensuring the safety of people and property on the ground, as well as protecting drones from hacking or malicious use, is a critical barrier. These issues require advanced security measures, increasing development costs and creating operational risks.
- Public Acceptance and Privacy Issues: Public Acceptance and Privacy Issues: Public concerns regarding noise, visual pollution, and data privacy can lead to resistance against drone operations. Negative public perception may result in stricter regulations and limit deployment, especially in densely populated areas.

2.6.2 Enablers:

- Advanced Autonomous Navigation Systems: Advanced autonomous navigation systems allow unmanned freight drones to operate safely and efficiently without human intervention, enabling reliable route planning, obstacle detection, and adaptive responses to changing environmental conditions, which are critical for large-scale deployment.

- Regulatory Frameworks and Airspace Integration: Regulatory frameworks and airspace integration establish the legal, safety, and operational guidelines necessary for unmanned drones to coexist with manned aircraft and other airspace users, thus facilitating authorization, risk management, and public acceptance essential for commercial operation.
- Battery and Energy Storage Technologies: Battery and energy storage technologies impact the flight duration, payload capacity, and operational cost of freight drones; improvements in these areas enable longer trips, heavier loads, and reduced recharge times, directly enhancing the feasibility and economic viability of drone logistics.
- Robust Communication and Control Networks: Robust communication and control networks ensure continuous and secure data exchange between drones, operators, and traffic management systems, supporting real-time monitoring, remote control capabilities, and coordinated swarm operations critical for safe and efficient drone traffic management.
- Cost-effective Manufacturing and Scalability: Cost-effective manufacturing and scalability reduce the production costs and increase the availability of drones, allowing logistics providers to deploy large fleets economically, fostering competition and innovation, and accelerating widespread adoption in the cargo transportation sector.

2.6.3 Stakeholders impacted:

- Logistics and Delivery Companies: Logistics and Delivery Companies will be impacted as unmanned freight drones introduce new delivery capabilities and efficiencies, reducing costs and enabling faster last-mile delivery, especially to remote or congested areas.
- Consumers: Consumers will experience faster, more reliable deliveries and potentially lower shipping costs due to the increased efficiency and automation of drone-based freight systems.
- Regulatory Authorities: Regulatory Authorities will need to develop and enforce new rules and frameworks to safely integrate unmanned drones into existing airspace, addressing concerns about safety, privacy, and air traffic management.
- Drone Manufacturers and Technology Providers: Drone Manufacturers and Technology Providers will see increased demand for their products and innovations, driving growth and advancing technologies in UAV design, navigation, and safety systems.
- Urban Planners and Local Governments: Urban Planners and Local Governments will be affected as they adapt city infrastructure and logistics frameworks to accommodate drone delivery corridors, landing zones, and noise management.

- Traditional Freight and Transportation Workers: Traditional Freight and Transportation Workers may face job displacement or need to reskill as automation changes the logistics labor market, particularly in last-mile delivery roles.
- Environmental Organizations: Environmental Organizations might be impacted positively due to the potential reduction in road traffic emissions and congestion, but also concerned with the environmental footprint of drone production and operation.
- Insurance Companies: Insurance Companies will need to develop new models for risk assessment and coverage as drones introduce different liability and operational risks compared to traditional freight transport.
- Retailers and E-commerce Businesses: Retailers and E-commerce Businesses stand to benefit from enhanced delivery speed and flexibility provided by drones, improving customer satisfaction and expanding market reach especially in underserved areas.
- Telecommunication Providers: Telecommunication Providers will be impacted as drones require reliable, high-bandwidth communication networks for control, navigation, and real-time data transmission, potentially driving investments in 5G and beyond.

2.6.4 Environmental impact:

- Greenhouse Gas Emissions: Deployment of battery-powered drones may decrease emissions compared to fossil-fueled trucks, but large drone networks require substantial electricity, which may be from non-renewable sources. Overall impact: medium, with potential for positive outcomes if renewable energy is used.
- Noise Pollution: Drones, especially large or numerous ones, generate high-frequency noise, potentially disturbing both urban and rural environments. Overall impact: medium, generally negative.
- Wildlife Disturbance: Increased drone traffic increases collision risk with birds and other wildlife, potentially disrupting habitats and migration. Overall impact: medium, negative.
- Plastic and Electronic Waste: Manufacturing, maintaining, and disposing of drones introduces additional plastic, lithium batteries, and electronic components, some of which may not be recycled. Overall impact: medium, negative.
- Energy Consumption: Fleet operation demands high energy input; if sourced sustainably, impact is limited. However, increased total delivery capacity may raise net energy usage. Overall impact: medium, mixed.
- Reduction in Road Congestion: Replacing trucks or vans with delivery

drones can reduce road congestion, leading to secondary environmental benefits such as lower urban air pollution. Overall impact: low to medium, positive.

2.6.5 Societal impacts:

- Economic Impact: The large-scale deployment of unmanned freight and cargo drones is expected to reduce logistics costs and increase efficiency, resulting in significant positive economic impact (high). Businesses may benefit from faster delivery and reduced overhead, but small logistics companies may face new competition.
- Employment Disruption: Automation of cargo transport could displace traditional jobs in trucking, delivery, and warehousing, causing negative short-term employment disruption (high). In the long run, new jobs in drone operations and maintenance may appear, but these may require different skill sets.
- Gender Gap: Since traditional freight and logistics roles are often male-dominated, job displacements may disproportionately affect men, possibly narrowing gender gaps in entry-level logistics jobs (medium). However, new high-skill drone-related jobs may not be as accessible to underrepresented groups without targeted training and inclusion efforts, potentially aggravating the tech industry gender gap.
- Environmental Impact: Drones have the potential to reduce road congestion and lower emissions if their energy use is optimized, offering a potential environmental benefit (medium to high). However, increased drone activity could introduce new environmental concerns such as noise pollution and wildlife disturbance.
- Access to Goods and Services: Unmanned cargo drones can improve access to essential goods and medical supplies in remote or underserved regions, having a positive impact on social equity and public health (medium). Reliable access can reduce disparities between urban and rural communities.
- Urban and Rural Well-being: Urban areas may experience increased well-being through faster deliveries and less road traffic, rated as a moderate positive impact. Rural and isolated communities stand to gain a high positive impact from improved supply chains and accessibility.
- Safety and Security: While automation may reduce human errors in freight transport, potential malfunction, cybersecurity threats, and drone-related accidents could pose new safety and security risks to communities (medium negative impact) if not properly managed.

2.7 On-Demand, Personalized Air Travel

Rise of on-demand, personalized air travel options, such as air taxis, scheduled charters, and custom flight experiences, providing more flexible and direct connections between destinations.

2.7.1 Barriers:

- Regulatory and Certification Challenges: Regulatory and Certification Challenges: On-demand personalized air travel involves new types of aircraft, such as air taxis and VTOLs, which require novel regulatory frameworks and certification processes. These can be lengthy and complex, delaying market entry and scaling while ensuring safety and compliance.
- Infrastructure Limitations: Infrastructure Limitations: Current airport and urban infrastructure is not adequately equipped to support widespread on-demand air travel, lacking sufficient vertiports, charging stations, and maintenance hubs. This limits operational feasibility and service reach.
- High Operational Costs: High Operational Costs: Personalized air travel often involves smaller fleets and higher per-flight costs compared to conventional airlines. Limited economies of scale, maintenance of advanced technology, and energy costs can make price points less accessible to broad customer bases.
- Safety and Public Acceptance: Safety and Public Acceptance: New flight modes and technologies require public trust in their safety. Any incidents or perceived risks can significantly hinder acceptance, slowing user adoption and investment in the sector.
- Airspace Integration and Traffic Management: Airspace Integration and Traffic Management: Integrating a large number of individualized flights into existing controlled airspace creates complexity for air traffic management systems, increasing the risk of congestion and requiring advanced solutions to ensure efficient and safe operations.

2.7.2 Enablers:

- Advanced Autonomous and Electric Vertical Takeoff and Landing (eVTOL) Technology: The advancement of autonomous and electric VTOL aircraft drastically reduces operating costs, noise, and emissions, enabling scalable on-demand air travel options like air taxis. This technology allows for vertical takeoff and landing in compact urban spaces, facilitating direct and flexible connections.
- Robust Digital Booking and Scheduling Platforms: Digital booking and scheduling platforms integrate real-time availability, dynamic pricing, and seamless payments, making it easier for customers to book personalized

flights on demand. These platforms enable operational efficiency and responsiveness to fluctuating customer demand patterns.

- Regulatory Frameworks and Air Traffic Management Integration: Clear and adaptive regulatory frameworks combined with modernized air traffic management allow safe integration of new types of aircraft and flights into existing airspace. This fosters trust and accelerates commercial deployment by ensuring compliance with safety standards and efficient flight routing.
- Development of Urban Air Mobility Infrastructure: The creation of vertiports, charging stations, and maintenance hubs strategically located within urban and regional areas supports operational readiness and convenience. Infrastructure development enhances network connectivity and reduces ground transit times, boosting the appeal of personalized air travel.
- Data-Driven Personalization and AI-Driven Customer Experience: Leveraging big data and AI enables highly personalized travel experiences by analyzing customer preferences, optimizing flight routes, and predicting demand. This improves customer satisfaction and operational efficiency, driving adoption of on-demand air travel services.

2.7.3 Stakeholders impacted:

- Passengers: Passengers will benefit from customizable travel options that provide greater convenience, direct routing, time savings, and enhanced user experience tailored to individual preferences.
- Airlines: Airlines may face competition from personalized air travel providers but can also collaborate or integrate on-demand services to offer hybrid travel solutions and improve customer loyalty.
- Air Taxi Operators: Air Taxi Operators will be directly impacted as their business models revolve around providing flexible and personalized air mobility, requiring adaptation to growing demand and evolving customer expectations.
- Airport Authorities: Airport Authorities will need to adjust infrastructure and operations to accommodate on-demand and smaller aircraft, managing new types of traffic and ensuring smooth integration within airspace and ground services.
- Regulators and Government Agencies: Regulators and Government Agencies will need to develop and enforce new safety, security, operational, and air traffic control regulations suited for on-demand, personalized air travel models.
- Aircraft Manufacturers: Aircraft Manufacturers will be challenged to innovate and design new types of aircraft, such as electric vertical takeoff and landing (eVTOL) vehicles, optimized for personalized and flexible air travel.

- Technology Providers: Technology Providers will play a critical role by supplying advanced software, booking platforms, navigation systems, and communication tools essential for enabling personalization and efficiency.
- Local Communities: Local Communities may experience changes in noise levels, traffic patterns, and economic opportunities due to increased air taxi activity and related developments in personalized air travel.
- Insurance Companies: Insurance Companies will need to adapt policies and pricing models to cover new risks associated with on-demand air travel, including new vehicle types and flexible operation patterns.
- Travel Agencies and Platforms: Travel Agencies and Platforms will expand their service offerings to include personalized and on-demand air travel options, creating new opportunities for customer engagement and tailored travel packages.

2.7.4 Environmental impact:

- Greenhouse Gas Emissions: HIGH (Negative): On-demand, personalized air travel (e.g., air taxis and small charters) will likely increase the total number of short, less-efficient flights with fewer passengers per trip. This raises overall greenhouse gas (GHG) emissions per passenger-kilometer compared to commercial aviation or ground transport, thereby worsening the greenhouse effect.
- Noise Pollution: MEDIUM (Negative): Increased frequency of flights, especially in urban areas, will elevate noise pollution. This impacts local communities and wildlife in ways that are generally worse than current commercial air traffic patterns.
- Plastic and Material Waste: MEDIUM (Negative): Personalized air services may increase demand for single-use plastics (water bottles, food packaging, cleaning products) and disposable service items onboard, plus increased waste from maintenance (oil, filters, packaging). While offset by some high-end, reusable alternatives in luxury segments, overall waste generation is expected to rise.
- Land Use and Infrastructure: LOW to MEDIUM (Negative): Developing infrastructure for personalized air travel, such as new vertiports, helipads, and support facilities, will require additional land use, potentially impacting urban or semi-urban green spaces and ecosystems.
- Air Quality: LOW to MEDIUM (Negative or Neutral): Air quality may worsen locally around new take-off/landing points due to increased emissions at low altitudes, especially if propulsion technologies remain fossil fuel-based. However, if widely electrified, the net effect could be less pronounced or even neutral, depending on the grid energy mix.

2.7.5 Societal impacts:

- Accessibility: On-demand, personalized air travel can increase accessibility for people living in remote or underserved regions by providing direct connections; impact level: medium, positive for underserved areas but may be limited by costs.
- Environmental Impact: Greater use of small aircraft and frequent flights could increase carbon emissions and airspace congestion unless electric or sustainable aviation technologies are widely adopted; impact level: medium, potentially negative unless mitigated by green innovation.
- Economic Inequality: If primarily affordable by the wealthy, these services could intensify economic inequality, as privileged groups gain new mobility advantages; impact level: high, negative.
- Well-Being and Productivity: Easier access to travel could enhance personal well-being, reduce stress associated with traditional travel, and increase productivity by saving time; impact level: medium, positive.
- Urban and Regional Development: New air mobility solutions may reshape urban planning, reduce roadway congestion, and revitalize certain areas, but could also lead to noise pollution and zoning conflicts; impact level: medium, mixed.
- Gender Gap: If services are biased by design or price, gender gaps in access to personal air travel may widen due to differences in income and mobility needs; however, well-designed, inclusive services could narrow gaps; impact level: low to medium, potentially positive or negative depending on implementation.

2.8 Integration of Remotely Piloted Aircraft Systems (RPAS)

Wider integration of remotely piloted and autonomous aircraft into commercial airspace, ensuring safe coordination among manned, remotely piloted, and fully autonomous vehicles.

