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Planning aerial drone infrastructures: a multi-criteria analysis approach to identify suitable areas for vertiports and corridors

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PLANNING DRONE INFRASTRUCTURES:

A MULTI-CRITERIA ANALYSIS APPROACH TO IDENTIFY SUITABLE AREAS FOR VERTIPORTS AND CORRIDORS

BY

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ABSTRACT

This dissertation addresses the emerging challenge of integrating drones into civil airspace, with a particular focus on the planning of infrastructures such as vertiports and aerial corridors. Within the broader context of the Digital European Sky and the implementation of U-space, the research explores how geospatial analysis and multi-criteria decision-making (MCA) can support infrastructure placement strategies.

Building upon regulatory frameworks developed by EASA and technological advancements promoted through SESAR initiatives, this study proposes a spatial methodology to assess the suitability of locations for vertiports and corridors. The approach considers a wide range of criteria including drone performance, safety constraints, regulatory limitations, environmental factors, and social acceptance. The analysis is implemented through a GIS-based framework, incorporating urban and extra-urban case studies.

By generating detailed suitability maps, the research identifies the most promising zones for infrastructure development, while also highlighting limitations due to regulatory, environmental, or technical constraints. Additionally, positioning and connectivity coverage analyses using 4G and 5G mobile antennas were conducted to assess the spatial quality of drone operations.

The results contribute to a more informed and sustainable integration of Urban Air Mobility into existing spatial and transport planning practices. The methodology developed can serve as a reference for public administrations, planners, and industry stakeholders involved in the design of drone-based transport systems.

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LIST OF ABBREVIATIONS

AAM - Advanced Air Mobility
ACARE - Advisory Council for Aviation Research in Europe
AEMET - Agencia Estatal de Meteorología (ES)
AESA - Agencia Estatal de Seguridad Aérea (ES)
AGL - Above Ground Level
AHP - Analytic Hierarchy Process
AHC - Agglomerative Hierarchical Clustering
AIP - Aeronautical Information Publication
AIXM - Aeronautical Information Exchange Model
AI - Artificial Intelligence
ANSP - Air Navigation Service Provider
API - Application Programming Interface
ARC - Air Risk Class
ARPAE - Agenzia Regionale per la Protezione Ambientale dell’Emilia-Romagna (IT)
ATCO - Air Traffic Control Officer
ATM - Air Traffic Management
ATS - Air Traffic Services
AURA - ATM U-space Interface
AV - Autonomous Vehicle
BUBBLES - Defining the BUilding Basic BLocks for a U-Space SEparation Management Service
BVLOS - Beyond Visual Line of Sight
CAA / CAAs - Civil Aviation Authority / Authorities
CEF - Connecting Europe Facility
CINEA - European Climate, Infrastructure and Environment Executive Agency
CNS - Communications, Navigation and Surveillance
CORUS - Concept of Operations for U-space
CRLB - Cramér-Rao Lower Bound
CRS - Coordinate Reference System
DACUS - Demand and Capacity Optimisation in U-Space
DAA - Detect And Avoid
DEM - Digital Elevation Model
DES - Digital European Sky
DIPAS - Digital Participation System
DORALab - Drone Operations Research and Application Lab
DSM - Digital Surface Model

DST - Decision Support Tool
DTM - Digital Terrain Model
EASA - European Union Aviation Safety Agency
EC - European Commission
ECAC - European Civil Aviation Conference
EIA - Environmental Impact Assessment
ENAC - Ente Nazionale per l’Aviazione Civile (IT)
ENAIRE - Empresa Nacional de Servicios de Navegación Aérea (ANSP spagnolo)
ETRF2000 - European Terrestrial Reference Frame 2000
EUROCONTROL - European Organisation for the Safety of Air Navigation
EV - Electric Vehicle
FAA - Federal Aviation Administration
FATO - Final Approach and Take-Off Area
FLARM - Flight Alarm (anticollisione per aviazione generale)
FOC - Flight Operations Center
GCAA - General Civil Aviation Authority
GDPR - General Data Protection Regulation
GIS - Geographic Information System
GNSS - Global Navigation Satellite System
GOF - Gulf of Finland
GRC - Ground Risk Class
GPS - Global Positioning System
ICAO - International Civil Aviation Organization
IFR - Instrument Flight Rules
IGM - Istituto Geografico Militare, Italian Military Geographic Institute
IR - Industrial Research
ISTAT - Istituto Nazionale di Statistica (IT)
JARUS - Joint Authorities for Rulemaking on Unmanned Systems
JU - Joint Undertaking
KPA - Key Performance Area
L_Aeq - Equivalent Continuous A-Weighted Sound Level
L_den - Day-Evening-Night Sound Level
L_max - Maximum Sound Level
MAWP - Multiannual Work Programme
MCA - Multi-Criteria Analysis
MTOW - Maximum Take-Off Weight
NOTAM - Notice to Air Missions (ex Notice to Airmen)
OD - Origin-Destination (pair/matrix)

OFS - Obstacle-Free Surface
OLS - Obstacle Limitation Surface
OSM - OpenStreetMap
OSO - Operational Safety Objectives
PGOU - Plan General de Ordenación Urbana (ES)
PNRR - Piano Nazionale di Ripresa e Resilienza (IT)
PRGC - Piano Regolatore Generale Comunale (IT)
PSC - Piano Strutturale Comunale (IT)
PSO - Public Service Obligation
PTR - Piano Territoriale Regionale (IT)
PTCP - Piano Territoriale di Coordinamento Provinciale (IT)
PTPR - Piano Territoriale Paesaggistico Regionale (IT)
PUC - Piano Urbanistico Comunale (IT)
PUG - Piano Urbanistico Generale (IT)
RPA - Remotely Piloted Aircraft
RRT / RRT* - Rapidly-Exploring Random Tree (algorithm)
RUE - Regolamento Urbanistico Edilizio (IT)
RTTA - Reasonable Time To Act
SAIL - Specific Assurance and Integrity Level
SDM - SESAR Deployment Manager
SEA - Strategic Environmental Assessment
SES - Single European Sky
SESAR - Single European Sky ATM Research
SORA - Specific Operations Risk Assessment
SUMP - Sustainable Urban Mobility Plan
SWIM - System Wide Information Management
TBO - Trajectory-Based Operations
TDOA - Time Difference of Arrival
TLOF - Touchdown and Lift-Off Area
TOL - Take-Off and Landing
TTC - Time To Conflict
TRL - Technology Readiness Level
UAM - Urban Air Mobility
UAS - Unmanned Aircraft System(s)
UAV - Unmanned Aerial Vehicle
UIC2 - UAM Initiative Cities Community
U-space - Digitised services enabling safe and efficient access to very-low-level airspace
USSP - U-space Service Provider

UTM - UAS Traffic Management
eVTOL - Electric Vertical Take-Off and Landing (aircraft)
VCA - Vertical-Take-Off-and-Landing Aircraft (term used in text; non-standard vs VTOL)
VFR - Visual Flight Rules
VLD - Very Large-scale Demonstration
VLL - Very Low-Level (airspace below ~120 m AGL)
VLOS - Visual Line of Sight
VTOL - Vertical Take-Off and Landing

INTRODUCTION

This thesis is the result of a doctoral research project supported by the Italian Ministry of University and Research (MUR) under the PNRR Mission 4, Component 2, 'From Research to Business' - Investment 3.3, aimed at introducing innovative PhD programs that address the innovation needs of companies and promote the recruitment of researchers by industry, co-financed by Geodatalab Srls. The research also received support from the Universitat Politècnica de València, as part of a cooperation agreement with the Università degli Studi di Genova, which facilitated my research stay in Valencia from March to August 2024. At the conclusion of this period, Professor Juan Vicente Balbastre Tejedor joined as a doctoral supervisor, alongside Professor Domenico Sguerso, academic supervisor of the Geomatics laboratory at the Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, and Chiara Sammarco, industrial supervisor at Geodatalab Srls.

The doctoral program announcement, set by the University of Genoa and Geodatalab Srls, was titled: 'Industrial application-driven research towards the Digital European Sky' with the following description: "*This PhD project, in collaboration with GeoDataLab Srls, aims to develop industrial application-driven research towards the Digital European Sky. The candidate will be expected to study and keep constantly aligned in terms of exploratory and industrial research directed at the implementation of the so-called 'Digital European Sky', more specifically in the U-Space area. Specific contributions to the research will be provided both in terms of concrete development of services and demonstration platforms in the U-Space sphere aimed at analysing and validating the scenarios proposed in the European sphere, and in terms of integrations with existing software or plug-ins, such as the U.Ph.O. application developed by the Geomatics Laboratory of the DICCA, University of Genoa, in the sphere of 3D photogrammetric survey accuracy. Finally, the candidate will develop specific analyses aimed at answering the open research points already identified in the first exploratory surveys. The candidate should have a background in Geomatics and Geospatial Technologies, and experience in programming and spatial data analysis. The candidate should show particular attitude to learning new programming languages. Previous study abroad is also welcome*".

Starting from the concepts of the Digital European Sky (DES) and U-space outlined in this brief description, I began my work by identifying a research area within the sector that had not yet been explored or where our expertise could have possibly relevance. The initial step was to progressively identify keywords and refine the search to determine which best represented the research focus we aimed to define. This approach provided a general understanding of the research area and helped clarify the direction in which it was heading. The main terms are Advanced Air Mobility (AAM) and Urban Air Mobility (UAM). As highlighted by (Garrow et al., 2021), when researching the drone sector, it is still challenging to determine which terms should be used, as this emerging field lacks standardized terminology. However, the terms AAM and UAM are among the most frequently mentioned in this sector. In addition, since this research was developed in Europe, the primary stakeholders in regulation and funding were identified. The main entities include EASA (European Union Aviation Safety Agency), EUROCONTROL

(European Organisation for the Safety of Air Navigation), and the European Commission, which, through the SESAR (Single European Sky ATM Research; ATM - Air Traffic Management) program (Bolić et al., 2021), contribute to developing the DES. The goal is to automate all flights to realize the Single European Sky (SES), thereby unifying EU airspaces. Although, in the future, all vehicles will share the same airspace, the one currently reserved for drones is called U-space. SESAR funds projects focused on developing and testing innovative solutions for integration into the aviation system to achieve the DES.