2.8.1 Barriers:

- Regulatory and Certification Challenges: The evolving nature of regulations and lack of standardized certification processes for RPAS create uncertainty and delay widespread adoption in commercial airspace. Without clear regulatory frameworks, manufacturers and operators face difficulties in compliance, slowing integration efforts.
- Airspace Management and Traffic Integration: Integrating RPAS with existing manned aircraft traffic requires advanced airspace management systems and protocols to prevent conflicts and ensure safe coordination.

Inadequate infrastructure and coordination mechanisms could lead to increased risk of mid-air collisions or operational inefficiencies.

- Safety and Reliability Concerns: Ensuring RPAS perform reliably under variable environmental conditions and technical failures is critical. Concerns about system failures or loss of control limit trust in RPAS operations, which affects both regulatory approval and operator willingness to deploy these systems.
- Cybersecurity Risks: Remotely piloted and autonomous aircraft are vulnerable to cyberattacks that could compromise control systems or data integrity. Insufficient cybersecurity measures increase the risk of malicious interventions, threatening both safety and privacy and hindering development and acceptance.
- Public Acceptance and Privacy Issues: Public apprehension about privacy invasion and safety risks associated with widespread RPAS operations can lead to resistance and restrictive policies. Gaining public trust is essential to allow these systems to be accepted and integrated broadly into commercial airspace.

2.8.2 Enablers:

- Advanced Air Traffic Management Systems: Advanced Air Traffic Management Systems are essential to safely integrate RPAS by coordinating the operations of manned and unmanned aircraft in shared airspace, enabling real-time tracking, conflict detection, and dynamic re-routing to prevent collisions.
- Regulatory Framework and Standardization: Regulatory Framework and Standardization provide clear rules and guidelines, harmonizing operations internationally. This fosters trust, defines responsibilities, certification processes, and compliance requirements critical for operational safety and scalability of RPAS flights.
- Robust Communication and Data Link Technologies: Robust Communication and Data Link Technologies ensure reliable and secure control and telemetry between RPAS and ground control stations, even in congested or remote areas, which is vital to maintain continuous command, monitoring, and quick response to contingencies.
- Enhanced Sense-and-Avoid Systems: Enhanced Sense-and-Avoid Systems equip RPAS with the capability to detect and autonomously avoid obstacles, other aircraft, and dynamic hazards, significantly increasing operational safety and enabling beyond-visual-line-of-sight (BVLOS) missions essential for commercial integration.
- Public Acceptance and Stakeholder Collaboration: Public Acceptance and Stakeholder Collaboration foster a societal and industry environment

supportive of RPAS. Engaging communities, industry partners, and authorities helps address privacy, safety concerns, and operational integration challenges, which is crucial for widespread adoption.

2.8.3 Stakeholders impacted:

- Regulatory Authorities: Regulatory Authorities will be impacted as they need to create, adapt, and enforce policies and regulations to ensure the safe integration of RPAS in shared airspace, balancing innovation with safety and privacy concerns.
- Air Traffic Management Organizations: Air Traffic Management Organizations must incorporate RPAS into existing traffic control systems, requiring upgrades in infrastructure and protocols to safely coordinate between manned and remotely piloted aircraft.
- Commercial RPAS Operators: Commercial RPAS Operators will be directly affected in terms of operational permissions, flight planning, and compliance with new airspace rules, impacting their business models and service delivery methods.
- Manned Aircraft Pilots: Manned Aircraft Pilots face operational and safety challenges due to increased traffic of RPAS in shared airspace, demanding heightened situational awareness and collaboration with remotely piloted vehicles.
- Technology Developers and Manufacturers: Technology Developers and Manufacturers will be driven to innovate and produce reliable, safe, and interoperable RPAS systems and associated technologies that meet regulatory and operational requirements.
- Local Communities: Local Communities will experience changes related to privacy, noise, and safety as RPAS operations become more common in urban and rural settings, necessitating public engagement and impact mitigation.
- Logistics and Delivery Companies: Logistics and Delivery Companies stand to benefit from enhanced efficiency but will also need to adapt to regulatory frameworks and invest in RPAS technology for last-mile delivery solutions.
- Military and Defense Agencies: Military and Defense Agencies will be impacted through expanded use of RPAS for surveillance, reconnaissance, and tactical operations, necessitating integration with civilian airspace management to avoid conflicts.
- Insurance Companies: Insurance Companies will need to develop new risk assessment models and insurance products addressing the unique liability and damage issues posed by remotely piloted aircraft.
- Emergency Services and Public Safety Organizations: Emergency Services

and Public Safety Organizations may leverage RPAS for faster response and monitoring capabilities but will also need to coordinate with other airspace users and ensure operational safety.

2.8.4 Environmental impact:

- Greenhouse Gas Emissions: The integration of Remotely Piloted Aircraft Systems (RPAS) could reduce greenhouse gas emissions if drones replace less efficient ground vehicles or larger aircraft for some transportation tasks, but could also increase emissions if they stimulate more total flights or if they rely on non-renewable energy sources. Overall, the impact level is likely low to medium, depending on the scale and energy source.
- Noise Pollution: Noise pollution from RPAS is generally lower than from conventional aircraft, but widespread use, especially in low-altitude urban environments, could become a nuisance and negatively affect human and animal populations. Impact level: low to medium.
- Plastic and Electronic Waste: The manufacture and eventual disposal of RPAS will add to plastic and electronic waste, especially if drones are produced and deployed at scale. Batteries, circuit boards, and composite materials present particular challenges for recycling, indicating a medium level of negative impact unless recycling practices are improved.
- Wildlife Disturbance: RPAS operating at low altitudes could disturb wildlife, particularly birds, through noise, physical presence, or collisions. The scale of this impact depends on usage patterns, but in sensitive habitats, impact could be medium.
- Energy Use: Increased use of RPAS will consume electricity (for electric drones) or fuel (for combustion drones). If energy is sourced from renewables, the impact is lower; if not, there are further indirect environmental effects. Impact is likely low to medium overall.

2.8.5 Societal impacts:

- economic transformation: Widespread integration of RPAS will significantly change logistics, agriculture, inspection, and delivery sectors, leading to high economic impact. New markets will emerge and traditional business models may be disrupted.
- employment and skills gap: There will be a medium to high impact on jobs: some traditional piloting and logistics jobs may be automated, but new roles in drone operation, maintenance, traffic management, and data analysis will be created. A skills gap may emerge, requiring workforce retraining.
- gender gap: The technology industry, including RPAS, is currently male-dominated. Without policy intervention or targeted training, the gender

gap could widen as RPAS jobs increase. Upskilling programs and STEM education targeting underrepresented genders can mitigate this impact (medium impact).

- privacy and surveillance: The increased use of RPAS raises privacy and surveillance concerns, as drones can collect large amounts of image and sensor data. Societal debates and new regulations will be necessary to balance innovation with personal privacy (high impact).
- public safety: RPAS can increase public safety through faster emergency response and safer inspection, but system failures or misuse could cause new safety issues in crowded urban environments. The overall impact is medium, depending on effective regulation and technology robustness.
- environmental impact: Drones may reduce the carbon footprint of logistics (positive, medium impact) but increase electronic waste or noise pollution if not managed. The net environmental impact can range from low to medium depending on implementation.
- well-being and accessibility: RPAS can improve accessibility in remote areas, delivering medical supplies or enhancing mobility for underserved populations, thus supporting well-being (medium to high positive impact).

2.9 Advanced U-Space and UAS Traffic Management

Advanced U-Space and UAS traffic management systems to ensure safe, efficient, and scalable integration of drones—both commercial and recreational—into urban and rural airspace.

2.9.1 Barriers:

- Regulatory and Standardization Challenges: The lack of harmonized regulations and international standards hinders the widespread deployment of Advanced U-Space and UAS traffic management systems. Differing rules between regions cause delays and increase costs, limiting scalability and interoperability of drone operations across borders.
- Technological Limitations: Current technology is still evolving, particularly in areas like reliable detect-and-avoid systems, real-time communication, and low-latency data processing. These limitations restrict the ability to safely manage high volumes of drones, thus delaying full operational capability and integration.
- Airspace Complexity and Integration: Integrating UAS traffic with manned aviation and existing air traffic management systems presents significant complexity. The airspace is already congested and controlled with strict rules, so incorporating autonomous drones requires sophisticated coordination to avoid conflicts and ensure safety.

- Data Security and Privacy Concerns: Handling vast amounts of data from multiple drone operators raises concerns about protecting sensitive information and ensuring secure communication links. Cybersecurity vulnerabilities could lead to malicious interference or data breaches, undermining trust in the system and potentially causing accidents or disruptions.
- Public Acceptance and Ethical Issues: Wide-scale adoption depends on public trust and ethical acceptance, including noise pollution, privacy intrusion, and safety fears. Negative public perception or opposition from local communities can result in restrictive policies or bans, limiting the deployment and development of U-Space systems.

2.9.2 Enablers:

- Robust Communication and Data Exchange Infrastructure: Robust communication and data exchange infrastructure is critical for real-time coordination between drones, U-Space service providers, and air traffic controllers. This infrastructure enables reliable transmission of telemetry, position, and mission data to ensure situational awareness and safety in increasingly congested airspace.
- Advanced Sense-and-Avoid Technologies: Advanced sense-and-avoid technologies allow unmanned aerial systems (UAS) to autonomously detect and evade obstacles, other aircraft, and restricted zones. These capabilities are essential to prevent mid-air collisions and ensure safe operations without continuous human intervention.
- Regulatory Frameworks and Standardization: A clear and harmonized regulatory framework combined with standardized protocols facilitates safe and predictable drone operations across jurisdictions. Regulations define the rules of the air, airspace classes, and operational limits, which are essential for broad adoption and public acceptance.
- Integration with Existing Air Traffic Management (ATM) Systems: Seamless integration with existing Air Traffic Management systems is necessary to coordinate manned and unmanned aircraft safely. This integration allows shared situational awareness and conflict management, enabling drones to operate alongside traditional aviation safely.
- Scalable Automated Traffic Management Platforms: Scalable automated traffic management platforms provide the capability to handle large numbers of drone flights simultaneously by automating flight authorization, traffic deconfliction, and dynamic rerouting. This scalability is key to supporting growth in commercial, delivery, and recreational drone uses within controlled airspace.

2.9.3 Stakeholders impacted:

- Regulatory Authorities: Regulatory Authorities will be impacted as they need to develop, implement, and enforce new rules and standards to manage the increased drone traffic safely and efficiently within shared airspace.
- Commercial Drone Operators: Commercial Drone Operators will experience changes in operational frameworks, requiring integration with UAS Traffic Management systems for compliance, flight authorization, and optimized route planning to scale their services.
- Recreational Drone Users: Recreational Drone Users will face new guidelines and potentially restricted zones, requiring awareness and adherence to U-Space protocols to ensure safety and avoid conflicts with other airspace users.
- Air Traffic Control Organizations: Air Traffic Control Organizations will need to collaborate with UAS Traffic Management systems to maintain safe separation between manned and unmanned aircraft, adapting existing control processes to accommodate drone traffic.
- Urban Planners and Local Governments: Urban Planners and Local Governments will be affected as drone activity influences city infrastructure planning, noise management, and public space utilization, requiring coordination on airspace allocations and use policies.
- Manufacturers and Technology Providers: Manufacturers and Technology Providers will need to innovate and supply compatible hardware and software solutions that integrate seamlessly with Advanced U-Space systems, enabling compliance and enhancing safety features.
- Logistics and Delivery Companies: Logistics and Delivery Companies will leverage UAS Traffic Management to improve efficiency and reliability of drone-based delivery services, requiring integration for real-time flight approval and tracking.
- Emergency Response and Public Safety Agencies: Emergency Response and Public Safety Agencies will benefit from improved airspace management to deploy drones effectively for search, rescue, surveillance, and disaster response while ensuring coordination with other airspace users.
- General Aviation Pilots: General Aviation Pilots will be impacted as they must adapt to a more congested airspace environment, requiring increased situational awareness and communication protocols to avoid conflicts with UAS operations.
- Telecommunication Providers: Telecommunication Providers will play a critical role by providing the communication networks and infrastructure necessary to support real-time data exchange and connectivity critical for UAS Traffic Management functionality.

2.9.4 Environmental impact:

- greenhouse_gas_emissions: Greenhouse Gas Emissions: The widespread adoption of drones managed by Advanced U-Space and UAS Traffic Management (UTM) may lead to reduced reliance on traditional fossil-fuel vehicles for certain logistics and delivery tasks, possibly cutting emissions in some sectors. However, the aggregate increase in drone flights—especially if powered by non-renewable electricity—could still add to overall emissions. The net greenhouse effect is expected to be low to medium but can be positive or negative depending on energy sourcing.
- noise_pollution: Noise Pollution: Increased drone traffic may introduce new sources of persistent noise, particularly in urban or suburban environments. The impact is generally considered negative and can reach medium levels, especially if large numbers of drones operate simultaneously.
- wildlife_disturbance: Wildlife Disturbance: More frequent low-altitude drone operations increase the chance of disturbing birds and other wildlife, potentially affecting habitats and behavioral patterns. This impact is negative and medium in scale, especially in rural and sensitive environments.
- plastic_and_electronic_waste: Plastic and Electronic Waste: Drones, sensors, and supporting infrastructure contain plastic and electronic components. Mass production and frequent upgrades or replacements may generate additional waste streams if proper recycling systems are not established. This negative impact is expected to be medium.
- resource_consumption: Resource Consumption: The manufacturing, deployment, and maintenance of drones and UTM infrastructure require additional raw materials (metals, rare earths, plastics, etc.). Although less than for larger vehicles, scale effects could add up to a medium impact, primarily negative.
- potential_urban_heat_reduction: Potential Urban Heat Reduction: Delivery drones may reduce the number of delivery trucks and vans, which contribute to urban heat through idling engines. If drone systems offset some ground vehicle usage, there may be a small positive impact on reducing urban heat, though the overall impact is likely low.

2.9.5 Societal impacts:

- Economic Impact: Advanced U-Space and UAS Traffic Management will expand markets such as drone delivery, inspection, and new types of businesses, likely having a high positive economic impact by creating new jobs and industries, though it may disrupt some traditional sectors.
- Well-being and Quality of Life: The integration of drones can improve well-being with faster emergency service delivery (like medical supplies),

reduced congestion, and enhancements in urban mobility—a high positive impact for public quality of life.

- Privacy and Surveillance: Increased drone traffic and monitoring could lead to a higher risk of surveillance and reduced personal privacy, which is a medium to high negative impact, depending on regulatory responses.
- Environmental Impact: Environmental impacts will be mixed: potential reductions in emissions from optimized logistics (positive, medium impact), but also more noise pollution and possible disturbance to wildlife (negative, medium impact).
- Gender Gap and Job Opportunities: The drone industry may initially reinforce existing gender gaps in STEM and aviation sectors unless targeted measures are taken, presenting a medium negative impact; however, remote work and non-traditional pathways may eventually open up more roles for underrepresented groups.
- Public Safety: Improved airspace management will enhance public safety by reducing accidents involving drones and coordinated responses to emergencies, a high positive impact.

2.10 Space-based Multilateration and Satellite Surveillance

Utilization of space-based multilateration and global satellite surveillance for accurate tracking of all aircraft, even in remote or oceanic airspace, greatly improving global situational awareness.

2.10.1 Barriers:

- High Development and Deployment Costs: The development, launch, and maintenance of space-based multilateration and satellite surveillance systems require substantial financial investment. High costs can limit funding availability and slow deployment, especially for countries or organizations with limited budgets.
- Technical Complexity and Integration Challenges: Integrating space-based multilateration with existing air traffic management systems is complex due to differing data formats, communication protocols, and real-time processing needs. Technical challenges in ensuring system reliability and accuracy can delay operational readiness.
- Regulatory and International Coordination: Air traffic surveillance is a global activity requiring cooperation across countries and regulatory bodies. Divergent regulatory frameworks, spectrum allocation, and sovereignty concerns can hinder harmonized implementation and data sharing, impacting seamless global coverage.
- Data Security and Privacy Concerns: The transmission and storage of surveillance data raise concerns about unauthorized access, potential es-

pionage, and data misuse. Ensuring robust cybersecurity measures is challenging but essential to maintain trust and prevent breaches that could compromise aviation safety.

- Limited Satellite Coverage and Latency Issues: Satellite constellations may face limitations in coverage density, leading to gaps in real-time tracking, especially over polar regions or crowded airspaces. Additionally, signal latency can affect the timeliness of surveillance data, impacting decision-making for air traffic control.

2.10.2 Enablers:

- Advancements in Satellite Technology: Improvements in satellite hardware, such as miniaturization, enhanced sensors, and longer lifespan, enable the deployment of sophisticated space-based multilateration and surveillance systems, allowing for more precise and reliable aircraft tracking worldwide.
- Increased Global GNSS Coverage and Accuracy: Global Navigation Satellite Systems (GNSS) enhancements improve positional accuracy and availability, crucial for multilateration techniques to accurately determine aircraft positions, especially in remote or oceanic regions beyond traditional radar coverage.
- Development of Real-Time Data Processing and Communication Systems: Real-time data processing and high-capacity communication networks allow the rapid collection, fusion, and dissemination of multilateration and surveillance data, ensuring timely situational awareness and decision-making capabilities for air traffic management.
- Regulatory Support and International Collaboration: Regulatory frameworks and agreements between countries and international aviation organizations facilitate the adoption, standardization, and integration of space-based surveillance technologies, enabling seamless global air traffic monitoring and interoperability.
- Cost Reduction in Launch and Satellite Deployment: Reductions in the costs of satellite manufacturing, launch services, and constellation deployment lower barriers to entry and allow for more extensive and frequent satellite launches, which expand the coverage and redundancy needed for effective space-based multilateration and surveillance.

2.10.3 Stakeholders impacted:

- Airlines: Airlines will benefit from enhanced flight safety and operational efficiency due to more accurate and continuous aircraft tracking, enabling optimized routing and fuel savings, particularly in remote or oceanic airspaces.

- Air Traffic Control Organizations: Air Traffic Control Organizations will experience improved situational awareness and traffic management capabilities, allowing them to monitor and direct flights globally without gaps, reducing the risk of accidents and delays.
- Aircraft Manufacturers: Aircraft Manufacturers will need to integrate compatible avionics and communication systems to ensure their aircraft can interface with space-based multilateration and satellite surveillance, enhancing the value and safety of their products.
- Satellite and Space Technology Providers: Satellite and Space Technology Providers will see increased demand for launch services, satellite manufacturing, and maintenance, as the infrastructure supporting multilateration and surveillance expands in orbit.
- Regulatory Authorities: Regulatory Authorities will have to develop new policies and standards to govern the use of space-based tracking technologies, ensure data privacy and security, and coordinate internationally on airspace surveillance protocols.
- Passengers: Passengers will benefit from increased flight safety, more reliable scheduling, and potentially smoother travel experiences due to better air traffic management and situational awareness.
- Military and Defense Agencies: Military and Defense Agencies will gain enhanced airspace surveillance capabilities, improving national security by enabling better monitoring of both civilian and potential threat aircraft worldwide.
- Search and Rescue Operators: Search and Rescue Operators will benefit from faster and more accurate location data for aircraft in distress, increasing the effectiveness and timeliness of rescue operations, especially over remote or oceanic regions.
- Airport Operators: Airport Operators will experience improved traffic flow management around airports as controllers receive more accurate approach and departure information derived from space-based surveillance data.
- Environmental and Research Organizations: Environmental and Research Organizations will have access to more precise flight data, enabling better monitoring of aircraft emissions, noise pollution, and enabling studies related to climate impact and atmospheric conditions.

2.10.4 Environmental impact:

- Greenhouse Gas Emissions: The manufacturing, launch, and eventual disposal of satellites require significant energy and resource inputs, often resulting in greenhouse gas emissions. Overall impact is low to medium, significantly lower than many terrestrial activities, but non-negligible as satellite constellations scale up.

- Space Debris and Orbital Pollution: Deployment of large numbers of satellites can contribute to an increase in space debris and orbital pollution. Old or defunct satellites can collide, generating debris that persists for years or decades. Impact is medium, with long-term risks if debris is not managed.
- Plastic and Material Pollution: The production of satellites involves the use of plastics, specialized metals, and composites. Rocket launches can cause some material fallout into the ocean or remote areas, but this impact is generally low compared to other industries; still, it is not zero.
- Potential Reduction in Airline Emissions: Space-based multilateration enables more efficient routing and real-time tracking of aircraft, reducing unnecessary detours and enabling better fuel usage. This may result in a positive (reducing) impact on airline-related CO2 emissions, which is a medium positive impact, given the global scale of aviation.
- Electromagnetic Interference: Increased satellite constellations could incrementally increase electromagnetic pollution in Earth's atmosphere, potentially affecting astronomical observations and wildlife navigation. This impact is low, but growing with frequency of launches and constellation size.

2.10.5 Societal impacts:

- Safety and Security: High positive impact: Space-based multilateration and satellite surveillance will greatly improve the safety and security of air travel by enabling real-time global tracking of aircraft, reducing accidents, search and rescue response times, and risks of collisions.
- Privacy: Medium negative impact: Enhanced surveillance capabilities may lead to increased monitoring of movements for individuals and organizations, potentially raising concerns about privacy, data protection, and civil liberties.
- Economic Opportunity: Medium positive impact: Improved airspace management and efficiency can drive economic growth and create new jobs in aerospace and data industries. However, benefits may be unevenly distributed and could disadvantage regions or groups less able to access these new technologies.
- Environmental Impact: Low to medium mixed impact: More efficient flight paths may reduce fuel consumption and emissions, benefiting the environment, but the additional energy consumption and resource use for producing, launching, and operating new satellite constellations could offset some gains.
- Gender Gap: Low to medium positive impact: By creating technical and operational career opportunities in aerospace, satellite, and engineering

sectors, this trend may help close the gender gap if coupled with policies that encourage diversity and inclusion in STEM fields.

- Well-being: High positive impact: Enhanced aviation safety and reliability improves societal well-being by making travel safer and more accessible, reducing anxiety associated with flying, and facilitating global connectivity.

2.11 Collaborative Decision-Making (CDM) and Military-Civil ATM Integration

Deep collaboration between civil and military aviation authorities through shared airspace management, coordinated operations, and integrated systems, increasing airspace efficiency and flexibility.

2.11.1 Barriers:

- Regulatory and Policy Differences: Differences in regulatory frameworks and policies between civil and military aviation create challenges for unified decision-making and integration. These discrepancies can slow down harmonization efforts and result in conflicting operational procedures, reducing the efficiency of collaborative airspace management.
- Security and Confidentiality Concerns: Military operations often involve classified information and security restrictions that limit the sharing of vital data with civil aviation authorities. This barrier restricts transparency and real-time collaboration, hampering decision-making processes and reducing the potential benefits of integration.
- Technological Incompatibilities: Civil and military ATM systems are often based on different technologies and standards which are not easily interoperable. Such technological incompatibilities complicate the development of integrated systems required for seamless coordination, increasing costs and implementation timelines.
- Cultural and Organizational Differences: Differences in organizational culture, priorities, and command structures between civil and military stakeholders can lead to misalignment in goals and cooperation challenges. This impacts trust, information exchange, and the willingness to adopt joint operational strategies, slowing progress towards effective CDM and integration.
- Limited Data Sharing and Communication Protocols: Inadequate or incompatible communication protocols and reluctance to share comprehensive, timely data can create gaps in situational awareness. Limited data sharing restricts the ability to perform accurate, collaborative decision-making and undermines integrated airspace management activities.

2.11.2 Enablers:

- Advanced Data Sharing and Communication Systems: Advanced data sharing and communication systems enable real-time, seamless exchange of information between civil and military air traffic management (ATM) entities. This fosters collaborative decision-making by providing a common operational picture, reducing delays, and enhancing situational awareness, which is critical for efficient and flexible use of shared airspace.
- Harmonized Regulatory Frameworks: Harmonized regulatory frameworks align civil and military policies, procedures, and safety standards, reducing legal and procedural barriers to integration. By standardizing rules and responsibilities, these frameworks facilitate smoother coordination and streamline joint operations in both peacetime and contingency scenarios.
- Joint Training and Exercises: Joint training and exercises build shared understanding, operational familiarity, and standardized procedures among civil and military personnel. These collaborative activities improve communication, coordination, and readiness, directly supporting the development and sustained effectiveness of integrated ATM operations.
- Integrated Airspace Management Tools: Integrated airspace management tools provide sophisticated decision-support capabilities that combine civil and military needs within a shared platform. These tools optimize allocation and dynamic reconfiguration of airspace sectors, helping to balance flexibility, capacity, and security considerations efficiently.
- Trust and Interagency Relationships: Trust and interagency relationships form the foundation for open collaboration and information exchange. Strong professional relationships and a culture of cooperation reduce institutional resistance, encourage proactive problem solving, and underpin successful joint governance of shared airspace resources.

2.11.3 Stakeholders impacted:

- Civil Aviation Authorities: Civil Aviation Authorities will need to collaborate closely with military counterparts to manage shared airspace more efficiently, adapting regulations and procedures to enable safer and more flexible integrated operations.
- Military Aviation Authorities: Military Aviation Authorities will be impacted as they must coordinate their operations with civil air traffic management, requiring integrated systems and processes to ensure that military missions can be conducted without compromising overall airspace safety and efficiency.
- Air Traffic Controllers: Air Traffic Controllers will experience changes to their workflows and responsibilities as they manage a more integrated

airspace environment, requiring enhanced communication, coordination, and decision-support tools to handle mixed civil and military traffic.

- Airlines and Commercial Operators: Airlines and Commercial Operators will benefit from increased airspace efficiency and reduced delays but will also need to adapt to new procedures and possibly more dynamic routing influenced by military traffic priorities and collaborative scheduling.
- Passengers: Passengers stand to gain from fewer flight delays, improved punctuality, and more reliable scheduling as a result of more flexible and efficient airspace management enabled by civil-military collaboration.
- Airport Operators: Airport Operators may need to coordinate more closely with both civil and military stakeholders to manage arrivals and departures effectively, potentially adapting infrastructure and ground operations to the evolving airspace usage patterns.
- Aerospace and ATM Technology Providers: Aerospace and ATM Technology Providers will be tasked with developing and supplying advanced integrated systems, communication tools, and decision-support platforms that enable real-time collaboration and data sharing between civil and military air traffic management.
- Defense and Security Agencies: Defense and Security Agencies will need to balance operational security and mission requirements with increased transparency and data sharing, influencing how sensitive military operations are coordinated alongside civilian air traffic.
- Airspace Users (General Aviation and Cargo Operators): Airspace Users (General Aviation and Cargo Operators) will be influenced by changes in airspace availability and procedures stemming from the integrated management approach, requiring them to stay informed and compliant with new collaborative decision-making frameworks.
- Regulatory Bodies: Regulatory Bodies will be responsible for designing, approving, and overseeing the new regulatory frameworks and standards that govern the integrated civil-military air traffic management environment to ensure safety, security, and efficiency.

2.11.4 Environmental impact:

- Greenhouse gas emissions: CDM and military-civil ATM integration typically result in more efficient use of airspace, reducing flight times, fuel burn, and consequently greenhouse gas emissions. This is a positive impact with a medium level of significance, since aviation is a major contributor to global greenhouse gases and improved ATM can further reduce emissions.
- Air pollution: Increased efficiency in flight routings and reduced holding patterns due to better collaboration can lead to lower emissions of NOx

and other pollutants, positively impacting local and regional air quality. This benefit is medium in impact.