SESAR is the most relevant program and develops various plans, primarily three, each with a different planning timeline. By analyzing these plans and building on my studies in urban planning and geographic information science, as well as my academic and professional experience, a development area was identified that also encompasses geomatics: the determination of the most suitable locations for drone infrastructure, specifically vertiports and corridors. This objective was later confirmed by additional plans, this time at a national rather than European or international level, such as the National Strategic Plan for AAM developed by ENAC (Italian Civil Aviation Authority - Ente Nazionale per l'Aviazione Civile) and the Italian Ministry of Transport. The plan specifically addresses: 'Integration of vertiport operations into urban structures to mitigate risk' and 'Identify any critical issues that need to be addressed to fully implement AAM in urban environments in accordance with city plans.

Once a clear objective was identified, the research refocused on finding more specific keywords, such as vertiport, corridor, AAM, UAM, and infrastructure. Many articles were then identified by consulting the bibliographies of other works.

Building on the institutional and funding context described above and on the doctoral call oriented to the DES, this dissertation addresses a persistent planning gap: where and under what conditions vertiports and aerial corridors should be located so that drone operations are safe, efficient, and socially acceptable in both urban and extra-urban settings within the European DES/SES ecosystem. The work positions U-space infrastructure siting as a spatial, criteria-driven decision problem that must reconcile regulatory constraints, environmental protection, technical feasibility, and socio-economic acceptance. In this perspective, I tried to work on a reproducible methodology to locate those infrastructures with the less impact.

The methodology adopted to achieve this objective is Multi-Criteria Analysis (MCA), which conceptually distinguishes between exclusions - hard constraints arising from law, safety, and environmental protection that render locations a priori ineligible - and eligibility factors. The first are applied either as end-of-pipeline masks or as an overriding decision filter, while the latter provide the weighted inputs used to construct the MCA suitability surface. This split allows us to define non-negotiable rules (e.g., permanent airspace prohibitions or protected areas) while comparing heterogeneous factors (e.g., noise, meteorology, grid connection, coverage/positioning proxies, accessibility, socio-economics) on a common spatial canvas. The analysis also clarifies role differences at nodes versus links: vertiports are governed by pad-level constraints (e.g., OLS/obstacles, horizontal noise stand-off, access to electricity and multimodal nodes), whereas corridors are shaped by altitude-dependent effects, airspace rules, continuity of CNS (Communications, Navigation and Surveillance) quality, and environmental factors.

The present work builds upon the methodology for positioning U-Space infrastructures proposed in previous studies, expanding the scope to include a multi-criteria spatial analysis. The study focuses on drones under 25 kg logistic transport in urban and extra-urban environments and discusses an exploratory passenger-transport framing in urban settings. In extra-urban environments, industrial rooftops and logistics compounds are examined as potential vertiport locations, balancing safety, noise and electrical connection; in dense urban environments, more articulated reading is required, harmonizing operations with existing soundscapes and urban form while complying with airspace and obstacle rules. The spatial analysis seeks to optimize airspace usage so that vertiports and corridors can be placed for efficiency with minimal impacts on people and the environment.

Emilia-Romagna is selected for the **extra-urban logistics scenario** thanks to regional datasets - especially meteorological records - well aligned with large-area processing requirements, while **Valencia** provides a dense **metropolitan** setting aligned with local mobility planning and with the collaboration established during the UPV research stay. The urban application calibrates the same logic to building morphology, noise/visual sensitivity, and multimodal access, keeping the vertiport/corridor distinction but applying some differentiations downstream through post-selection checks where integrated landscape instruments at the same scale are not available. Across both contexts, results are presented as decision-support - auditable maps and shortlists to inform planning choices rather than deterministic prescriptions.

The thesis is structured as follows:

- **Chapter 1** (State of the art) lays the theoretical foundations by surveying the state of the art and the institutional framework of U-space within the DES/SES ecosystem. It aligns terminology (UAM/AAM), stakeholders, and European programmatic instruments (e.g., SESAR) with the planning challenges of vertiports and corridors, and reviews urban planning and GIS (Geographic Information System) methods relevant to site selection. By synthesizing regulatory, technical, and planning strands, the chapter explains the research gap that motivates the spatial, criteria-driven siting approach developed in the remainder of the thesis.
- **Chapter 2** (Methodology) presents the methodological workflow. It formalizes the exclusion - eligibility split, the operationalization of factors into GIS layers, and the MCA aggregation process. The chapter clarifies how common evidence bases - regulatory rules and AIP (Aeronautical Information Publication) masks, protected/natural areas, meteorology, noise and visual exposure, land use and population risk (SORA-informed), energy availability and proximity to the grid, CNS coverage and 4G/5G-based positioning (via CRLB - Cramér-Rao Lower Bound), accessibility to multimodal nodes, and socio-economic proxies - are standardized and read to locate nodes (vertiports) and links (corridors). It also outlines how network concepts (e.g., least-cost paths over corridor surfaces and

Delaunay skeletons over shortlisted nodes) translate raster suitability into indicative connective structures.

- **Chapter 3** (Case studies) applies the methodology in two contrasting use-case studies to test transferability and shows how regulatory, morphological and data conditions shape outcomes. In Emilia-Romagna (extra-urban logistics), the screening emphasizes industrial/logistics compounds and warehouse rooftops as candidates, with upstream differentiation of vertiport - versus corridor-oriented layers facilitated by integrated landscape instruments; shortlisted nodes are clustered and connected to sketch plausible intercity main lines. In Valencia (urban last-mile), the same MCA is calibrated to the metropolitan mobility framework and dense built form; given available instruments, a single MCA surface is produced and the vertiport/corridor differentiation is applied downstream through post-selection checks (pad-level OLS and horizontal noise offset for vertiports; altitude-dependent constraints, air-risk (ACR) and CNS continuity for corridors). An exploratory framing for passenger operations highlights how the same logic extends beyond cargo.
- **Chapter 4** (Result and discussion) reports composite suitability patterns, shortlists and indicative network structures for each context, and discusses how levers such as altitude policies, treatment of protected areas, and pad-level noise/visual thresholds shift feasibility. This chapter documents post-aggregation checks - AIP, OLS/obstacles, environmental masks and CNS coverage - used to confirm or discard candidates and frames the outputs explicitly as decision-support with sensitivity notes and policy reading for deployment pathways.
- **Conclusions** synthesize the scientific and operational contributions: a transparent, replicable GIS-MCDA approach for siting vertiports and corridors under current European rules and data realities; empirical insights from two different territorial regimes; and a **roadmap** toward auditable programmatic tools (API - Application Programming Interface) with dynamic inputs, validation and standardization - so that cities, agencies and researchers can **reuse, parameterize and scrutinize** the same logic on their own data

1. STATE OF THE ART

This chapter consolidates the scientific literature, European and national policy documents, and research initiatives that underpin the conceptual and regulatory background of this PhD research. Its purpose is twofold: (i) to frame the current state of knowledge on the integration of unmanned aircraft into civil airspace - especially within the European context - and (ii) to extract the elements that are directly actionable for spatial planning, with a specific emphasis on vertiports (nodes) and aerial corridors (links). The chapter focuses on how policies, operational concepts, and scientific contributions translate into planning constraints, spatial criteria, and GIS-processable layers, which are then formalized in Chapter 2.

The chapter is structured as follows.

Section 1.1 (Research scope and context) introduces the research problem and clarifies the scope of the dissertation. It explains why the expected growth of air traffic and the rise of drone-based services - particularly in complex urban environments - create a need for new types of infrastructures and planning procedures. It then positions the work within the European evolution towards an increasingly interoperable and automated airspace by introducing the key conceptual frameworks, alongside the main institutional actors and stakeholder groups relevant to drone integration and infrastructure development.

Section 1.2 (Policy and operational context for UAS - Unmanned Aircraft System infrastructure planning in Europe) establishes the European policy and operational setting that motivates infrastructure siting as a spatial decision problem. It first introduces SESAR as the main European mechanism linking strategic planning, research and innovation, and deployment, and clarifies which program elements are referenced in the thesis and why. It then frames AAM/UAM and U-space as operational concepts that imply spatially explicit requirements (e.g., operational volumes, geo-awareness constraints, and deconfliction/monitoring needs). Finally, it discusses the core planning implication adopted throughout the dissertation: infrastructures are treated through a node–link abstraction, where vertiports and corridors respond to different constraints and require different planning logics. This section anticipates how these drivers are translated into spatial criteria and staged checks in Chapter 2.

Section 1.3 (Urban and transport planning for UAS integration) narrows the focus from the European context to the planning and governance frameworks that shape feasibility in real territories, with reference to the two national contexts of the case studies (Italy and Spain). It reviews national strategic documents for advanced air mobility and outlines how transport and spatial planning responsibilities are organized across levels of government, highlighting why infrastructure decisions must be consistent with existing planning instruments and regulatory constraints. The section also introduces the relevance of planning tools derived from conventional aviation such as the Airport Risk Plan, as it provides an established approach for translating safety requirements into spatial restrictions.

Section 1.4 (Urban GIS methodologies for area selection) introduces the methodological building blocks used later in the dissertation to operationalize planning constraints and suitability factors in a geospatial workflow. It summarizes the role of GIS in spatial decision support and presents the core analytical approaches adopted in the thesis and network constructs explicitly as tools to convert heterogeneous planning requirements into comparable spatial evidence.