- Noise pollution: More direct routing and better traffic management can reduce the frequency and intensity of noise impacts over environmentally sensitive areas and populated zones, a positive impact with a low to medium level of significance depending on implementation.
- Plastic pollution: ATM integration and CDM have minimal direct influence on plastic pollution, so their impact here is low and likely negligible.
- Resource efficiency: By maximizing the utilization of available airspace and reducing congestion, these systems improve overall resource efficiency in aviation, indirectly lowering fuel consumption and operational waste. This is a positive, medium impact.

2.11.5 Societal impacts:

- Airspace Efficiency and Accessibility: High positive impact: The integration of CDM and military-civil ATM will make airspace use more efficient, enabling smoother operations for both civil and military flights, reducing delays, and potentially increasing the number of available routes for commercial and humanitarian flights.
- Public Safety and Security: Medium positive impact: Enhanced information sharing and coordination can improve national security response to emergencies, natural disasters, or hostile acts, benefiting society at large. However, military interests may sometimes take precedence, causing occasional disruptions to civil aviation.
- Economic Opportunity: Medium positive impact: Improved airspace management can lead to growth in aviation-related industries, job creation, and more equitable regional connectivity. However, if not carefully managed, regions near military installations could face more restrictions.
- Gender Gap: Low to medium positive impact: While the aviation industry remains male-dominated, improved efficiency and collaboration may create new roles in air traffic management and data analytics, gradually encouraging more diverse participation, including women and other underrepresented groups.
- Societal Well-being: Medium positive impact: Increased travel flexibility and reliability can improve quality of life, ease family connections, and enhance disaster response capabilities, overall supporting societal well-being.
- Privacy and Surveillance: Low to medium negative impact: Closer civil-military integration may increase surveillance and data collection, raising concerns about privacy for passengers and airspace users, particularly in regions with weaker civil oversight.

2.12 Trajectory-Based Operations and 4D Trajectory Management

Establishment of Trajectory-Based Operations (TBO) and four-dimensional trajectory management that enable precise, flexible, and efficient route planning to maximize capacity and minimize environmental impact.

2.12.1 Barriers:

- Technological Integration Complexity: Integrating diverse systems across airlines, air traffic control, and airports is technologically complex. This complexity slows the implementation of TBO and 4D trajectory management as it requires seamless interoperability and real-time data exchange to maintain accurate and consistent trajectories.
- Data Sharing and Security Concerns: The need for extensive data sharing between multiple stakeholders raises concerns about cybersecurity and data privacy. These concerns can delay cooperation and the development of unified platforms essential for trajectory management, impacting trust and willingness to share sensitive operational data.
- Regulatory and Standardization Challenges: Lack of harmonized regulations and global standards hinders the uniform adoption of TBO and 4D trajectory management. Differences in national aviation rules and policies create operational inconsistencies, making global deployment challenging and potentially limiting the benefits of these advanced operations.
- Infrastructure and Investment Requirements: Developing the necessary infrastructure, including upgraded communication networks and surveillance systems, requires significant financial investment. Limited budgets and competing priorities can restrict the pace and scope of implementation, delaying the full realization of efficient trajectory-based operations.
- Human Factors and Workforce Training: The shift to TBO and 4D trajectory management demands new skills and training for air traffic controllers, pilots, and system operators. Resistance to change, along with the time and resources required for effective workforce development, can impede smooth transition and operational reliability during rollout.

2.12.2 Enablers:

- Advanced Surveillance and Communication Systems: Advanced surveillance and communication systems such as ADS-B and CPDLC provide accurate, real-time aircraft position and intent information, enabling precise tracking and coordination essential for 4D trajectory management and TBO. This ensures safer and more efficient routing.
- Data Sharing and Integration Platforms: Data sharing and integration platforms enable seamless exchange of trajectory, flight plan, weather, and

airspace data between stakeholders, including airlines, ANSPs, and airports. This shared situational awareness allows dynamic trajectory adjustments and collaborative decision-making.

- Enhanced Air Traffic Management Algorithms: Enhanced air traffic management algorithms optimize trajectory planning by considering multiple constraints such as weather, traffic demand, and airspace capacity. These algorithms facilitate conflict detection and resolution, allowing flexible, efficient, and predictive flight trajectories.
- Regulatory Harmonization and Standards: Regulatory harmonization and common standards across countries and regions ensure interoperability of systems and procedures. This alignment is critical for implementing consistent TBO and 4D trajectory management globally, supporting cross-border operations and scalability.
- Artificial Intelligence and Machine Learning: Artificial intelligence and machine learning enable predictive analytics and adaptive control of trajectories by learning from historical and real-time data. These technologies improve decision support systems, helping to optimize routes for efficiency, capacity, and environmental impact.

2.12.3 Stakeholders impacted:

- Airlines: Airlines will benefit from improved fuel efficiency and optimized flight paths, reducing operational costs and environmental impact while improving schedule reliability through precise trajectory management.
- Air Traffic Controllers: Air Traffic Controllers will experience enhanced situational awareness and workload management due to the integration of 4D trajectories, enabling safer and more efficient traffic flow management.
- Airports: Airports will see improved arrival and departure sequencing, leading to increased capacity and reduced congestion, which can enhance airport efficiency and passenger experience.
- Passengers: Passengers will benefit from more reliable and predictable flight schedules, potentially shorter flight times, and reduced delays due to better-managed airspace and optimized trajectories.
- Aircraft Manufacturers: Aircraft Manufacturers will need to integrate advanced avionics compatible with TBO and 4D trajectory data, driving innovation in aircraft systems and ensuring future fleet readiness.
- Air Navigation Service Providers (ANSPs): Air Navigation Service Providers (ANSPs) will be required to upgrade infrastructure and systems to support trajectory-based operations, enabling more dynamic and efficient airspace management.
- Regulatory Authorities: Regulatory Authorities will need to adapt policies,

standards, and certification processes to accommodate the procedural and technological changes introduced by TBO and 4D trajectory management.

- Environmental Organizations: Environmental Organizations will observe reduced carbon emissions and noise pollution as more precise routing minimizes fuel burn and enables environmentally optimized flight profiles.
- Technology Providers: Technology Providers will have increased demand for developing and supplying advanced software, automation tools, and communication systems essential for implementing TBO and 4D trajectory management.
- Cargo and Logistics Companies: Cargo and Logistics Companies will gain from more predictable and efficient air transport schedules, allowing better planning and optimization of supply chains and delivery commitments.

2.12.4 Environmental impact:

- Greenhouse Gas Emissions: Trajectory-Based Operations (TBO) and 4D Trajectory Management are expected to have a positive and medium-level impact on reducing greenhouse gas emissions. By optimizing flight paths for efficiency and reducing delays, aircraft will burn less fuel, leading to lower CO2 and other greenhouse gas outputs.
- Noise Pollution: The enhancement in trajectory planning will reduce holding patterns and unnecessary flight time over populated areas, which can lower noise pollution. This is a positive impact and is likely to be medium in scale, especially around busy airports.
- Air Quality: Optimizing air traffic flows can decrease emissions of pollutants like NOx and particulate matter by minimizing inefficient idling and low-altitude flying. This results in a positive, medium-level impact on local air quality.
- Plastic Pollution: There is expected to be a negligible to low impact (neutral) on plastic pollution, since trajectory management does not directly affect the use or disposal of plastics in aviation operations.
- Wildlife Disturbance: Improved flight efficiency reduces the time aircraft spend over certain areas, potentially lessening repeated disturbance to wildlife habitats. This is a positive but low-level impact.

2.12.5 Societal impacts:

- operational efficiency: Trajectory-Based Operations (TBO) and 4D trajectory management will significantly enhance operational efficiency by allowing more precise and flexible planning of flight paths. This leads to reduced delays, optimized airspace usage, and potentially lower operating costs—a high, positive impact.

- environmental sustainability: The technology will help minimize environmental impact by reducing fuel consumption, emissions, and contrails through optimal routing. Airlines can adhere better to environmentally friendly procedures, delivering a high, positive environmental impact.
- economic growth and employment: These advancements may foster economic growth by enabling more flights and increasing the capacity of the airspace while reducing costs. Job roles might shift from traditional air traffic control to more technologically-focused positions. This impact is medium to high and mostly positive, but may also require workforce reskilling.
- passenger well-being and travel experience: Passengers will benefit from greater predictability, shorter travel times, and fewer disruptions, directly improving their well-being and satisfaction—a high, positive impact.
- gender gap and social equity: While TBO could increase accessibility and flexibility in air travel, the requirement for advanced technical skills may further widen gender gaps if STEM and aviation roles continue to see an imbalance in gender participation. Without targeted interventions, the impact here could be medium and somewhat negative; otherwise, positive if inclusivity is prioritized.
- safety and reliability: Safety and reliability will be improved, as more accurate trajectory management reduces the risk of conflicts and incidents in increasingly crowded skies. This brings a high, positive impact to public safety.

2.13 AI and Machine Learning for Predictive Analytics in ATM

Application of artificial intelligence and machine learning for predictive analytics, traffic forecasting, and decision support in air traffic management, leading to smarter, proactive operations.

2.13.1 Barriers:

- Data Privacy and Security Concerns: Air traffic management involves highly sensitive and critical data. Ensuring privacy and security is paramount, and concerns about data breaches or misuse restrict data sharing. This limitation hampers the training of comprehensive AI models, reducing their predictive accuracy and effectiveness.
- Data Quality and Availability: Machine learning models require large amounts of high-quality, labeled data. In ATM, data may be incomplete, inconsistent, or siloed across different organizations, which leads to challenges in building reliable predictive analytics solutions and delays in development.

- Regulatory and Certification Challenges: ATM systems must comply with stringent safety and operational regulations. The certification processes for AI-based predictive tools are complex and time-consuming, which slows down the adoption of new AI technologies and limits innovation pace.
- Integration with Legacy ATM Systems: Existing air traffic management infrastructure often relies on legacy systems that are not designed for interoperability with modern AI and machine learning frameworks. This creates significant technical and operational integration challenges, increasing costs and complexity for deployment.
- Lack of Domain-Specific AI Expertise: Developing effective AI solutions for ATM requires deep understanding of both machine learning and the specific domain of air traffic control. The scarcity of professionals with this combined expertise restricts progress and the creation of tailored, high-impact predictive models.

2.13.2 Enablers:

- High-quality Data Availability: Access to large, diverse, and high-quality datasets, including aircraft trajectories, weather data, and traffic flows, is crucial. This data fuels machine learning models and predictive analytics to accurately forecast traffic and detect anomalies, improving ATM situational awareness and decision-making.
- Advanced Computing Infrastructure: The development of AI and ML for predictive analytics requires significant computational power for processing and training complex models. Advances in cloud computing, edge computing, and GPU/TPU acceleration enable faster experimentation and deployment of these AI solutions in real-time ATM environments.
- Domain-specific AI Models and Algorithms: Tailored AI models and algorithms that understand the unique characteristics and constraints of air traffic management enhance prediction accuracy. Developing domain-specific approaches enables better handling of non-linearities, uncertainties, and safety-critical requirements inherent in air transportation.
- Integration with Air Traffic Management Systems: Seamless integration of AI-driven predictive analytics with existing ATM systems and tools ensures that insights are actionable. Real-time data exchange and interoperability enable proactive traffic flow management, optimized routing, and improved controller support, enhancing overall efficiency and safety.
- Regulatory Support and Collaboration: Supportive regulatory frameworks and multi-stakeholder collaboration foster innovation while ensuring compliance with safety and privacy standards. Regulatory endorsement and coordinated efforts among aviation authorities, airlines, and technology providers accelerate adoption and trust in AI-powered ATM predictive analytics.

2.13.3 Stakeholders impacted:

- Air Traffic Controllers: Air Traffic Controllers will benefit from AI-driven predictive analytics by receiving enhanced decision support, enabling them to anticipate traffic flow and potential conflicts, thus improving safety and efficiency.
- Airlines: Airlines will experience smarter scheduling and route optimization through predictive analytics, reducing delays and fuel consumption, leading to cost savings and better on-time performance.
- Passengers: Passengers will be positively impacted by more reliable and punctual flights as predictive analytics help preempt disruptions and optimize traffic management, improving overall travel experience.
- Airport Operators: Airport Operators will leverage predictive insights to manage runway usage, gate assignments, and ground operations proactively, increasing throughput and reducing congestion.
- Regulatory Authorities: Regulatory Authorities will need to adapt policies and frameworks to safely integrate AI and machine learning into air traffic management, ensuring compliance and oversight while supporting innovation.
- Technology Providers: Technology Providers will play a crucial role in developing, deploying, and maintaining AI and ML systems for predictive analytics, shaping the future tools used across the ATM ecosystem.
- Meteorological Services: Meteorological Services will integrate AI-based forecasts with traffic models, enabling more accurate weather impact predictions on air traffic and supporting dynamic flow management.
- Aircraft Manufacturers: Aircraft Manufacturers will need to incorporate data connectivity and system compatibility to support AI-driven operational insights and predictive maintenance aligned with ATM advancements.
- Maintenance and Ground Handling Teams: Maintenance and Ground Handling Teams will utilize predictive analytics to optimize resource allocation and schedule maintenance proactively, reducing downtime and enhancing operational reliability.
- Data Scientists and Analysts: Data Scientists and Analysts will be essential in developing, refining, and interpreting AI and machine learning models tailored for predictive analytics in ATM, driving continuous improvement and innovation.

2.13.4 Environmental impact:

- Greenhouse Gas Emissions: The use of AI and machine learning for predictive analytics in air traffic management (ATM) is likely to have a

positive medium impact on greenhouse gas emissions by optimizing flight paths, reducing delays, and minimizing unnecessary fuel burn. This leads to more efficient operations and decreased CO2 output by aircraft. However, there is a moderate increase in emissions associated with the data centers and computation power required for AI processing, but this is generally outweighed by the larger emissions reductions in aviation.

- Plastic Pollution: The direct impact on plastic pollution from AI and machine learning in ATM is low. The technology itself does not require significant physical plastic components, so no meaningful increase or decrease in plastic waste is expected from its development or operation.
- Electronic Waste: The deployment of AI systems may marginally increase electronic waste over time due to the need for specialized or upgraded hardware (e.g., servers and processors). This impact is considered low and could be mitigated by responsible e-waste management and recycling practices.
- Energy Consumption: Energy consumption for powering the data centers and communication networks that support AI and machine learning may increase slightly, constituting a low to medium negative impact. Yet, if the systems drive significant gains in aviation efficiency, the net energy savings (from less fuel used in air transport) will likely be greater than the extra energy spent on computation.
- Air Quality: By supporting more efficient flight operations and reducing unnecessary holding patterns, AI can contribute to improved air quality near airports (less idling and fewer emissions during takeoff/landing cycles), representing a positive but low to medium impact on local environments.

2.13.5 Societal impacts:

- Safety and Operational Efficiency: The deployment of AI and Machine Learning for predictive analytics in Air Traffic Management (ATM) can significantly improve operational efficiency and flight safety by enabling faster, more accurate decision-making and proactive management of air traffic flows. The level of impact is high and largely positive as it reduces delays, optimizes routes, and prevents human error.
- Employment and Skills Gap: Predictive analytics will automate many routine tasks, leading to potential reductions in certain types of manual or lower-skilled jobs while increasing demand for data science, engineering, and AI management roles. This impact is medium and mixed: while new, higher-skilled jobs are created, those with outdated skills may face job loss or require retraining.
- Gender Gap in Aviation and Tech: The gender gap may widen if proactive measures are not taken, since both aviation and AI/tech sectors currently lack gender diversity. Without targeted interventions, the benefits of AI in

ATM could disproportionately accrue to existing male-dominated groups. The level of impact is medium, and potentially negative unless addressed deliberately by policy and education.

- Well-being and Work-Life Balance: Improved ATM efficiency can reduce stress for both air traffic controllers and passengers by lowering delays and increasing predictability, thereby positively impacting well-being and work-life balance. This is a positive, medium-level impact.
- Environmental Impact: More efficient ATM leads to fewer delays, less fuel waste, and more optimal routing, which can contribute to lowering aviation's environmental footprint. The impact is high and positive, supporting societal and regulatory goals for emissions reduction.
- Privacy and Data Security: The use of AI in ATM requires processing vast amounts of personal and operational data, creating risks around privacy breaches and cyber-attacks if not managed properly. The impact is medium and negative unless strong safeguards are implemented.
- Economic Impact & Accessibility: Predictive analytics can help airlines and airports reduce costs and improve service, potentially lowering ticket prices and making air travel more accessible to wider segments of society. High and positive impact, though benefits will vary by region and implementation.

2.14 Urban Air Mobility (UAM) and Drone Integration

Seamless integration of urban air mobility vehicles, such as passenger drones and automated air taxis, into city environments, including sharing airspace and ground infrastructure with traditional aviation.

2.14.1 Barriers:

- Regulatory and Certification Challenges: Regulatory and certification frameworks for Urban Air Mobility (UAM) and drones are still evolving. The lack of standardized rules delays development and deployment because manufacturers and operators cannot ensure compliance across different jurisdictions, impacting certification timelines and operational approvals.
- Airspace Management and Traffic Integration: Integrating UAM vehicles and drones into already congested urban airspace requires sophisticated traffic management systems. Without effective airspace management solutions, risks of midair collisions increase, and uncontrolled traffic may lead to operational disruptions and decreased public safety.
- Safety and Security Concerns: Safety concerns, including vehicle reliability, collision avoidance, and vulnerability to cyberattacks, pose significant hurdles. Ensuring robust safety and security protocols is critical; failure to do so can prevent regulatory approval and undermine public trust.

- Infrastructure and Ground Support Limitations: Current urban infrastructure is not designed to support widespread UAM operations. Lack of designated vertiports, charging or refueling stations, and maintenance facilities limits operational scalability and efficiency, delaying the adoption of these technologies.
- Public Acceptance and Noise Pollution: Public acceptance is crucial for widespread adoption of UAM, but concerns over noise pollution, privacy, and visual impacts can result in resistance from communities. Negative public perception can lead to political and regulatory pushback, constraining deployment.

2.14.2 Enablers:

- Advanced Air Traffic Management Systems: Advanced Air Traffic Management Systems enable safe and efficient integration of UAM vehicles and drones into already congested urban airspace by providing real-time monitoring, collision avoidance, and dynamic routing, which is crucial for coexistence with traditional aviation.
- Regulatory Framework and Certification: Regulatory Framework and Certification provide the legal and safety guidelines necessary to operate UAM vehicles and drones legitimately, defining standards for design, operation, and pilot training that build trust and enable large-scale deployment.
- Battery and Propulsion Technology Improvements: Battery and Propulsion Technology Improvements increase the range, endurance, and reliability of UAM vehicles and drones by providing lightweight, high-capacity energy sources and efficient propulsion systems, reducing operating costs and expanding operational feasibility.
- Infrastructure Development: Infrastructure Development, including vertiports, charging stations, and dedicated air corridors, establishes the physical and logistical groundwork necessary for launch, landing, maintenance, and integration with multimodal transport, thus facilitating operational scalability.
- Public Acceptance and Safety Assurance: Public Acceptance and Safety Assurance are foundational to UAM adoption, as transparent safety records, community engagement, noise mitigation, and privacy protections build societal trust and reduce barriers related to perception and regulatory pushback.

2.14.3 Stakeholders impacted:

- Urban Air Mobility Vehicle Manufacturers: Manufacturers of UAM vehicles and drones will be impacted as they must innovate to create safe, efficient, and regulatory-compliant products suited for urban environments.

- Regulatory Authorities: Regulatory bodies will need to develop new policies, safety standards, and certification processes specifically addressing urban air traffic and autonomous flight operations.
- City Governments and Urban Planners: City governments and planners will be responsible for integrating UAM infrastructure such as vertiports into urban landscapes while managing noise, safety, and zoning challenges.
- Traditional Aviation Industry: The traditional aviation industry must adapt to shared airspace with UAM vehicles, potentially facing new competition and collaborating on traffic coordination and airspace management.
- Passengers and General Public: Passengers and the general public will experience new mobility options that impact daily commutes and logistics, while also raising concerns about privacy, safety, and noise pollution.
- Air Traffic Management Providers: Providers of air traffic management systems will need to evolve technologies to handle increased traffic density, including low-altitude urban airspace with diverse types of aircraft.
- Emergency Services and Public Safety Organizations: Emergency services will be affected by both opportunities for faster response times using UAM and challenges in coordinating airspace during emergencies to avoid conflicts.
- Telecommunications Providers: Telecommunications providers are essential for enabling reliable communication, navigation, and control systems required for safe UAM operation, especially for autonomous flights.
- Infrastructure Developers: Infrastructure developers and operators will need to design, build, and maintain new ground facilities like charging stations and vertiports integrated with existing transportation hubs.
- Environmental Organizations: Environmental organizations will monitor and influence policies related to noise, energy consumption, emissions, and wildlife impacts caused by increased low-altitude urban flying vehicles.

2.14.4 Environmental impact:

- Greenhouse Gas Emissions: The widespread adoption of Urban Air Mobility (UAM) and drones could reduce greenhouse gas emissions if the vehicles are fully electric and powered by renewable energy; however, if fossil fuels or non-renewable electricity are used, overall emissions could increase due to additional flights. The impact level is medium, with positive effects possible if infrastructure is sustainable.
- Air Pollution: Electrically powered UAM may reduce tailpipe emissions compared to conventional vehicles, but if battery production and charging grids rely on fossil fuels, there could be indirect increases in air pollution. Impact is medium and depends on energy sourcing.

- Noise Pollution: Increased numbers of drones and air taxis operating at low altitude could significantly raise noise pollution levels in urban environments. The impact is likely negative and medium to high, especially if flight frequency is high and noise mitigation technologies are not advanced.
- Plastic and Electronic Waste: Production and disposal of drones and UAM vehicles will generate plastic and electronic waste. The use of composite materials, plastics, and electronics in these vehicles can contribute to long-term pollution and recycling challenges. Impact is negative and rated as medium.
- Land Use and Urban Sprawl: Supporting infrastructure for UAM (e.g., vertiports, charging stations) may require additional urban land development, potentially contributing to urban sprawl or loss of green space. The effect is negative but likely low to medium depending on city planning.
- Wildlife Disturbance: Low-flying vehicles can disturb birds and other wildlife, potentially impacting migration routes or breeding patterns. The impact is negative and rated as low to medium, depending on local ecosystems and flight regulations.

2.14.5 Societal impacts:

- Mobility and Accessibility: UAM and drone integration can significantly increase urban mobility and accessibility, allowing faster transportation across dense city environments. Impact: Positive, High.
- Environmental Impact: Depending on energy sources and noise management, UAM may reduce ground congestion and emissions but introduce new noise pollution and energy demands. Impact: Mixed, Medium.
- Economic Opportunities and Employment: Creates new jobs in aviation, engineering, logistics, and support sectors, but may lead to job displacement in traditional transportation roles. Impact: Mixed, Medium.
- Social Equity and Gender Gap: Could either bridge or widen the gap for underserved communities or underrepresented genders, depending on equitable access, cost structures, and hiring practices. Potential for positive impact on gender gap if actively addressed, but risk of negative impact without regulation. Impact: Mixed, Medium.
- Well-being and Urban Living: Improved well-being due to reduced commute times and novel transportation options, but increased anxieties for some regarding low-flying vehicles and urban noise. Impact: Mixed, Medium.
- Safety and Security: Potential for improved emergency response but concerns over accidents, airspace congestion, and misuse. Regulatory challenges remain to ensure safety. Impact: Mixed, High.
- Privacy Concerns: Greater surveillance capabilities and data collection

by drones raise significant privacy issues, especially in densely populated areas. Impact: Negative, Medium.

2.15 Cybersecurity Capabilities and Cyber-Resilience

Comprehensive development of cybersecurity tools and cyber-resilience strategies to safeguard increasingly digital and connected aviation systems from malicious cyber threats.

2.15.1 Barriers:

- Legacy Systems and Infrastructure: Many aviation systems still rely on outdated technology that was not designed with cybersecurity in mind. This limits the ability to implement advanced cyber-resilience measures and increases vulnerability to attacks.
- Fragmented Regulatory Environment: The aviation sector is governed by multiple national and international authorities with differing cybersecurity standards, leading to inconsistent implementation and gaps in defense across regions and stakeholders.
- Insufficient Skilled Cybersecurity Workforce: There is a global shortage of cybersecurity professionals with expertise specific to aviation, which hinders the development and maintenance of robust cybersecurity capabilities tailored to air transportation.
- High Cost of Cybersecurity Implementation: Implementing comprehensive cybersecurity solutions demands significant financial resources, which can be a barrier for airlines and airports operating under tight budget constraints, delaying necessary upgrades.
- Complex Supply Chain and Third-Party Risks: The interconnected nature of aviation involves numerous suppliers and service providers, whose cyber vulnerabilities can propagate through the supply chain, complicating risk management and resilience efforts.

2.15.2 Enablers:

- Advanced Threat Intelligence Sharing: Advanced threat intelligence sharing enables timely identification and mitigation of cyber threats by allowing aviation stakeholders to collaborate, exchange data on vulnerabilities, and anticipate emerging attack patterns, thereby strengthening overall cyber-resilience.
- Robust Regulatory Frameworks and Standards: Robust regulatory frameworks and standards provide clear security requirements and guidelines tailored for the air transportation sector, ensuring consistent cybersecurity practices across organizations and reinforcing compliance to mitigate cyber risks effectively.

- Investment in Skilled Cybersecurity Workforce: Investment in a skilled cybersecurity workforce ensures the availability of experts capable of designing, implementing, and managing complex cyber defense mechanisms in aviation systems, which is critical for protecting sensitive infrastructure and sensitive data.
- Integration of Artificial Intelligence and Machine Learning: Integrating artificial intelligence and machine learning allows for real-time threat detection and automated response to cyber incidents, improving the speed and accuracy of identifying anomalies and reducing the impact of cyber attacks on aviation systems.
- Comprehensive Incident Response and Recovery Plans: Comprehensive incident response and recovery plans enable air transportation organizations to promptly react to cyber incidents, minimize operational disruptions, and restore systems efficiently, thus enhancing the resilience of digital aviation infrastructure against cyber threats.

2.15.3 Stakeholders impacted:

- Airlines: Airlines will be impacted as they rely on secure digital systems for operations, ticketing, and communication. Enhanced cybersecurity and resilience reduce risks of operational disruption, data breaches, and financial losses.
- Airports: Airports need to protect critical infrastructure such as access control systems, baggage handling, and passenger information systems. Cyber-resilience safeguards these systems from attacks that could cause safety hazards or operational paralysis.
- Air Traffic Control Organizations: Air Traffic Control Organizations manage highly sensitive and real-time flight information. Cybersecurity capabilities ensure uninterrupted, secure communication and coordination preventing accidents or airspace breaches.
- Aircraft Manufacturers: Aircraft Manufacturers are impacted through the increasing integration of connected avionics and onboard systems. Cybersecurity development helps protect intellectual property and ensures aircraft systems cannot be compromised remotely.
- Regulatory Authorities: Regulatory Authorities will shape and enforce cybersecurity standards and compliance requirements. Their role expands in monitoring and responding to cyber threats within the aviation sector, impacting policy and oversight frameworks.
- Passengers: Passengers' safety and privacy are safeguarded by resilient cybersecurity measures protecting personal data, ticketing systems, and overall operational continuity, which enhances passenger trust and experience.