Section 1.5 (Foundational domains for UAM siting: a literature review) provides a structured state-of-the-art synthesis of the principal domains that literature identifies as determinants of infrastructure feasibility. The review is organized around the key dimensions that later become criteria families in the methodology (e.g., safety and risk-related constraints, social acceptance and nuisance, technical/drone performance limitations, planning and regulatory alignment, infrastructure compatibility, and accessibility). This section therefore functions as the conceptual bridge between "what is known" in the literature and "what can be represented" as spatial layers and decision rules.

Finally, Section 1.6 (Synthesis: the need for a criteria-based siting methodology) closes the chapter by consolidating the main implications emerging from the policy context and the scientific literature. It clarifies the planning gap addressed by the dissertation - namely the need for a transparent, auditable, and transferable locating procedure able to reconcile regulatory constraints, safety and nuisance considerations, technical feasibility, and planning coherence - and prepares the transition to Chapter 2, where these requirements are formalized into the proposed GIS-based MCA workflow.

1.1. RESEARCH SCOPE AND CONTEXT

Traditional air traffic has increased in recent years and is expected to keep growing, driven in part by demand expansion in emerging economies and the consequent development of airport infrastructures (SESAR Join Undertaking, 2020). This trend increases pressure on already constrained systems and highlights the need for more efficient and sustainable transport solutions. In parallel, technological progress - especially in electric propulsion and automation - has enabled new types of aerial vehicles, including drones that are no longer limited to recreational or professional uses, but are increasingly considered for the transport of goods and, prospectively, people. Consequently, new airspace and operational needs have emerged, particularly in urban environments, where safety, nuisance, and governance constraints are more pronounced.

Against this background, this thesis focuses on the infrastructure required to enable drone-based operations at scale and on how their spatial planning can be supported through transparent process. The work addresses the need to define and support: (i) **ground nodes such as vertiports**, intended as take-off/landing and servicing locations; (ii) **aerial corridors** or preferred flight paths to structure traffic and reduce interference with sensitive areas; and (iii) **risk-mitigation strategies** that support safety objectives and regulatory compliance.

During the initial phase of the doctoral research, the analysis also considered trajectory-based navigation concepts for drones, including the identification of feasible routes between departure and arrival nodes while accounting for restrictions like those adopted in conventional aviation. However, as the research evolved through the review of EU-funded projects and academic literature, the central problem became the lack of practical and transferable planning procedures for infrastructure placement. Accordingly, **the thesis concentrates on how vertiports and corridors can be planned as complementary infrastructures to the ones existing**.

In this work, two potential commercial operating models are considered to distinguish between two domains: extra-urban and urban. By analogy with terrestrial logistics, larger drones may cover longer distances and connect with logistics hubs located outside dense urban areas, while smaller vehicles may provide “last mile” services to reach destinations closer to end users. This distinction has direct planning implications, as nodes and links play different roles and are subject to different constraints across the two domains.

Energy consumption remains a major limiting factor, together with technological constraints that can reduce safety margins compared with other modes of transport. Battery autonomy therefore strongly influences the operational range and the set of areas over which flights can be performed with acceptable risk, especially when densely populated zones are involved. For this reason, additional supporting infrastructures - such as maintenance facilities and charging hubs, often co-located with vertiports - are expected to be important to increase mission reliability and to enable extended operations in early deployment stages.

This work was initiated more than three years ago and originally drew on the programmatic objectives set out in European development roadmaps for these technologies. As these roadmaps are periodically updated, some of the earlier targets that informed the direction of this research are no longer explicitly reflected in the most recent versions; nonetheless, they remain useful to contextualize the rationale underpinning this study. The European policy and innovation context is framed by the Single European Sky (SES), which aims to reduce fragmentation across national regulatory frameworks and improve the efficiency, safety, and sustainability of European airspace through common rules and interoperability. SES is supported by the SESAR programme as its technological development and validation pillar, while EASA provides the regulatory baseline for safety in civil aviation and has progressively extended its remit to include the approval and certification of relevant aviation systems and organizations, including those related to unmanned operations. Within this evolution, the Digital European Sky (DES) can be interpreted as an increasingly automated trajectory of SES: enhanced information sharing, secure connectivity, resilience, and the integration of manned and unmanned operations are expected to enable scalable services, including those envisaged under U-space, the European framework for the safe and efficient integration of drone operations.

In this thesis, SES and DES are introduced to motivate the need for auditable, criteria-based spatial planning tools for UAS infrastructures. A more detailed overview of institutional roles, stakeholder groups, and additional program/document descriptions is provided in the Appendix A and Appendices C-E.

1.2. OPERATIONAL CONTEXT FOR UAS INFRASTRUCTURE PLANNING IN EUROPE

This section outlines the policy and operational context that frames UAS infrastructure planning in Europe. It first introduces the SESAR program as the main European vehicle linking strategic planning with research, innovation, and deployment actions. It then presents AAM/UAM and U-space as operational concepts that shape the assumptions, services, and constraints relevant to scalable UAS operations. Finally, it discusses the planning implications of these concepts by framing vertiports and corridors as node-link decision objects, anticipating how they are translated into spatial criteria and GIS layers in Chapter 2.

1.2.1. Evolution, structure, and objectives of the SESAR program

SESAR represents the main European framework that links strategic planning, research and innovation, and deployment actions to modernize air traffic management and to enable the progressive integration of new airspace users. In this thesis, SESAR is introduced to clarify why the European vision for a digital, interoperable and service-oriented airspace is directly relevant to the emergence of scalable drone operations and, consequently, to the need for dedicated infrastructures (vertiports and corridors) and spatial planning procedures.

From an institutional perspective, the SESAR ecosystem includes two complementary entities: the SESAR Joint Undertaking (SJU), responsible for coordinating research and innovation activities, and the SESAR Deployment Manager (SDM), supporting the large-scale deployment of validated solutions. In the remainder of this dissertation, SESAR references mainly relate to the SJU, as the methodological focus is linked to how programmatic objectives and research output shape operational assumptions, services, and constraints that can be translated into spatial criteria for infrastructure planning (Bolić et al., 2021).

Historically, SESAR has progressed through three phases. The Definition Phase (2005 - 2008) produced the first European ATM Master Plan, setting the strategic direction. The Development Phase (2008 - 2016), managed by SJU, focused on designing and validating solutions. The Deployment Phase (2014 - present), coordinated through the SDM, supports the transition from validated concepts to large-scale implementation (SESAR Joint Undertaking, 2022b). This phased structure is mentioned here to motivate the link between strategic objectives and operationally usable outputs (services, procedures, assumptions), which later chapters translate into spatial layers and constraints.

SESAR’s strategic objectives are operationalized through a set of programmatic plans that provide a common reference for European stakeholders, linking long-term modernization goals to coordinated research, innovation, and deployment activities. These documents are periodically updated and differ in scope and temporal horizon: the longer the horizon, the more strategic the guidance; as the horizon becomes shorter, the documents become progressively more operational and specific.

The European ATM Master Plan acts as the overarching roadmap, synthesizing the modernization vision and identifying key capabilities and operational changes required over time (SESAR, 2020b). Complementary to the Master Plan, the Multiannual Work Program details how strategic priorities are translated into a multi-year research and innovation agenda within the SESAR 3 Joint Undertaking mandate (SESAR 3 Joint Undertaking, 2022). At a shorter time scale, the Bi-Annual Work Program provides a more operational articulation of priorities and actions, supporting continuity between program objectives and specific R&I activities (SESAR Joint Undertaking, 2022a). In addition, SESAR documents discussing the Digital European Sky perspective highlight the increasing role of digitalization, secure information exchange, and automation as enabling drivers for future operations (SESAR, 2020a).

Within this programmatic framework, the European ATM Master Plan and the associated work programs are referenced mainly for three classes of objectives directly connected to the problem addressed in this thesis. First, they emphasize the progressive transition toward a digital and service-oriented aviation system based on harmonized information exchange and interoperability, which motivates the need for planning approaches that are transparent and transferable across contexts. Second, they support the safe integration of new airspace users, particularly unmanned operations - through structured operational concepts and enabling services, which justifies the focus on defining ground nodes and aerial links as part of a scalable ecosystem. Third, they promote performance- and sustainability-oriented developments (safety, environmental impact, and operational efficiency), which in planning terms translate into the need to account for safety-related constraints and nuisance-sensitive receptors (e.g., population exposure and noise-sensitive land uses) alongside feasibility and accessibility considerations.

Finally, SESAR’s work is operationalized through dedicated funding and project instruments that support different maturity levels of research and demonstration activities. In this chapter these instruments are mentioned only to clarify how the European program translates objectives into concrete R&I actions, while extended summaries, document-by-document descriptions, and additional programmatic details are provided in the Appendices C-E.

1.2.2. Advanced Air Mobility (AAM), Urban Air Mobility (UAM) and U-space

The emergence of Advanced Air Mobility (AAM) and, more specifically, Urban Air Mobility (UAM) is closely linked to progress in electric propulsion, autonomy, and digital connectivity, which has expanded the operational potential of unmanned aircraft beyond recreational and professional uses. In this thesis, AAM/UAM are introduced as they motivate a change of scale: from isolated flights to structured, repeatable operations that must be supported by services, rules, and dedicated infrastructures on large scale from urban to extra-urban context. This shift is particularly relevant in urban environments, where safety, nuisance, and governance constraints are more stringent and where planning decisions must consider multiple stakeholders and competing land uses.

Within the European context, the transition toward scalable UAS operations is framed by the concept of U-space. U-space can be interpreted as a service-based ecosystem intended to enable safe, secure, and efficient UAS operations at very low altitude through standardized information and traffic management services (CORUS-XUAM, 2022). In practical terms, the relevance of U-space for this dissertation is not the full taxonomy of services itself, but the fact that these services imply spatially explicit requirements. Examples include: the definition of operational volumes and conditional access, the availability of geo-awareness information and constraints (e.g., areas where operations are limited or prohibited), and the need for mechanisms supporting strategic deconfliction and monitoring, which in turn affect how corridors can be conceived and how candidate vertiport locations must be screened.

From a technical and architectural standpoint, U-space has been described as a modular, service-oriented environment that emphasizes interoperability, progressive automation, secure-by-design principles and resilience (Barrado et al., 2020). These principles matter for infrastructure planning because they motivate why planning outputs must be auditable, data-driven, and transferable: vertiports and corridors are not standalone objects, but elements that must remain compatible with the information services and constraints that will govern real operations.

Finally, AAM/UAM feasibility and uptake depend not only on vehicle capabilities but also on demand patterns, network effects, and socio-economic conditions. These aspects help explain why infrastructure planning cannot be limited to technical feasibility; it must also account for context-dependent constraints and sensitivities that influence acceptance and operational viability (Garrow et al., 2021; Di Stefano et al., 2018). For this reason, the methodological workflow proposed in this thesis is designed to translate heterogeneous requirements - regulatory limits, safety and risk considerations, environmental and social constraints, and infrastructure compatibility - into spatial criteria and staged checks.

Extended descriptions of AAM/UAM concepts, U-space service taxonomies, architecture diagrams, and project-based formulations are reported in Appendices D and E.

1.2.3. Planning implications: infrastructures as node-link

The operational concepts introduced in the previous subsections lead to a clear planning consequence: once UAS operations are envisioned at scale, infrastructures become enabling components rather than optional elements. In this thesis, infrastructures are framed as a coupled system composed of (i) physical assets on the ground and in the air, and (ii) digital and communication capabilities that support safe, secure, and repeatable operations under a service-based paradigm. This framing is consistent with the shift described in European research and demonstration activities, where operational feasibility increasingly depends on the availability of integrated UAS Traffic Management (UTM)/U-space services and robust connectivity rather than on vehicle performance alone (Lappas et al., 2020; Barrado et al., 2020; CORUS-XUAM, 2022).

A key choice of this thesis is to treat infrastructures through a node–link abstraction. Ground nodes (vertiports) and aerial links (corridors) respond to different constraints and therefore require different planning logics. Vertiports must satisfy discrete site conditions (availability, access, local sensitivities, ground risk, energy and service capacity), while corridors require a continuous assessment of exposure, compatibility with sensitive areas, and feasibility under separation and deconfliction strategies. This asymmetry motivates the staged, GIS-based workflow proposed later: the planning problem is not simply to "place infrastructures", but to translate heterogeneous requirements into spatial layers and decision rules that treat nodes and links coherently, yet differently.

In UAS contexts, infrastructures include tangible elements - such as take-off and landing facilities, ground support equipment, and route structures - as well as intangible enabling systems, such as communication and information services required for traffic organization. European research projects highlight that the integration of UAS into shared airspace relies on coordinated infrastructures that support data exchange, monitoring, and operational constraint enforcement. For instance, EuroDRONE describes the role of an integrated UTM testbed to validate service provision and interoperability in realistic conditions, stressing the importance of reliable information flows and supporting technologies (Fransoy et al., 2021; Lappas et al., 2020). Connectivity is also repeatedly identified as a practical enabler for scalable operations, and the feasibility of corridor-like concepts has been investigated in relation to network robustness and security, reinforcing that communication constraints can influence the structure and placement of aerial routes (Bhuyan et al., 2022).

In this context, corridors and vertiports act as the most visible components of an integrated system. Their definition is not only a planning issue but also an operational one: their geometry, location, and connectivity affect how constraints can be enforced and how traffic can be organized. Demonstration activities have explored both static and dynamic approaches, including temporary corridor activations under specific mission windows, precisely to manage complexity in dense environments while keeping operations auditable and compatible with service-based U-space assumptions (Fransoy et al., 2021; CORUS-XUAM, 2022). Extended project descriptions and implementation-specific details are provided in Appendix E.

Vertiports represent discrete nodes that concentrate multiple operational functions. They are not only "landing pads", but facilities that may enable charging, maintenance, staging, passenger handling and multimodal integration, thereby supporting both cargo and passenger-related concepts. This is aligned with recent literature that frames vertiports as part of an integrated mobility system, where adoption depends on the ability to coordinate stakeholders, ensure accessibility, and evaluate economic impacts beyond pure aviation metrics (Garrow et al., 2021; Niklaß et al., 2020; Rahman et al., 2023).

From a design standpoint, vertiport operations require defined areas for landing and take-off, parking/stands, and, for passenger-oriented concepts, terminal functions and connections to ground transport. Prototype technical specifications and guidance documents highlight the relevance of obstacle-free volumes and operational surfaces, which are particularly challenging in urban environments where physical constraints and safety margins must coexist with other land uses (EASA, 2022). At the national level, regulatory guidance also addresses requirements for operations, airspace and infrastructures for VTOL-capable aircraft, contributing additional constraints that must be interpreted in planning terms (ENAC, 2024). While these documents initially prioritize manned VTOL operations, their structure provides a useful baseline for identifying categories of constraints that also inform early-stage UAV-oriented planning, even when direct applicability is limited.

In this thesis, the vertiport planning problem is therefore framed as a multi-domain screening task, in which the suitability of candidate sites must reflect physical feasibility, operational safety, and compatibility with the urban and territorial context. Recent studies propose GIS-based procedures for identifying candidate locations and combining multiple criteria into suitability assessments, supporting the need for transparent and replicable spatial workflows. These approaches align with the methodological stance adopted here: rather than defining a single “optimal” vertiport network through complex optimization, the focus is on producing defensible, data-driven eligibility and suitability outputs that can inform planners and stakeholders. Alongside the SESAR-driven operational literature, recent academic contributions are increasingly operationalizing complementary parts of the same planning problem. For vertiports, structured decision frameworks are consolidating and ranking location criteria (Mercan et al., 2025), while bibliometric analyses are documenting the rapid growth and diversification of vertiport-related research themes (Lu et al., 2025). For links and airspace constructs, corridor planning is being framed as a network design problem with explicit complexity trade-offs (He et al., 2025), and safety-oriented work is proposing 3D, risk-informed exclusion volumes (Zhenyu Gao et al., 2025) that can be interfaced with GIS-based constraints and trajectory optimization. These studies confirm the increasing research effort devoted to spatially explicit planning methods and provide a useful backdrop for the GIS–MCA workflow formalized in Chapter 2. In fact, this thesis does not claim that all regulatory and operational dimensions can be exhaustively modelled at the planning stage. Instead, it adopts a staged approach: the objective is to filter and rank candidate areas based on the constraints that can be represented spatially, while acknowledging that subsequent design and certification steps require additional engineering and operational analyses.

A central planning implication is that vertiport and corridor decisions sit at the intersection of regulatory constraints and spatial planning practice. Regulations define operational limitations and safety requirements, while planning determines what is feasible and socially acceptable within a given territorial context. The original discussion synthesis this interplay by identifying four planning domains that support a structured assessment of vertiport feasibility: (i) physical capacity and surrounding environment; (ii) social context and stakeholders; (iii) accessibility and multimodal integration; and (iv) business model and regulatory framework. This categorization is consistent with the need to jointly consider safety, nuisance (especially noise), land availability, integration with existing mobility systems, and legal coherence with local and regional plans (Maria Krylova, 2022).

Compared to vertiport siting, the literature on drone corridors remains less consolidated, and many corridor concepts are still rooted in research prototypes and project-based formulations rather than standardized planning practice. Nonetheless, corridor planning is increasingly recognized as a necessary mechanism to structure low-altitude flows, reduce interference with sensitive land uses, and support strategic deconfliction in dense environments (Bauranov et al., 2021; Doole et al., 2021; Yu Wu et al., 2021). In this thesis, corridors are treated as link infrastructures whose feasibility depends on continuous spatial constraints (e.g., exposure over sensitive receptors, protected areas, critical infrastructures) and on separation/deconfliction assumptions consistent with U-space.

The original discussion highlights that separation methods can vary substantially, ranging from fixed separation concepts to more dynamic approaches and, in some contexts, the absence of standardized separation rules. These differences are not merely operational; they affect planning because they change how “tight” or “conservative” corridors must be in relation to obstacles, other traffic, and sensitive zones. Research and project outputs also explore alternative implementations, such as cell-based airspace management (density-based approaches) and corridor-like tubes, which are used to balance flexibility with predictability in complex urban settings (CORUS-XUAM, 2022; Calvo, 2020; Valera et al., 2021; Vila Carbó et al., 2021; Bueno et al., 2022; Martínez et al., 2022). These approaches reinforce the rationale of the node-link abstraction adopted here: even when corridors are implemented through different operational constructs, they still correspond to spatially definable link structures that can be explored through GIS-based modelling and scenario testing.

In planning terms, corridor identification therefore becomes a problem of translating operational intent into spatial paths that minimize conflicts and exposure while remaining feasible under connectivity, separation, and regulatory constraints. The thesis leverages this idea later by distinguishing hard constraints (areas where corridors cannot pass) from preferential cost factors (areas where routing is possible but less desirable), and by treating corridor design as a link-planning task complementary to node siting.

Extended implementation narratives that support these concepts are reported in Appendix E.

1.3. URBAN AND TRANSPORT PLANNING FOR UAS INTEGRATION

This section explores the operational and regulatory integration of UAS within urban and transport planning frameworks, focusing on the case studies of Valencia (Spain) and Emilia-Romagna (Italy). The aim is to understand how and where infrastructures such as vertiports and aerial corridors can be incorporated within existing legislative frameworks.

The following subsections begin by providing an overview of the territorial and transport planning structures in both national contexts of the case studies, highlighting how each country organizes and coordinates its infrastructure, mobility, and urban planning policies. The discussion then focuses on national strategic documents dedicated to advanced air mobility, drafted respectively by ENAC in Italy and AESA (Spanish Civil Aviation Authority - Agencia Estatal de Seguridad Aérea) in Spain. These plans define priorities, implementation strategies for AAM - as well as institutional coordination mechanisms to ensure safe and integrated management of urban airspace.