- Cybersecurity Solution Providers: Cybersecurity Solution Providers will see increased demand for specialized products and services tailored to aviation security needs, driving growth and innovation opportunities within the sector.
- Maintenance and Ground Handling Teams: Maintenance and Ground Handling Teams rely on digital tools for aircraft servicing and logistics. Cyber-resilience ensures these systems remain secure and functional, preventing delays or safety incidents due to cyber interruptions.
- Government and Security Agencies: Government and Security Agencies must enhance their roles in national and international aviation cyber defense, collaborating on threat intelligence and response to protect critical air transport infrastructure.
- Suppliers and Vendors: Suppliers and Vendors who provide software, hardware, and connectivity solutions to the aviation industry will be required to adopt higher security standards and practices, affecting product development and compliance criteria.

2.15.4 Environmental impact:

- Greenhouse Gas Emissions: The development and deployment of advanced cybersecurity hardware and datacenters require substantial energy, mainly from fossil fuels in many regions, contributing to greenhouse gas emissions. However, the magnitude is expected to be low compared to other major digital infrastructure because cybersecurity capabilities are a subset of existing IT systems.
- Electronic Waste: As more specialized cybersecurity hardware, such as secure servers, firewalls, intrusion detection devices, and endpoint security appliances are produced and eventually decommissioned, they add to the growing issue of electronic waste (e-waste). The impact is considered medium, due to the relatively long lifecycle of enterprise devices but notable cumulative effects over time.
- Plastic Pollution: Production of cybersecurity-related hardware involves the use of plastics for casings, cabling, and packaging materials. While this is not a leading source of plastic pollution compared to other sectors, there is still a low level of negative impact due to increased device turnover as threats and standards evolve.
- Resource Consumption: Ensuring cyber-resilience may promote more frequent upgrades or redundancy of systems, leading to greater consumption of rare earth metals, minerals, and water during manufacturing, resulting in a medium negative impact.
- Positive Environmental Protection: Positively, robust cybersecurity protects digital and automated systems in air transportation, helping to

prevent operational disruptions, accidents, and data loss that could result in emergency responses, rerouted flights, or inefficiencies—all of which have a higher environmental cost if a cyberattack leads to them. The positive impact is low but meaningful when successful protection averts ecological harm.

2.15.5 Societal impacts:

- Security and Personal Safety: High positive impact: Improved cybersecurity and cyber-resilience in society, especially in critical sectors like air transportation, will greatly reduce risks of malicious attacks, data breaches, and disruptions. This enhances the safety of individuals and organizations, and fosters confidence in digital services.
- Economic Stability and Trust: High positive impact: Robust cyber defense preempts costly disruptions, protects business operations, and maintains public trust in digital infrastructure, indirectly promoting economic stability and growth. However, organizations may need to allocate substantial resources to maintain such capabilities.
- Digital Inclusion and Gender Gap: Medium negative and positive impact: Gaps in digital literacy and access to cybersecurity education or resources can worsen existing inequalities, including the gender gap in technology fields. Proactive measures and inclusive policies can help close these gaps by supporting underrepresented groups' participation in cybersecurity careers and awareness programs.
- Mental Well-being: Medium positive and negative impact: Enhanced security can reduce anxiety about cyber threats (improving well-being), but heightened focus on cybersecurity risks and the prevalence of security protocols may also increase stress and perceived complexity for some users.
- Privacy and Civil Liberties: Medium negative and positive impact: Advanced cyber-resilience may necessitate more data monitoring and stricter identity verification, which could pose risks to privacy and civil liberties if not carefully managed. Yet, transparent and ethical frameworks can offset negatives by empowering users to protect their data.

2.16 Fully Autonomous Commercial Aircraft

Commercial introduction of fully autonomous, passenger-carrying aircraft, eliminating onboard pilots and relying on advanced AI, sensors, and remote control for safe operation.

2.16.1 Barriers:

- Regulatory and Certification Challenges: Regulatory and Certification Challenges impact development because current aviation authorities have

strict certification processes designed around human pilots. Developing standards and regulations that validate fully autonomous systems for commercial passenger aircraft is complex and time-consuming, delaying approval and commercial deployment.

- Safety and Reliability Concerns: Safety and Reliability Concerns affect progress as autonomous systems must guarantee performance under all conditions, including emergencies. Demonstrating the AI's fail-safe capabilities to match or exceed human pilot reliability is difficult, creating a significant hurdle for developers to achieve certification and public acceptance.
- Cybersecurity Risks: Cybersecurity Risks introduce potential vulnerabilities where autonomous aircraft systems could be targeted by hackers. Ensuring robust protection against cyberattacks is critical to prevent unauthorized control or system disruptions, but developing and proving such defenses is challenging and essential to prevent catastrophic risks.
- Public Acceptance and Trust: Public Acceptance and Trust represent a major social barrier, as passengers may be reluctant to fly without a human pilot onboard. Overcoming fears about AI decision-making, transparency, and accountability is necessary to ensure widespread adoption, which requires extensive education, proven safety records, and cultural shifts.
- Technological and Infrastructure Limitations: Technological and Infrastructure Limitations slow progress because current sensor, AI, communication, and ground control technologies may not yet fully support all autonomous operational requirements. Additionally, existing airport and air traffic infrastructure must evolve to accommodate and integrate autonomous aircraft seamlessly.

2.16.2 Enablers:

- Advanced Artificial Intelligence and Machine Learning: Advanced AI and machine learning are critical for enabling real-time decision making, flight control autonomy, and adaptation to dynamic environments without human intervention. Enhancing AI capabilities directly impacts the reliability and safety of autonomous commercial aircraft operations.
- Robust Sensor and Communication Technologies: Robust sensors (such as LIDAR, radar, and optical systems) combined with resilient communication networks ensure continuous situational awareness and remote monitoring. These technologies are essential for obstacle detection, navigation, and maintaining secure links between aircraft and control centers.
- Regulatory Framework and Certification Standards: Development of comprehensive regulatory frameworks and certification processes is necessary to establish operational standards and ensure safety compliance for autonomous aircraft. Clear regulations will facilitate industry investments and public confidence in the new technologies.

- Cybersecurity and Data Integrity Measures: Cybersecurity measures protect autonomous systems from malicious attacks and unauthorized access, safeguarding flight data, control commands, and communication links. Ensuring data integrity is paramount to prevent system failures and maintain operational safety.
- Public Trust and Acceptance: Public trust and acceptance influence market adoption and airline readiness to deploy fully autonomous aircraft. Demonstrating safety, reliability, and benefits to passengers will drive positive perceptions and regulatory support.

2.16.3 Stakeholders impacted:

- Passengers: Passengers will be impacted through potentially improved safety, reduced ticket prices due to lower operational costs, and new travel experiences, but also may face concerns about trust in autonomous systems and changes in in-flight service dynamics.
- Airlines: Airlines will experience operational cost reductions by eliminating pilot salaries, potentially increased aircraft utilization, but will need to invest significantly in new technology integration and cybersecurity measures.
- Pilots and Crew: Pilots and crew face job displacement risks as onboard human roles diminish, requiring potential retraining or transition to new roles such as remote operation or in-cabin customer service.
- Aircraft Manufacturers: Aircraft manufacturers will need to redesign aircraft to accommodate autonomous technologies, integrate advanced AI and sensors, and shift their engineering focus from human interfaces to automated systems.
- Air Traffic Control Authorities: Air Traffic Control authorities will need to adapt to new traffic patterns and communication protocols with fully autonomous aircraft, requiring upgrades in infrastructure and possible changes in regulatory oversight methods.
- Regulatory Agencies: Regulatory agencies must develop new certification standards, safety regulations, and liability frameworks specific to autonomous flight technology to ensure public safety and acceptance.
- Insurance Companies: Insurance companies will need to reassess risk models and coverage plans due to the shift from human pilot error to technology and cybersecurity risks in autonomous aircraft operation.
- Airport Operators: Airport operators may adjust infrastructure to support autonomous aircraft including changes in boarding processes, ground support automation, and altered passenger flow management.
- Technology Providers: Technology providers, including AI developers,

sensor manufacturers, and cybersecurity firms, will see increased demand to develop reliable, secure, and fail-safe systems integral to autonomous aircraft operation.

- Maintenance and Repair Organizations: Maintenance and repair organizations will face new challenges and opportunities servicing advanced autonomous systems, requiring specialized training and tools to maintain AI, sensors, and related hardware.

2.16.4 Environmental impact:

- Greenhouse Gas Emissions: Greenhouse Gas Emissions: The shift to fully autonomous commercial aircraft may lead to slightly improved fuel efficiency due to optimized flight paths and more precise operations. However, unless there is a widespread transition to low- or zero-carbon propulsion systems, the physiological greenhouse gas impact will remain high. The impact is likely to be low to medium positive in the short term due to efficiency gains but remains subject to the emissions profile of the underlying aircraft technology.
- Resource Consumption: Resource Consumption: Autonomous aircraft require advanced sensors, computing hardware, and redundancies, resulting in increased demand for rare earth metals, semiconductors, and complex manufacturing processes. This slightly increases resource consumption compared to traditional aircraft. The level of impact is medium negative.
- Plastic and Electronic Waste: Plastic and Electronic Waste: The development and deployment of autonomous systems could increase e-waste and non-biodegradable materials, both during production and as equipment reaches end of life. The net effect may be medium negative due to the regular need for hardware updates, replacements, and disposal of outmoded AI-driven avionics.
- Noise Pollution: Noise Pollution: Autonomous operations could enable more precise takeoff and landing procedures, potentially reducing noise exposure for humans and wildlife, especially near airports. This is a low to medium positive impact.
- Wildlife Disturbance: Wildlife Disturbance: Improved navigation and scheduling may reduce unnecessary holding patterns or low-altitude flight over sensitive habitats, potentially lessening the disturbance to wildlife. The overall impact is low positive.

2.16.5 Societal impacts:

- Employment & Workforce: High negative impact: Pilots and associated personnel may face significant job losses or transitions, leading to workforce disruption, although new technical roles (e.g., AI maintenance) could emerge.

- Safety & Public Trust: Medium to high mixed impact: If autonomous aircraft are proven highly safe, public confidence may increase, but accidents or hacking events could sharply decrease trust, affecting adoption rates.
- Economic Efficiency: High positive impact: Airlines could operate more efficiently with reduced labor costs and potentially lower ticket prices, benefiting consumers and industry profitability.
- Gender Gap: Medium positive impact: The pilot profession has historically been male-dominated; automation could reduce gender barriers in aviation, though broader STEM gaps may persist if new roles require specialized skills.
- Environmental Impact: Medium positive impact: Optimized autonomous flight paths and more energy-efficient operation could reduce fuel usage and emissions, advancing environmental goals.
- Well-being & Accessibility: Medium to high positive impact: Autonomous aircraft could expand air transportation access to underserved or remote communities, improving societal well-being, though initial adoption may be uneven.

2.17 Global Supersonic and Hypersonic Travel

Emergence and scalability of supersonic and hypersonic passenger flights, drastically reducing intercontinental travel times and expanding the range of rapid global connections.

2.17.1 Barriers:

- Technological Challenges: Developing aircraft capable of sustained supersonic and hypersonic speeds requires advanced materials, propulsion systems, and thermal management technologies. These technological hurdles slow down development and increase costs, as existing aviation technology cannot be directly scaled to such extreme conditions.
- Environmental Impact and Regulations: High-speed flight generates significant noise pollution (sonic booms) and increased emissions, raising environmental concerns. Stringent regulations to limit noise and emissions will restrict operational routes and flight frequencies, impacting the commercial feasibility of global supersonic and hypersonic services.
- Economic Viability: The high cost of developing, building, and operating supersonic/hypersonic aircraft leads to expensive ticket prices. Without a large enough market willing to pay a premium, programs may not achieve economic sustainability, limiting investment and scaling opportunities.
- Safety and Reliability Concerns: At extreme speeds, aerodynamic and structural stresses increase risks of mechanical failure or accidents. Ensuring

safety and reliability demands extensive testing and certification, extending development timelines and adding regulatory complexity.

- Infrastructure and Airspace Integration: Current airports, air traffic control systems, and global airspace management are not designed to accommodate the speed and operational profiles of supersonic/hypersonic flights. Significant upgrades and coordination with aviation authorities worldwide are required, delaying integration and commercial deployment.

2.17.2 Enablers:

- Advanced Materials and Aerodynamics: The development of lightweight, heat-resistant materials and optimized aerodynamic designs enables aircraft to sustain the extreme temperatures and stresses encountered at supersonic and hypersonic speeds. This advancement improves efficiency, safety, and durability, making commercial supersonic and hypersonic travel viable.
- Next-Generation Propulsion Systems: Innovative propulsion technologies, such as advanced jet engines, ramjets, or scramjets, are critical to achieving and sustaining supersonic and hypersonic speeds efficiently. These systems directly impact fuel consumption, environmental footprint, and operational costs, facilitating scalable high-speed air transportation.
- Regulatory and Environmental Frameworks: Clear and supportive international regulations, alongside frameworks addressing noise, emissions, and sonic booms, are essential for public acceptance and operational feasibility. Harmonized environmental policies enable smoother certification and integration of supersonic and hypersonic aircraft into global airspace.
- Infrastructure and Airport Adaptation: Upgrading airport infrastructure to handle high-speed aircraft operations, including specialized runways, maintenance facilities, and air traffic management systems, is necessary to support the commercial deployment of these aircraft. This ensures safety and operational reliability in current aviation ecosystems.
- Investment in Research and Development: Sustained funding and focused research accelerate breakthroughs in materials, propulsion, noise mitigation, and environmental impact reduction. Investment from governments and private sectors drives innovation, reduces technical risks, and shortens the timeline to market entry for global supersonic and hypersonic travel.