The role of airport risk plans is also briefly examined, as these documents initially inspired the analytical approach adopted to identify suitable areas for drone infrastructure. They provide a methodological foundation for defining operational limits and safety requirements which, although developed for conventional aviation, could be equally applicable to the drone domain and are supported by an existing legislative framework.

1.3.1. Italian National Plan for advanced mobility

In Italy, the integration of AAM into urban and regional mobility frameworks has been promoted by ENAC through the development of the National Strategic Plan for Advanced Air Mobility (2021-2030). The strategic plan outlines several key areas for the sustainable and safe integration of AAM, underlining the importance of aligning technological advancement with urban and regional planning.

Specifically, the ENAC strategy emphasizes the necessity of:

1. integrating vertiport operations within urban structures to mitigate operational risks,
2. proposing dynamic corridor allocation and advanced traffic management as central components of future airspace design.

According to ENAC's vision, the successful integration of AAM requires addressing multiple interconnected dimensions, including regulatory, infrastructural, economic, technological, and societal factors. A core element of this vision is to:

3. establish a harmonized regulatory framework aligned with municipal plans, enabling seamless incorporation of drone infrastructure such as vertiports and air corridors into existing urban environments. To facilitate this alignment, ENAC advocates coordinated policy actions among government bodies, regional and local institutions, and industrial stakeholders, ensuring that AAM initiatives are consistent with broader strategic objectives such as environmental sustainability, technological innovation, and improved accessibility.

The strategic plan identify four primary application scenarios that will serve as pilot cases for the initial integration phases: urban and suburban air-taxi services, medical and goods delivery, infrastructure inspection and mapping, and agricultural support. These cases will guide the deployment of AAM, progressively filling regulatory and infrastructural gaps while enabling more complex operations. Critical issues identified for implementation include addressing public acceptance through transparent stakeholder engagement, harmonizing urban planning regulations with aviation standards, and ensuring the digitalization and integration of public services and processes to foster efficient coordination.

To support the strategic deployment of vertiports, the plan underscores the importance of accurately assessing:

4. OLS, which define the three-dimensional space around vertiports, critical for ensuring safety during take-off, landing, and maneuvering operations. ENAC highlights that careful management of OLS within dense urban contexts is vital for both operational safety and public acceptance, thus requiring robust integration within municipal urban planning frameworks.

ENAC's strategic vision resonates with academic methodologies and international best practices, highlighting the need for comprehensive GIS-based approaches, such as those presented by Fadhil et al., Rahman et al., and Lee and Cho, to identify optimal locations for AAM infrastructure.

1.3.2. Spanish National Plan for advanced mobility

In Spain, the deployment of advanced air mobility services is strategically guided by the Plan de Acción Nacional para el Despliegue del U-space (2022-2025) (Ministerio de Transportes y Movilidad Sostenible, 2022), jointly developed by the Dirección General de Aviación Civil (DGAC), the AESA, and ENAIRE (Spanish National Air Navigation Services Provider - Empresa Nacional de Servicios de Navegación Aérea). The document outlines Spain's comprehensive approach to facilitating safe, efficient, and sustainable integration of drone operations within national and local mobility frameworks, aligning closely with the European regulatory framework and standards.

Central to Spain's strategic vision is the explicit establishment of clearly defined U-space airspaces, dedicated geographical zones intended exclusively or predominantly for drone operations. The plan emphasizes the critical role of coordinated urban planning to avoid potential conflicts with traditional air traffic and ensure smooth integration into existing urban contexts. To achieve this, local and regional authorities should be actively involved in the design and regulation of these air spaces, emphasizing harmonization with existing urban infrastructure and mobility plans. Such integration directly addresses potential operational conflicts and risks inherent in dense urban settings, ensuring coherent interaction between aerial and terrestrial infrastructures.

To manage airspace dynamically and maintain robust safety standards, Spain adopts a centralized service model for delivering U-space services. Specifically, ENAIRE has been designated as the national Common Information Services Provider (CISP), responsible for centralizing critical operational data and providing uniform, real-time access to drone operators and other stakeholders. This centralization facilitates advanced traffic management capabilities, enabling dynamic corridor allocations and supporting strategic operational decisions through reliable and standardized data exchange. This strategic decision simplifies governance, ensures safety, and fosters technological interoperability across diverse stakeholders.

The national plan also outlines concrete steps to operationalize essential U-space services, identifying digitalization as a foundational element. AESA and ENAIRE are tasked with developing and certifying comprehensive digital platforms capable of supporting fundamental U-space functionalities, such as geofencing, drone identification, authorization procedures, and traffic information sharing. The certification and validation processes are critical to ensuring reliable operations, with pilot projects and live demonstrations planned to validate these technologies under real-world conditions, enhancing public trust and regulatory robustness.

An essential component highlighted in the Spanish strategy is the governance mechanism established to ensure coordinated and effective implementation. Spain emphasizes strong inter-administrative collaboration, recognizing the importance of synchronizing national aviation policies with local and regional urban development plans. The plan explicitly details mechanisms such as the formation of high-level steering groups and technical management committees that foster regular communication, decision-making transparency, and stakeholder alignment at various governmental levels. This coordination is designed to ensure operational coherence, regulatory compliance, and harmonization of spatial planning requirements, ultimately facilitating smoother integration of drone infrastructure into urban contexts.

1.3.3. Italian overview of transport and spatial planning levels

Compared to other European countries, Italy strikes a balance between prescriptive and directive planning, resembling the French model but being less centralized (Janin Rivolin Yoccoz, 2016). This institutional complexity makes harmonization across governance levels and collaboration among local authorities crucial, particularly for integrating European policies in areas such as sustainable mobility and urban regeneration.

At the European level, territorial planning has evolved through diverse approaches, often influenced by national legal and administrative traditions. The main models include:

- **Conformative model**: Predominantly used in Italy and Spain, this approach is based on binding instruments that define precise rules for land use.
- **Performative model**: Common in Anglo-Saxon countries like the United Kingdom, this model is goal-oriented and performance-driven, granting greater flexibility to local actors.
- **Neo-performative model**: Developed in Scandinavian countries such as Sweden, it combines traditional planning elements with innovative practices, focusing on sustainability and public participation.

These models reflect distinct historical and administrative systems. For example, in the United Kingdom, planning is closely tied to national policies, adopting a more centralized approach than in France, where local regulatory plans operate within a broad but non-binding national framework. Sweden, on the other hand, is characterized by decentralized planning emphasizing community involvement and environmental sustainability.

In Italy, territorial planning is developed at multiple levels (national, regional, and local), with strong interactions between European regulations and internal institutional competences. At the European level, the European Spatial Development Perspective (ESDP), introduced in 1999, was jointly developed by EU Member States, the European

Commission, and the Council of Europe. In line with the cohesion policies outlined in EU treaties, the ESDP aims to promote polycentric and sustainable territorial development, strengthening the link between urban and rural areas, improving accessibility, and protecting natural and cultural heritage. These goals are supported by tools such as the Interreg and ESPON programs, which foster transnational cooperation and the development of integrated strategies.

The ESDP has influenced Italian planning, particularly through the introduction of the Strategic Environmental Assessment (SEA) and the Environmental Impact Assessment (EIA). Regulated by Directive 2001/42/EC, the SEA applies to plans and programs with potentially significant environmental impacts, such as urban and territorial plans. Conversely, the EIA, regulated by Directive 2011/92/EU, focuses on specific projects, evaluating their environmental effects before approval. In the context of drone infrastructure, the SEA is particularly relevant for assessing the effects of planned infrastructure, such as vertiports and air corridors, on the territory and population.

The Italian system is characterized by the conformative model, where the Municipal General Regulatory Plan (PRGC) defines zoning, technical standards, and constraints for municipal territories. Following the reform of Title V of the Constitution in 2001, regions have gained greater legislative autonomy in territorial planning under the principle of subsidiarity. This has led to diverse terminologies and characteristics for municipal urban plans across regions; for example, in some areas, the PRGC has been replaced by the Municipal Urban Plan (PUC) or the Municipal Structural Plan (PSC). Regional legislation has assumed an increasingly significant role, with instruments such as Regional Landscape Territorial Plans (PTPRs) regulating landscape and environmental aspects.

The principle of subsidiarity, enshrined in Article 118 of the Constitution, establishes that administrative functions are assigned to municipalities unless their unified exercise is necessary, in which case they are attributed to provinces, metropolitan cities, regions, or the state, based on the principles of subsidiarity, differentiation, and adequacy. This principle implies that decisions should be made at the level of government closest to the citizens, promoting local autonomy and more efficient resource management. In the context of drone infrastructure planning, subsidiarity is crucial, as identifying suitable areas requires careful evaluation of territorial specificities and local needs while ensuring coherence with regional and national policies.

At the national level, the Ministry of Infrastructure and Transport coordinates strategic guidelines through economic development plans and sectoral programs, but the indicative nature of these instruments often limits their operational capacity.

In Emilia-Romagna, territorial planning is regulated by Regional Law No. 24 of December 21, 2017, titled “Regional regulation on the protection and use of the territory.” This law introduced a new framework for planning instruments, structured across different levels:

- **Regional Territorial Plan (PTR)**: Defines the objectives to ensure development and social cohesion, enhance the competitiveness of the regional territorial system, and ensure the qualification and valorization of social and environmental resources.

- **General Urban Plan (PUG)**: At the municipal level, the PUG replaces previous urban planning instruments, such as the General Regulatory Plan (PRG), unifying structural and operational planning into a single document.
- **Provincial Territorial Coordination Plans (PTCP)**: At the provincial level, these plans define strategies for territorial development and serve as a reference for municipal planning.