2.17.3 Stakeholders impacted:

- Passengers: Passengers will benefit from dramatically reduced travel times for intercontinental flights, enabling faster business trips and more convenient global travel experiences.
- Airlines: Airlines will be impacted by the need to invest in new fleets and infrastructure for supersonic and hypersonic aircraft, potentially gaining

competitive advantages through offering premium, high-speed services.

- Aircraft Manufacturers: Aircraft Manufacturers must develop advanced technologies and materials to create viable supersonic and hypersonic aircraft, opening new markets and driving innovation in aerospace engineering.
- Airport Authorities: Airport Authorities will need to adapt facilities to accommodate new aircraft specifications, including runway modifications and specialized passenger processing systems.
- Regulatory Bodies: Regulatory Bodies will be required to establish new safety, noise, and environmental regulations tailored to the unique challenges posed by supersonic and hypersonic travel.
- Environmental Groups: Environmental Groups will be concerned with the increased emissions and noise pollution associated with faster aircraft, advocating for sustainable development and mitigation strategies.
- Investors and Shareholders: Investors and Shareholders will be affected by new investment opportunities and risks associated with the development, production, and commercialization of these advanced aircraft technologies.
- Governments: Governments may experience impacts through changes in national security, airspace management, and economic growth resulting from enhanced global connectivity.
- Tourism Industry: The Tourism Industry stands to gain from increased accessibility and attractiveness of remote or previously time-consuming destinations, potentially boosting cross-border tourism.
- Suppliers and Maintenance Providers: Suppliers and Maintenance Providers will need to update their capabilities and inventories to support the maintenance and parts requirements of cutting-edge supersonic and hypersonic fleets.

2.17.4 Environmental impact:

- Greenhouse Gas Emissions: Supersonic and hypersonic aircraft typically consume more fuel per passenger-kilometer than subsonic aircraft, leading to significantly higher CO2 emissions. As the fleet size increases, this will contribute a high negative impact to global warming and the greenhouse effect.
- Stratospheric Ozone Depletion: Flights traveling at high altitudes emit pollutants such as nitrogen oxides (NOx) directly into the stratosphere, which can deplete ozone. Supersonic travel (at or above the stratosphere) increases this risk with a medium to high negative impact, depending on fuel type and fleet adopted.

- Noise Pollution: Supersonic and hypersonic aircraft generate intense sonic booms and higher noise during take-off and landing, affecting both human populations and wildlife. This represents a localized but potentially significant negative impact (medium level).
- Resource Consumption: Faster aircraft require advanced materials and more complex manufacturing, increasing the demand for rare metals, composites, and energy-intensive processes. This impact on resource use and mining is medium and negative.
- Particulate and Non-CO2 Emissions: Apart from CO2, these high-speed jets emit water vapor, black carbon, and other particulates at cruise altitudes where their climate effects are amplified. The cumulative climate impact from non-CO2 emissions is medium to high and negative.
- Plastic and Material Waste: Manufacturing, operating, and maintaining a global hypersonic fleet will increase the production and disposal of specialized plastics and composites, contributing slightly to plastic pollution and landfills. The impact is likely low to medium and negative.

2.17.5 Societal impacts:

- Economic Inequality: HIGH (mostly negative, some positive): Supersonic and hypersonic travel is likely to be accessible primarily to the wealthy due to high ticket costs, increasing disparities between those who can afford rapid travel and those who cannot.
- Global Mobility: HIGH (positive): The ability to travel across continents in a matter of hours will foster a more interconnected world, enabling rapid global collaboration and opportunity.
- Environmental Impact: MEDIUM-HIGH (negative): Such technologies will likely have significant carbon and noise footprints, unless major advances in green propulsion are achieved; this could worsen global environmental challenges.
- Business Productivity: MEDIUM (positive): Faster travel will allow business leaders, scientists, and policymakers to attend more urgent meetings and activities in person, potentially increasing productivity and innovation.
- Gender Gap: LOW-MEDIUM (mixed): While women may benefit from enhanced global networking and opportunities, entrenched economic inequality means initial access may skew towards affluent men, so effects on the gender gap will depend heavily on social and policy responses.
- Cultural Exchange: MEDIUM (positive): Quicker travel facilitates cultural exchange, collaborative research, and shared global experiences, potentially fostering empathy and understanding among diverse populations.
- Well-Being: LOW-MEDIUM (mixed): For individuals who frequently

travel for work, reduced travel time can improve well-being by minimizing time away from home, but increased travel demand may also raise stress and expectations for constant availability.

2.18 Distributed Air Mobility Networks (Air Taxis and Urban VTOLs)

Deployment of distributed networks of air taxis and urban vertical take-off and landing (VTOL) aircraft, transforming urban and suburban mobility through on-demand, point-to-point air service.

2.18.1 Barriers:

- Regulatory and Certification Challenges: Regulatory and Certification Challenges: The lack of established regulations specifically tailored for air taxis and urban VTOLs creates uncertainties and delays in certification processes. Without clear and harmonized rules, manufacturers and operators face difficulties proving safety and operational readiness, which slows down development and deployment.
- Infrastructure Limitations: Infrastructure Limitations: Existing urban infrastructure is not designed to support distributed networks of VTOLs and air taxis. The scarcity of vertiports, charging stations, maintenance facilities, and integration with ground transport networks limits scalability and operational efficiency.
- Air Traffic Management and Safety Integration: Air Traffic Management and Safety Integration: Integrating a large number of low-altitude urban air vehicles into existing airspace requires advanced traffic management solutions to prevent collisions and ensure safe operations. The complexity of managing dense, distributed flight operations poses a significant technical and regulatory challenge.
- Technological Maturity and Reliability: Technological Maturity and Reliability: Many critical technologies, such as battery energy density, autonomous flight systems, and secure communication links, are still under development or not yet proven at scale. Issues with reliability, endurance, and maintenance can hinder commercial viability and public trust.
- Public Acceptance and Noise Pollution: Public Acceptance and Noise Pollution: Concerns over noise levels, privacy, and safety can lead to resistance from communities and local governments. Negative public perception may result in restrictive policies and slow adoption rates, thereby limiting the growth of distributed air mobility networks.

2.18.2 Enablers:

- Advanced Electric Propulsion Systems: Advanced electric propulsion systems provide quieter, cleaner, and more efficient energy use for VTOL aircraft, enabling sustainable urban air mobility with lower operational costs and reduced environmental impact, which is critical for widespread adoption.
- Regulatory Framework and Air Traffic Management: A comprehensive regulatory framework along with enhanced air traffic management systems is essential to ensure safety, noise regulation compliance, and efficient integration of numerous air taxis into crowded urban airspace, which will facilitate scalable and secure operations.
- Urban Infrastructure Development: Development of urban infrastructure such as vertiports, charging stations, and dedicated flight corridors supports the physical and operational needs of distributed air mobility networks, enabling convenient takeoff, landing, and maintenance necessary for reliable service.
- Autonomous Flight and AI Technologies: Autonomous flight control systems and artificial intelligence improve safety, reduce pilot dependency, optimize routing, and enable real-time traffic adjustments, which collectively increase operational efficiency and reduce costs, accelerating rollout and scalability.
- Public Acceptance and Market Demand: Public acceptance combined with strong market demand drives investment, regulatory support, and ecosystem development while ensuring the service meets user needs and societal expectations, thereby ensuring sustained growth and integration into daily urban transportation.

2.18.3 Stakeholders impacted:

- Urban Commuters: Urban commuters will be directly impacted as distributed air mobility networks provide faster, flexible, and on-demand travel options within and between urban and suburban areas, reshaping daily transportation choices.
- Local Governments and Urban Planners: Local governments and urban planners must integrate air mobility into city infrastructure, regulate airspace usage, manage vertiport placement, and ensure safety and noise management, impacting urban development and policy frameworks.
- Air Taxi and VTOL Manufacturers: Air taxi and VTOL manufacturers will experience demand growth, innovation pressures, and regulatory challenges as they develop, produce, and maintain new types of aircraft tailored for urban air mobility.

- Air Traffic Control and Aviation Regulators: Air traffic control and aviation regulators will face the challenge of managing increased low-altitude traffic, designing new air traffic management systems, establishing certification standards, and ensuring safety and security compliance.
- Infrastructure Providers: Infrastructure providers will need to design, build, and maintain vertiports, charging stations, and supporting facilities, enabling the physical network that allows distributed air mobility operations to function efficiently.
- Environmental Organizations: Environmental organizations will monitor and influence the sustainability and emissions impact of widespread VTOL use, advocating for eco-friendly technologies and assessing noise pollution effects on communities.
- Insurance Companies: Insurance companies will have to develop new policies and risk assessment models adapted to the unique risks of urban VTOL operations, including accident liability, cybersecurity threats, and operational reliability.
- Public Transportation Operators: Public transportation operators may face competition or opportunities for integration with air mobility services, impacting ridership, service planning, and multi-modal connectivity strategies.
- Technology and Software Providers: Technology and software providers will be crucial in delivering navigation systems, autonomous flight software, traffic management platforms, and passenger booking solutions specific to distributed air mobility.
- Real Estate Developers: Real estate developers will be affected by changes in land value and usage patterns near vertiports and along air taxi routes, creating new opportunities for development and influencing urban real estate markets.

2.18.4 Environmental impact:

- Greenhouse Gas Emissions: If powered predominantly by batteries charged from non-renewable sources, distributed air mobility networks (air taxis and urban VTOLs) could contribute to greenhouse gas emissions. However, if renewable energy is used, the impact is potentially less than traditional combustion-engine vehicles or helicopters. Overall, impact is medium and highly dependent on the energy mix.
- Noise Pollution: VTOL aircraft, especially during takeoff and landing, can contribute to high-frequency noise pollution in urban environments. Even with electric motors, propeller and fan noise is significant, with a medium to high negative impact on urban soundscapes and quality of life.

- Plastic and Composite Material Pollution: The manufacturing and eventual decommissioning of air mobility vehicles will increase demand for plastics and composite materials. Improper disposal or accidental loss could contribute to plastic and microplastic pollution. The impact level is low to medium but may increase as scale grows.
- Urban Heat Island Effect: The operation of airborne vehicles in large numbers over cities may have minimal but non-negligible effects on local airflow and heat patterns, potentially aggravating the urban heat island effect. This impact is likely low but should be monitored as networks scale.
- Land Use and Habitat Disruption: Development of vertiports and supporting infrastructure could lead to the conversion of urban green spaces or disruption of natural habitats, especially if not carefully managed. The impact is generally low compared to ground-based infrastructure but could become medium with widespread adoption.
- Air Quality: Urban air taxis could shift some transportation emissions from ground to air. Electrification limits direct emissions, but battery production and energy consumption could release pollutants elsewhere. Impact is low if renewables are prioritized, but medium if legacy grids persist.
- Resource Consumption (Energy and Rare Materials): Widespread deployment will require batteries, electronics, and lightweight metals (e.g., lithium, cobalt, rare earths). Mining and refining these have environmental impacts, including pollution and ecosystem disruption. Overall impact is medium unless recycling and sustainable sourcing improve.

2.18.5 Societal impacts:

- Urban Mobility and Traffic Congestion: Deployment of air taxis and VTOLs can relieve surface-level traffic congestion, enabling faster point-to-point urban travel. The impact is potentially high and positive, especially in densely populated cities.
- Socioeconomic Accessibility and Inequality: Air taxis may initially be accessible only to wealthier individuals, potentially increasing mobility inequality. Without regulatory intervention or targeted subsidies, the impact is high and negative in terms of socioeconomic equity.
- Gender Gap: Gender gaps may be influenced depending on affordability, safety, and the inclusivity of these services. If designed with user safety and affordability in mind, air taxis can improve women's ability to travel independently, particularly at night or in less-safe areas. The impact can be medium and either positive or negative based on implementation.
- Environmental Sustainability: Urban VTOLs can reduce emissions compared to traditional cars if operated using electric propulsion and renewable

energy. However, this depends heavily on the energy source and the number of flights. The environmental impact is medium and can be positive if sustainability is prioritized.

- Urban Planning and Infrastructure: Urban infrastructure will need significant upgrades, such as vertiports and dedicated air corridors, affecting city planning and property development. The impact is high and can be disruptive, but also presents new opportunities for urban evolution.
- Public Well-being and Convenience: The convenience and reduced travel time can improve overall well-being, reduce stress, and increase productivity for users. The impact is medium and generally positive, primarily for people who can regularly access the service.
- Job Market Disruption: New jobs will be created in engineering, maintenance, and operations, but jobs in legacy transportation sectors (e.g., taxi driving) may be disrupted. The impact is medium and can be negative for affected workers, requiring retraining and support.
- Noise and Urban Disruption: Widespread VTOL operations may introduce new sources of noise and visual disruption, impacting urban quality of life. The impact is medium and negative if not addressed through design and regulation.

2.19 Quantum Computing-Optimized ATC (Air Traffic Control)

Integration of quantum computing into air traffic control, enabling ultra-fast optimization, conflict detection, and operational planning across complex, dynamic airspace environments.

2.19.1 Barriers:

- Quantum Hardware Limitations: Current quantum hardware is still in its infancy, characterized by limited qubit counts, high error rates, and instability (noise). These limitations restrict the ability to run large-scale, reliable quantum algorithms necessary for complex ATC optimization and real-time operations.
- Algorithmic and Software Development Challenges: Developing quantum algorithms specifically tailored for dynamic airspace optimization is challenging. Existing classical ATC algorithms are mature, and designing quantum counterparts that demonstrate clear advantage requires new methodologies and significant research, slowing progress.
- Integration with Existing ATC Infrastructure: Air Traffic Control systems are critical safety components with deeply embedded classical computing architectures. Integrating quantum computing solutions demands seamless

interoperability without disruption, requiring complex hybrid systems and substantial redesigns which complicate deployment.