Regional Law No. 24/2017 introduced a more integrated and sustainable approach to territorial planning, promoting urban regeneration and limiting the consumption of undeveloped land.

Before the entry into force of Regional Law No. 24/2017 in Emilia-Romagna, municipal urban planning was divided into several separate instruments:

- **Municipal Structural Plan (PSC)**: Defined long-term strategic objectives, organizing major decisions regarding development and territorial protection.
- **Municipal Operational Plan (POC)**: Identified medium-term interventions, with a validity of five years, intended for specific transformations.
- **Urban and Building Regulation (RUE)**: Established technical rules for implementing urban and building interventions.

With the 2017 reform, these instruments were replaced by the General Urban Plan (PUG), which unifies structural and operational planning into a single document, making the process more coherent and integrated. The PUG introduced a more simplified approach compared to the previous subdivision, maintaining both a strategic vision (long-term) and an operational dimension (short- and medium-term), integrated within a single tool.

1.3.4. Spanish overview of transport and spatial planning levels

Spain exemplifies how a decentralized system can combine autonomy and coordination, ensuring territorial management that responds both to local specificities and the need for national consistency. This adaptability allows the country to tackle modern planning challenges, integrating economic development, environmental sustainability, and public participation within a regulatory framework that continues to evolve.

In Spain, territorial planning is characterized by a highly decentralized system, reflecting the country’s administrative structure. The Spanish Constitution of 1978 assigns extensive legislative and administrative powers to the Autonomous Communities, making them the primary actors in territorial management. This autonomy allows each region to adapt planning instruments to its specific characteristics, ensuring flexibility and sensitivity to local peculiarities. At the same time, the central government retains certain essential competencies, primarily concerning the definition of general principles through framework laws and the management of nationally significant projects.

At the national level, the central government establishes the regulatory framework through instruments such as the *Ley del Suelo*, which provides general criteria for land management, and the *Ley de Evaluación Ambiental*, which regulates the procedures for Strategic Environmental Assessment (SEA) and Environmental Impact Assessment (EIA). These laws ensure that plans and projects at all levels meet sustainability and environmental protection objectives. However, the state’s role is mainly focused on specific areas, such as strategic infrastructures, major works, and the protection of areas of national relevance.

The Autonomous Communities represent the intermediate level of territorial planning and have significant responsibilities in this area. Each region develops its own planning instruments, including the Planes de Ordenación del Territorio (POT), which outline regional development strategies, and Regional Master Plans, used for specific interventions such as natural resource management or urban development. These tools reflect the legislative autonomy of the regions, allowing them to adopt their own regulations and ensure precise adaptation to territorial needs.

At the local level, municipalities play a crucial role in planning and managing the territory. The primary instrument is the General Urban Planning Plan (PGOU), which regulates land use, zoning, and landscape constraints. In many cases, municipalities also develop additional specific plans, such as Partial Plans for interventions in defined areas or Special Plans aimed at protecting historical heritage or urban regeneration. This level ensures that planning directly addresses the needs of the local population while adhering to the regulatory framework set by higher levels.

The Spanish system, due to its structure, is positioned between the conformative model, typical of continental Europe, and an autonomist approach that values local and regional autonomy (Janin Rivolin Yoccoz, 2016). While it retains prescriptive elements, such as the PGOU - a clear legacy of the Napoleonic model - the administrative decentralization allows the Autonomous Communities to develop more flexible and adaptable tools. This balance between regulatory rigor and operational flexibility enables effective responses to territorial challenges, integrating economic development needs with environmental protection and respect for local specificities.

Despite its strengths, the Spanish planning system also presents certain challenges, particularly regarding coordination among the various levels of government. The autonomy of the Autonomous Communities, while a strength, can sometimes lead to disparities between regions and difficulties in harmonizing territorial policies at the national level. However, recent regulatory developments, aligned with European directives, aim to address these challenges by promoting greater integration among levels and a more systemic approach to planning.

1.3.5. Airport Risk Plan

It is possible to identify tools within traditional aviation that already assess the appropriate placement of airports within a territory and ensure compliance with safety zones around them, as dictated by urban planning instruments. One such tool in Italy is the Piano di Rischio Aeroportuale (PRA) translated Airport Risk Plan, an urban planning instrument focused on mitigating aviation risks in areas surrounding airports.

The PRA is regulated by the Italian Navigation Code, particularly Articles 707 (ENAC, 2010) and following, which impose restrictions on private properties within these zones to minimize exposure to potential aviation incidents. These provisions take precedence over other regulations and become effective immediately upon municipal approval and publication.

The PRA includes comprehensive risk assessments associated with airport operations, as well as the necessary mitigation measures. These measures often involve evaluating flight paths, analyzing the likelihood of incidents, and determining their potential consequences for the surrounding areas. Such planning ensures the integration of safety considerations into urban development near airport zones, balancing aviation needs with the protection of local communities.

The PRA is based on the Italian Navigation Code and Legislative Decree No. 96/2005 (Ente Nazionale per l'Aviazione Civile, 2005), with subsequent amendments and integrations. These legal frameworks establish urban planning restrictions and limitations on incompatible activities, such as chemical industries, schools, hospitals, and shopping centers, to mitigate the consequences of potential aviation incidents.

The protection zones outlined by the PRA are divided into four categories - A, B, C, and D - each associated with varying levels of construction restrictions. The delineation of these zones follows the guidelines set forth in the Regulations for the Construction and Operation of Airports and the APT-33 Circular issued on August 30, 2010, by the Italian Civil Aviation Authority (ENAC). These restrictions impact landowners and developers in areas surrounding airports by limiting the types of permissible development and requiring specific adjustments to ensure safety. In particular, the zones prioritize restrictions on sensitive activities, such as educational institutions, healthcare facilities, and high-density public spaces, aiming to minimize exposure to aviation risks.

The PRA's protection zones are categorized based on the level of risk and the potential consequences of aviation incidents. Each category imposes different degrees of building and land-use limitations to reduce inhabitants' exposure to potential dangers. For instance, more stringent restrictions are applied in zones closest to airport operations, progressively relaxing in areas further away. These classifications are directly informed by ENAC's Regulations for the Construction and Operation of Airports and the APT-33 Circular, ensuring uniform application across Italian municipalities.

The approval procedure for the PRA lacks explicit details in ENAC directives or national legislation. Most Italian municipalities adopt the PRA through resolutions in their Municipal Council. However, there are no specific legislative provisions governing its formal adoption, which necessitates coordination between the airport operator and local and national authorities to ensure compliance with safety and urban planning regulations. In cases where the airport or its protection zones extend across multiple municipalities, the PRA must be developed collaboratively among all affected local governments, fostering joint responsibility for safety and regulatory adherence.

The "Regolamento per la Costruzione e l'Esercizio degli Aeroporti", referenced in the APT-33 Circular, is a regulatory document that establishes guidelines and technical requirements for the design, construction, and management of airports. It covers safety standards, construction requirements, air traffic management, environmental considerations, and maintenance operations.

Chapter 9, paragraph 6 of the ENAC Regulation, is specifically dedicated to Airport Risk Plans (PRA) and outlines key aspects such as the purpose of the plans, their applicability, contents, zoning restrictions, and guidelines for drafting and adopting the plans. This section highlights the critical role of PRAs in safeguarding areas surrounding airports. The document is organized as follows:

- **Purpose of Risk Plans** (6.1): This section emphasizes the importance of risk plans in mitigating incidents that could affect areas near airports. The focus is on enhancing the protection of airport-adjacent zones through effective territorial governance.

- **Applicability** (6.2): It specifies that the regulations related to risk plans apply to all airports open to civil traffic, as stipulated by Article 707 of the Navigation Code. The restrictions imposed by risk plans pertain to new developments and activities in areas surrounding airports.
- **Nature and Content of Risk Plans** (6.3): Risk plans are documents containing recommendations and prescriptions that must be integrated into the urban planning tools of individual municipalities. These prescriptions aim to safeguard territories from potential incident consequences.
- **Zoning Restrictions** (6.4): Article 707 of the Navigation Code establishes restrictions in areas subject to limitations, such as takeoff and landing paths, to mitigate the consequences of incidents.
- **Identification and Definition of Protection Zones** (6.5): Protection zones are defined based on the type of flight operations and aircraft. Each zone is classified, with specific building restrictions and compatible activities outlined for each.
- **Guidelines for Drafting Risk Plans** (6.6): This section provides guidance for municipalities in drafting risk plans, considering population density and identifying compatible activities for each protection zone.
- **Adoption of Risk Plans** (6.7): Risk plans are drafted by the relevant municipalities. In cases where protection zones affect multiple municipalities, the plan must be developed in a coordinated manner. ENAC provides its opinion on these risk plans based on aeronautical evaluations.

This regulatory framework could serve as a model for planning UAV infrastructures, offering a comprehensive approach for integrating safety measures into urban and territorial planning. It ensures that areas surrounding airports are safeguarded against risks associated with aviation activities. By providing clear guidelines for municipalities, the regulation encourages coordinated efforts between local authorities and ENAC to enhance safety and compliance, aligning with the objectives envisioned for developing a specific methodology for drones in the research project of this thesis.

1.4. URBAN GIS METHODOLOGIES FOR AREA SELECTION

Documents such as the GIS-based Analysis for Selecting Ground Infrastructure Locations for Urban Air Mobility by (Fadhil, 2018) highlight the applicability of MCA methodologies for weighing various criteria, such as accessibility, environmental impact, and existing land use. Similarly, the CITYAM project has developed a geospatial Decision Support Tool (DST) that incorporates MCA within GIS to facilitate the planning of launch and landing sites, emphasizing criteria such as proximity to urban nodes, safety, and noise mitigation.

Other studies have adopted related approaches that, while not strictly MCA, aim to assign scalar suitability or risk levels to urban areas. For instance, (Primatesta, Scanavino, et al., 2020) and (Primatesta, Rizzo, et al., 2020) propose probabilistic risk assessments for urban areas based on factors like population density and collision risks, providing a quantitative framework for identifying low-risk zones. These methodologies contribute to the growing body of research emphasizing spatially informed planning for UAM infrastructure.

The integration of MCA and similar analytical approaches into UAM infrastructure planning represents a step toward harmonizing technological advancements with urban development goals. By synthesizing spatial, social, and regulatory considerations, these frameworks offer a comprehensive pathway for addressing the complex challenges associated with the siting of vertiports and corridors, laying the groundwork for sustainable and efficient UAM systems. Furthermore, the clear and structured outputs provided by MCA empower local administrations to better understand the implications of UAM infrastructure, facilitate dialogue across multiple governance levels, and ensure that planning decisions are both inclusive and evidence based.

Building on this literature review, Section 1.5 is organized into five interrelated subsections that guide the reader through our GIS-MCA methodology. We begin with a review of GIS fundamentals and data management (Section 1.5.1), where the essentials of spatial data types, coordinate systems, and software tools are introduced as the foundation for all subsequent analyses. In Section 1.5.2, we delve into the mechanics of Weighted Multi-Criteria Analysis itself, illustrating how weights are assigned to each planning factor and highlighting key case studies - such as Fadhil (2018) and the CITYAM DST - that demonstrate the method's practical utility. Section 1.5.3 then explores what is the Least Cost Path. Finally, Section 1.5.4 discusses what the Delaunay network is.

1.4.1. Introduction to GIS

A Geographic Information System (GIS) is a versatile framework that integrates hardware, software, and spatial data to capture, manage, analyze, and visualize geographically referenced information. It enables the spatial representation of data and its attributes, serving as a foundational tool for spatial analysis and decision-making in various domains. The ability to connect spatial data with descriptive attributes allows GIS to address a wide range of challenges, from environmental management to urban planning.

The functionality of a GIS relies on multiple interconnected components, including data, hardware, software, databases, procedures, and skilled personnel. Together, these elements support the collection and processing of data, enabling operations such as analysis, visualization, and the generation of thematic maps. These maps play a vital role in highlighting patterns and relationships within spatial data, facilitating informed decisions across diverse applications.

The data utilized in GIS can be broadly categorized into spatial and attribute data. Spatial data defines the location, geometry, and structure of features, while attribute data provides descriptive details about these features. These datasets are commonly stored in vector or raster formats. Vector data represents discrete features like points, lines, and polygons, making it ideal for representing infrastructure or administrative boundaries. On the other hand, raster data consists of a grid of cells, each containing a value, which is particularly suited for continuous phenomena such as temperature gradients or elevation models.

One of the critical steps in GIS workflows is the classification of data, which organizes features based on shared attributes to simplify spatial analysis. Variables are often categorized according to their measurement scales, such as nominal, ordinal, interval, or ratio. This classification process enables the creation of maps like choropleth or isoline maps, which effectively communicate spatial distributions and trends. These tools are indispensable for understanding and addressing complex spatial phenomena.

The integration of multiple datasets in GIS allows for advanced spatial analysis through techniques such as overlay, buffering, and density calculations. Overlay analysis, for instance, can combine various spatial layers to reveal areas that meet specific criteria, while density analysis helps model spatial intensity, such as the distribution of population or activity patterns over a region. These analytical capabilities make GIS a powerful instrument for tackling multi-dimensional problems.

The effectiveness of GIS depends heavily on the quality of the data it uses. Reliable and accurate datasets are essential for producing meaningful results. Official data sources, such as national or regional geoportals, provide key datasets including demographic statistics, land use information, and environmental parameters. In addition, satellite imagery and remote sensing data enhance GIS applications by providing images to process to get information.

1.4.2. Weighted Multi-Criteria Analysis for decision-making

MCA represents a structured approach to decision-making, allowing for the evaluation of multiple conflicting criteria in complex scenarios. This methodology is widely used in spatial analysis due to its ability to synthesize diverse datasets into a unified framework, guiding decision-making.

In its essence, MCA integrates different layers of data, each representing specific factors that influence the suitability of a given area for a particular purpose. For instance, in the context of spatial planning, it involves assigning weights to various criteria based on their relative importance. These criteria can include land use restrictions, environmental regulations, population density, or noise sensitivity. The weighted data layers are combined to produce a suitability map, which highlights areas meeting the predefined criteria.

A practical example of MCA is the work by (Ifkirne et al., 2022), who used GIS-based MCA to identify suitable sites for onshore wind farms in Southeast France. Their analysis combined six factors, including wind speed, proximity to electrical substations, and topographical features, assigning different weights to reflect their relative importance. The resulting suitability map provided a clear visual representation of optimal locations, demonstrating the practical application of MCA in spatial energy planning.

Similarly, (Nadi et al., 2011) applied MCA for personalized route planning using quantifier-guided ordered weighted averaging (OWA) operators. Their methodology allowed for the aggregation of user-defined criteria to compute impedance values for route segments. This approach enabled dynamic route adjustments based on user preferences and real-world constraints, showcasing MCA's flexibility in adapting to diverse decision-making contexts.

Kim et al. (2022) explored the application of MCA in determining suitable locations for UAM vertiports. Their study identified accessibility, safety, and proximity to existing transportation nodes as critical factors, employing statistical methods to weigh their influence. This methodology is particularly relevant to this thesis, which aims to identify areas suitable for vertiports and drone corridors.

While the study by (Primatesta, Scanavino, et al., 2020) did not explicitly employ MCA, their risk-based path planning strategy aligns conceptually with its principles. By integrating probabilistic risk assessments with spatial constraints, they demonstrated how multiple factors can be evaluated concurrently to optimize flight paths for unmanned aerial systems.

1.4.3. Least Cost Path (LCP)

The computation of the Least Cost Path (LCP) is a methodology widely applied within GIS to optimize the alignment of linear infrastructures, such as roads, by identifying the most suitable route through the minimization of a cumulative cost calculated over a raster surface, rather than relying solely on the shortest geometric distance.

Typically, the cost is determined by a combination of physical and environmental constraints - such as slope, elevation, and the presence of protected areas (Samy et al., 2025; Shuyao Wu et al., 2022) - as well as social factors, including urban density, land values, and accessibility, or engineering requirements, for instance the need to respect maximum or minimum curvature radii (McDonald et al., 2022; Strzalka et al., 2024; Salamati et al., 2022).

All relevant factors are integrated into a raster that assigns higher or lower costs depending on whether the overlap of layers results in a greater cumulative value. From this basis, at least two points - representing the origin and the destination - are defined, and the raster grid is analyzed by connecting the centroids of the cells to determine the path with the lowest overall cost. In practice, the LCP performs what is most essential in transport planning: it translates territorial constraints and preferences into an optimized route, consolidating heterogeneous factors (technical, environmental, social) into a single cost metric that guides the selection of the alignment.

1.4.4. Delaunay network

Delaunay triangulation forms the foundation of many interpolation techniques, 3D meshes constructions (Shewchuk, 1996), and topographic modelling (De Floriani et al., 1992). Its objective is to connect a set of points in such a way that no point lies inside the circumcircle of any triangle, thereby maximizing the minimum angle among all possible triangulations of the same point set. This property avoids the creation of elongated, “skinny” triangles, producing meshes that are more stable and better suited for spatial analysis and surface representation.

The Delaunay triangulation is closely related to the Voronoi diagram, which can be considered its dual structure (Okabe et al., 2025). In a Voronoi diagram, the plane is partitioned into polygons such that each polygon contains the region of space closer to a given point than to any other. In other words, every location within a Voronoi cell is closer to its generating point than to the points generating adjacent cells. The duality lies in the fact that connecting the centers of adjacent Voronoi cells yields the Delaunay triangulation.

Practical applications of Delaunay triangulation include the construction of Triangulated Irregular Networks (TINs), which are commonly used to represent continuous surfaces, such as elevation models. It also underpins several spatial interpolation methods - for example, Inverse Distance Weighting (IDW) - and provides a robust structure for graph-based analyses, visibility modelling, and hydrological or topographic simulations.

1.5. FOUNDATIONAL DOMAINS FOR UAM SITING: A LITERATURE REVIEW

The identification and planning of suitable areas for UAM infrastructure - such as vertiports and drone corridors - require a multi-domain approach that goes well beyond purely technical siting or logistical optimization. Before formalizing the methodology (Chapter 2), it is therefore necessary to establish which criteria are consistently recognized in literature as foundational for a systematic assessment.

This section does not aim to provide a general GIS tutorial. Instead, it synthesizes the literature-based domains that ground the criteria selection adopted in this dissertation and clarifies how these domains are translated into spatially representable constraints and factors. In doing so, it also anticipates the rationale of the proposed workflow, which advances beyond many MCDA-based siting studies - not by merely expanding the list of factors, but by structuring the decision process through staged constraints, a node-link interpretation (vertiports as nodes and corridors as links), and post-selection checks.

To support this framing, the literature was reviewed to map how previous studies address the core challenges tackled by this PhD research and to organize them into a coherent set of criteria families. Drawing on recurring issues and constraints across the reviewed contributions, six key domains are identified as essential for multi-criteria decision-making. This section integrates findings from diverse studies to outline these domains and to illustrate how each typically requires a combination of theoretical framing, participatory practice, technical assessment, and evidence-informed policy considerations. These domains provide the conceptual basis for the factors selected, processed, and analyzed in this thesis.

Table 1 summarizes the six foundational domains emerging from the literature review, which form the basis for criteria selection in this dissertation.