- Regulatory and Safety Certification: Air traffic control is highly regulated to ensure safety and reliability. Introducing quantum computing technologies necessitates rigorous validation and certification processes that are currently undefined for quantum systems, delaying approval and operational adoption.
- High Costs and Resource Requirements: Quantum computing infrastructure entails significant capital investment in specialized hardware, cooling systems, and expert personnel. These costs create economic barriers for widespread adoption in the traditionally cost-sensitive air transportation sector.

2.19.2 Enablers:

- Advanced Quantum Hardware Development: The creation of scalable, stable, and error-corrected quantum processors is essential to handle the complex computations required for real-time air traffic control optimization. Advances in quantum hardware will allow systems to process vast amounts of airspace data faster than classical systems, enabling rapid conflict detection and dynamic route planning.
- Quantum Algorithms for Optimization and Conflict Detection: Developing specialized quantum algorithms tailored for air traffic control problems—such as multi-objective optimization, scheduling, and conflict resolution—is critical. These algorithms leverage quantum principles like superposition and entanglement to provide superior solutions compared to classical heuristics, improving overall safety and efficiency in airspace management.
- Integration with Classical ATC Systems: Effective development depends on seamless integration with existing classical ATC infrastructures and databases to ensure continuity and reliability. Hybrid quantum-classical approaches will allow gradual adoption by enabling quantum-enhanced decision support while maintaining proven classical control systems, reducing risk during transition.
- Robust Quantum Communication Networks: Robust, secure quantum communication networks are necessary to transmit quantum states between central quantum processors and distributed control centers. This enables synchronized decision-making and real-time data sharing with enhanced security, which is vital in the highly interconnected and safety-critical air traffic control environment.
- Regulatory and Standardization Frameworks: The establishment of clear regulatory and standardization frameworks will facilitate the adoption of quantum computing technologies within civil aviation authorities worldwide. Harmonized standards ensure interoperability, safety compliance, and

build stakeholder confidence, accelerating development and deployment of quantum-optimized ATC solutions.

2.19.3 Stakeholders impacted:

- Air Traffic Controllers: Quantum computing-optimized ATC will enhance air traffic controllers' ability to rapidly optimize flight paths, detect conflicts, and plan operations, improving safety and efficiency and reducing workload.
- Airlines: Airlines will benefit from more efficient routing and scheduling enabled by quantum-powered ATC, leading to reduced fuel costs, improved on-time performance, and increased operational reliability.
- Pilots: Pilots will experience smoother and safer flight operations facilitated by faster conflict detection and optimized flight trajectories, contributing to better situational awareness and decision-making.
- Passengers: Passengers will gain from reduced delays, improved flight safety, and potentially lower ticket prices due to operational efficiencies introduced by quantum computing in ATC.
- Airport Operators: Airport operators will face changes in traffic flow management and gate scheduling, requiring adaptation to the more dynamic and optimized airspace environment enabled by quantum computing.
- Regulatory Authorities: Regulatory authorities will need to develop updated standards, certification processes, and oversight mechanisms to safely integrate quantum computing technologies into national and international ATC systems.
- Air Traffic Management Technology Providers: Air traffic management technology providers will be impacted as they develop, integrate, and maintain advanced quantum computing solutions, creating new opportunities and challenges in system design and cybersecurity.
- Military and Security Agencies: Military and security agencies will be influenced by the enhanced capacity for managing complex and congested airspace with higher precision and faster response times, affecting defense and surveillance operations.
- Environmental Organizations: Environmental organizations will observe potential environmental benefits from optimized routing reducing fuel consumption and emissions but may also monitor any unintended consequences of new ATC technologies on noise and local environments.
- Local Communities: Local communities near airports and flight corridors may experience changes in noise patterns and air traffic density due to more precise and efficient routing enabled by quantum computing-optimized ATC.

2.19.4 Environmental impact:

- Greenhouse Gas Emissions: Quantum computing-optimized ATC can enable more efficient flight routing, reduce holding patterns, and minimize delays, potentially leading to a medium positive impact on greenhouse gas emissions by reducing total fuel burn from aircraft. However, any efficiency gains will also depend on actual air traffic demand and operational implementation.
- Energy Consumption: Quantum computers themselves require significant energy to operate and cool, especially with current early-stage technology. While the ATC optimization may reduce aircraft fuel usage (a positive impact), the energy demand to run quantum systems in ATC centers could pose a low to medium negative impact depending on the energy source used.
- Electronic Waste: The deployment of new quantum computing hardware for ATC will eventually lead to additional electronic waste as older systems are replaced or updated. The scale of deployment is relatively limited compared to consumer electronics, so this effect is likely low negative.
- Plastic Pollution: Plastic pollution relating directly to quantum computing-optimized ATC is minimal. Hardware components do include plastics, but relative to the potential environmental benefits, the impact is expected to be low negative or negligible.
- Noise Pollution: More efficient ATC should reduce the need for airborne holding and rerouting, which can lower instances of arrivals and departures around airports, thereby slightly reducing localized noise pollution. This is considered a low positive impact.

2.19.5 Societal impacts:

- Safety and Reliability: Quantum-optimized ATC can greatly reduce the risk of human error and increase the reliability and safety of air travel, leading to a high positive impact on society's overall trust in aviation.
- Economic Efficiency: By enabling more efficient route planning and minimizing delays, quantum computing in ATC can reduce operational costs and increase airline profitability, benefiting both consumers and the air transport industry. This impact is high and positive.
- Employment and Workforce Transformation: The automation of complex decision-making may reduce the need for some traditional ATC roles but also create demand for new skill sets in quantum computing and AI, leading to medium to high workforce transformation. This impact could be mixed—positive for highly skilled workers but potentially negative for those whose roles become obsolete.

- Environmental Impact: Optimization of flight paths can minimize fuel consumption and emissions, resulting in a significant environmental benefit. This positive impact is medium to high, as it supports sustainability goals.
- Gender Gap and Diversity: Advanced technology integration may help close the gender gap if inclusive education and hiring practices are adopted, making skill sets, rather than traditional backgrounds, the main selection criteria. However, if accessibility to quantum computing education remains unequal, the impact could be low or even negative, perpetuating tech gender gaps.
- Well-being and Stress Reduction: Reduced flight delays and enhanced travel predictability improve the experience for passengers and decrease stress and pressure on ATC personnel, leading to a medium positive impact on overall well-being.

2.20 AI-Driven Predictive Maintenance and Self-Healing Systems

Widespread use of artificial intelligence in predictive aircraft maintenance, early fault detection, and onboard self-healing systems, minimizing unscheduled downtime and improving safety.

2.20.1 Barriers:

- Data Quality and Availability: AI-driven predictive maintenance and self-healing systems require large volumes of high-quality, accurate, and diverse data from aircraft sensors and systems. Inconsistent or incomplete data hinders model training and reduces the reliability of predictions, delaying development and deployment.
- Regulatory and Certification Challenges: The aviation industry is highly regulated to ensure safety. Obtaining certification for AI systems, which often behave as black boxes, is challenging due to strict requirements for transparency, validation, and reliability. This regulatory hurdle slows innovation and adoption.
- Integration Complexity: Integrating AI-driven systems with existing aircraft architectures and legacy maintenance workflows is complex. The need to ensure compatibility without disrupting current operations complicates development and prolongs testing phases.
- Cybersecurity Risks: Introducing AI and connectivity increases potential attack surfaces for cyber threats. Ensuring robust cybersecurity to protect critical aircraft systems is mandatory but difficult, adding constraints and necessitating additional research and safeguards.
- High Implementation Costs: Developing and deploying advanced AI predictive maintenance and self-healing capabilities involve substantial upfront

investment in technology, infrastructure, and training. High costs may limit adoption, especially by smaller operators or in cost-sensitive markets.

2.20.2 Enablers:

- Advanced Sensor Technologies: Advanced sensor technologies enable real-time, high-precision data collection from aircraft systems, which is critical for accurate fault detection and prediction. By continuously monitoring engine performance, structural health, and other critical parameters, sensors provide the foundation for AI-driven predictive maintenance and self-healing capabilities.
- Big Data Analytics and Cloud Computing: Big data analytics and cloud computing offer the necessary infrastructure to store, process, and analyze massive volumes of data generated by aircraft sensors. These technologies allow for scalable, fast, and cost-effective analysis, enabling timely maintenance predictions and the assessment of complex system interactions across fleets.
- Machine Learning and AI Algorithms: Machine learning and AI algorithms analyze sensor and operational data to detect patterns and anomalies indicative of impending failures. These algorithms improve over time through training on historical data, enhancing the accuracy of maintenance forecasts and enabling autonomous self-healing responses that reduce unscheduled downtime.
- Robust Communication Networks: Robust communication networks, including satellite and ground-based systems, ensure continuous and secure data transmission between aircraft and maintenance centers. Reliable connectivity is essential for real-time diagnostics, remote monitoring, and timely activation of self-healing protocols, especially during flight.
- Regulatory Support and Standardization: Regulatory support and standardization provide the necessary frameworks to safely integrate AI-driven systems into aviation operations. Clear guidelines and industry-wide standards facilitate certification, promote interoperability between systems, and build trust among manufacturers, operators, and regulatory bodies, accelerating adoption.

2.20.3 Stakeholders impacted:

- Airlines: Airlines will benefit from reduced operational disruptions and maintenance costs due to predictive maintenance and self-healing systems, leading to improved fleet availability and profitability.
- Aircraft Manufacturers: Aircraft Manufacturers will need to integrate AI-driven systems into new aircraft designs, enhancing aircraft reliability and performance while maintaining competitive advantage.

- Maintenance Service Providers: Maintenance Service Providers will shift from reactive to proactive maintenance approaches, requiring new skills and tools to manage AI-driven predictive analytics and self-healing technologies.
- Pilots and Flight Crew: Pilots and Flight Crew will experience increased flight safety and fewer emergency situations as AI systems detect and mitigate faults early or autonomously resolve issues during flight.
- Passengers: Passengers will enjoy greater flight punctuality, improved safety, and overall enhanced travel experience resulting from minimized unscheduled downtime and fewer technical delays.
- Regulatory Authorities: Regulatory Authorities must update and enforce safety regulations and certification standards to address new AI-enabled maintenance and self-healing technologies, ensuring compliance and safety.
- Airport Operators: Airport Operators will face changes in ground operations management as predictive maintenance reduces unexpected aircraft groundings, requiring more dynamic scheduling and resource allocation.
- AI and Technology Developers: AI and Technology Developers will be key enablers by creating and continuously improving the algorithms, sensors, and systems that enable predictive maintenance and autonomous fault resolution.
- Insurance Companies: Insurance Companies will need to adjust risk assessment models and policies reflecting the reduced likelihood of mechanical failures and accidents due to predictive and self-healing technologies.
- Investors and Shareholders: Investors and Shareholders will be impacted by potential changes in company valuation and growth prospects driven by operational efficiencies, cost savings, and enhanced safety due to these AI systems.

2.20.4 Environmental impact:

- Greenhouse Gas Emissions: AI-driven predictive maintenance and self-healing systems can have a positive medium-level impact on reducing greenhouse gas emissions by increasing aircraft operating efficiency, optimizing flight schedules, reducing fuel wastage from unscheduled maintenance and flight delays, and enabling earlier detection of inefficiencies; thus, aircraft engines and systems operate more efficiently and emit less CO2 over time.
- Resource Consumption and E-waste: The deployment of advanced AI systems requires additional sensors, computing hardware, and digital infrastructure, leading to increased consumption of rare earth elements, metals, and other electronic resources. Over time, as more aircraft are equipped and older hardware becomes obsolete, this can create a moderate negative impact in the form of electronic waste (e-waste).

- Plastic Pollution: The integration of AI systems might slightly increase plastic pollution due to the use of polymer-based components in sensors and circuit boards; however, the impact is likely low and could be offset by reduced need for spare parts and physical diagnostic equipment resulting from more accurate maintenance.
- Chemical Pollution: Better predictive maintenance can decrease the use of environmentally harmful chemicals since early detection reduces catastrophic failures and the need for intense cleaning or emergency repairs, producing a small positive impact on reducing chemical pollution.
- Noise Pollution: In some cases, self-healing systems or predictive repairs might reduce the number of emergency landings and aborted take-offs, which are typically noisy and disruptive, creating a low to medium positive effect on local noise pollution at and around airports.

2.20.5 Societal impacts:

- Safety and Reliability: AI-driven predictive maintenance and self-healing systems can significantly reduce the risk of unexpected failures in critical infrastructure, like air transportation, leading to fewer accidents, less downtime, and improved reliability. This will have a high and positive impact on public safety and trust in technology.
- Economic Efficiency and Job Market: Automation of maintenance tasks could reduce demand for certain manual labor roles, potentially displacing workers but also creating new jobs in AI and data management. The overall economic efficiency will increase (high impact), but there may be negative effects in specific sectors unless reskilling initiatives are provided.
- Environmental Impact: By optimizing maintenance schedules and extending equipment lifespan, these systems can lower waste and decrease resource consumption, supporting environmental sustainability efforts. This is a medium to high positive impact.
- Reduction in Gender Gap: As AI-driven systems can help remove bias from recruitment by prioritizing skills needed for technology-driven roles, there is potential for narrowing the gender gap in STEM and technical maintenance jobs, provided access to education is equally distributed. Impact level: medium, with the possibility of positive structural change if accompanied by inclusive policies.
- Overall Well-being: With increased reliability and the reduction of failures and accidents, people's sense of security and trust in public services, especially transportation, will grow. This will positively affect mental well-being and quality of life; impact level: high.