Foundational Domain	Key Components from Literature Review
Safety	Ground risk modelling (population, obstacles), airspace design (separation, restrictions), meteorological hazards, and operational constraints
Social Acceptance	Public participation (PPGIS), noise and privacy impacts, socio-economic effects (property values, equity), and user-oriented factors (trust, cost, convenience)
Drone Performance	Technical metrics (battery endurance, energy consumption, payload), flight dynamics (wind, altitude), and integration with connectivity (5G) for routing
Urban Planning	Alignment with existing policy (zoning, SUMPs), strategic transport plans, multi-level governance, and repurposing of existing infrastructure (heliports)
Infrastructure	Digital systems (UTM, GPS, 5G connectivity) and physical systems (electrical grid access, charging stations, multimodal connections)
Accessibility	User-centric factors (travel time, cost, convenience), spatial justice, equitable access for diverse populations, and integration with public transport hubs

Table 1. Key points from literature per foundational domain

1.5.1. Safety: managing risks and operational constraints

Safety is the foundation stone upon which all UAM planning must be built, given the inherent risks associated with low-altitude flight especially over urbanized or densely populated areas. Literature consistently highlights several dimensions of safety, from ground risk modeling to the identification of operational constraints that influence both siting and corridor design.

Bauranov et al. (2021) offer a comprehensive review of airspace design concepts for UAM, emphasizing the criticality of risk-based path planning and the need to model obstacle avoidance, inter-drone separation, meteorological hazards (especially wind), and the implications of both dynamic and static flight restrictions. Their synthesis points to the necessity of developing sophisticated, multi-layered risk maps as an input for infrastructure localization.

Primatesta, Scanavino, et al. (2020) and (Primatesta, Rizzo, et al., 2020) operationalize these concepts, demonstrating the use of probabilistic ground-risk maps derived from factors such as population density, obstacles, protected areas, and no-fly zones. Their work goes a step further by implementing advanced algorithms – specifically, a modified Rapidly exploring Random Tree (RRT*) – that incorporate real-time environmental variables like wind, as well as drone-specific parameters (mass, parachute presence, fly-away risk) to produce optimal, minimum-risk flight paths. Moreover, their approach integrates exposure, impact, event, stress, and harm models, calculating risk at the pixel level and offering a granular basis for both route and infrastructure planning.

Kim et al. (2022) advance this risk-based logic by applying the DACUS (Demand and Capacity Optimisation in U-space) framework to corridor capacity analysis overpopulated areas, combining ground-risk sub-models to quantify airspace safety and thus inform the design and capacity management of urban drone corridors. The output is a set of risk-informed, capacity-optimized corridors that can be flexibly managed according to real-time risk assessments. Finally, the operational context – often overlooked in spatial-only models – was brought to the forefront by (Vascik et al., 2018), who identified nineteen classes of operational constraints (from pilot staffing and aircraft scheduling to weather and takeoff/landing site management) across case studies in Los Angeles, Boston, and Dallas. Their system-level approach reveals how safety is not only a matter of route or site selection, but of harmonizing multiple factors – human, technical, and environmental – across the lifecycle of UAM operations.

1.5.2. Social acceptance: noise, privacy, and the need for participatory processes

No infrastructure for aerial mobility can succeed without the buy-in and support of the communities it serves. Literature increasingly acknowledges that technical feasibility must be matched by social acceptance, a domain shaped by both perceived and real impacts such as noise, privacy, and distributive equity.

The importance of public participation is powerfully illustrated (Santos et al., 2018), who leverage a web-based Public Participation Geographic Information System (PPGIS) to gather community feedback around airports. Their approach allows residents to map and report their experience of aircraft noise, revealing that conventionally calculated noise zones often dramatically underestimate the lived impact of aviation on neighborhoods. This participatory mapping not only enhances the granularity of impact assessment but fundamentally changes the dialogue between planners and the public, making it possible to identify and address concerns that might otherwise be missed in real time.

Taylor et al. (2020) and Li (2023) extend the discussion by interrogating the socio-economic ripple effects of vertiport placement. Taylor et al. highlights the implications of vertiport construction for nearby property values, and the potential for both positive and negative externalities - ranging from noise to increased real estate prices and changes in desirability in land use. Li’s (2023) scenario analysis of Southern California similarly finds that spatial restrictions imposed by noise, airspace regulations, and buffer zones around sensitive sites (like schools) can limit the accessibility of vertiports for low-income populations and blue-collar workers. Their findings underscore the need for explicit equity policies and proactive engagement with communities that risk being underserved by UAM initiatives.

Hwang et al. (2023) and KIM et al. (2023) bring a user-oriented perspective, showing that social acceptance is deeply influenced by factors like trust in autonomous operations, cost, convenience, and even psychological comfort with sharing space or vehicles with others. Their survey-based approaches reveal variability in willingness to use UAM across different demographic segments and scenarios, further reinforcing the necessity of context-specific engagement and iterative feedback processes.

1.5.3. Drone performance: technical and environmental constraints

UAM infrastructure planning is intimately tied to the performance characteristics of drones, which in turn shape both spatial requirements and operational feasibility.

Fadhil (2018) demonstrates the value of integrating **drone performance metrics** – such as **battery endurance**, **energy consumption**, **climb and descent capabilities**, and **payload** – into multi-criteria decision models. His use of AHP (Analytic Hierarchy Process) and MCA, embedded within GIS, makes it possible to overlay technical constraints with urban spatial realities. The study finds that initial UAM infrastructure is best located at high-demand nodes (city centers, airports, intercity rail stations), but only when operational requirements can be met reliably and efficiently (e.g., easy access).

The literature on **energy consumption** confirms its complexity. Several authors calculate consumption based on distance and mission profile, but Hong et al. (2021) notes that simply *increasing battery capacity is not a solution, as added weight increases* the energy required to maintain altitude. Environmental factors, especially *wind*, also significantly affect autonomy. To address this, adaptive algorithms have been proposed, such as the “AirMatrix” concept by Yu Wu et al. (2021), which pre-assesses energy needs and dynamically adjusts trajectories. Other theoretical models decompose energy consumption into induced, profile, and parasitic power to provide accurate estimations, or apply optimal transport theory to reduce overall power consumption. This body of work confirms that *energy-efficient route planning*, which accounts for contingency (such as alternate vertiports), is essential for operational feasibility.

Connectivity and positioning are similarly critical. While 5G and future 6G networks offer high data transfer rates and low latency, their infrastructure is often optimized to serve ground-level users, not aerial platforms at altitude. This limitation must be encoded into infrastructure design.

Bhuyan et al. (2022) further advance the integration of drone performance into corridor planning, using **5G network coverage and signal quality** to calculate optimal, low-risk drone routes. Their approach employs Time-to-Conflict (TTC) models to anticipate and mitigate collision risks, illustrating how real-world technological limitations must be encoded into infrastructure design from the outset.

The methodological innovations seen in the works of Primatesta, Rizzo, et al. (2020) and also contribute to this domain, through the use of risk-optimized path planning and scenario modeling that accounts for **wind, altitude, and flight dynamics** - each a critical determinant of energy use, safety, and operational reliability.

1.5.4. Urban planning frameworks: policy and regulation alignment

The alignment of UAM infrastructure with existing urban and transport planning frameworks is a recurring theme across the literature. Effective integration requires not just technical compatibility, but compliance with land-use regulations, strategic transport plans, and multi-level governance structures.

Li (2023) provides an exemplary scenario analysis, examining how existing infrastructures - such as heliports and elevated parking - can be repurposed for UAM, contingent on regulatory acceptance and spatial fit within city master plans. This work highlights how local zoning, buffer regulations, and planning priorities (including environmental justice and modal integration) directly shape the availability and suitability of sites for UAM infrastructure.

Taylor et al. (2020) explore the impact of vertiport siting on broader urban systems, analyzing traffic patterns, commuter flows, and the distribution of demand using traffic data from the San Francisco Bay Area. Their methodology, which incorporates k-means clustering for optimal vertiport placement and scenario-based travel time comparisons, illustrates the complexity of embedding aerial mobility in multi-modal transport networks.

The critical role of regulation is further emphasized by (Bauranov et al., 2021), who underscore the need for harmonized, risk-based regulatory frameworks that are both flexible and robust enough to accommodate the unique operational profiles of UAM vehicles - especially in dense, complex urban environments.

1.5.5. Infrastructure compatibility: integrating digital and physical systems

The viability of UAM is inseparable from the compatibility of supporting infrastructure, both digital and physical. Charging stations, data connectivity, positioning systems, and integration with air traffic management are all foundational for reliable and scalable operations.

Nguyen et al. (2021) and SESAR-related initiatives detail how digital infrastructure - especially GPS-defined waypoints and UTM services - can be synchronized with existing air traffic control systems to ensure safe and efficient aerial operations. These systems are essential for dynamic route management, collision avoidance, and priority-based scheduling within crowded urban airspace.

Li (2023) and Fadhil (2018) also stress the importance of evaluating the proximity of candidate sites to the electrical grid and robust communications infrastructure, as these elements are non-negotiable for both charging and continuous operation of UAM vehicles. Bhuyan et al. (2022) provide a clear demonstration of how 5G connectivity is not only a facilitator of low-risk routing, but a constraint that can preclude certain locations from consideration altogether.

KIM et al. (2023) reinforce the role of infrastructure compatibility by incorporating variables such as multimodal connections (to buses and trains), safety and noise management systems, and other technologies that enhance operational safety and user experience. Their work demonstrates that “soft” systems - such as information platforms and citizen engagement tools - can be just as critical as “hard” physical infrastructure.

1.5.6. Accessibility: Ensuring Equitable and Effective Service Provision

The final domain, accessibility, is perhaps the most crosscutting of all, ensuring that the benefits of UAM are distributed fairly and that services are actually usable by those who need them most. KIM et al. (2023) and (Hwang et al., 2023) foreground the user experience, employing surveys and regression analysis to explore variables such as travel time, transfer distance, fare sensitivity, and perceived convenience. Their results show that the location of vertiports relative to transport hubs, residential areas, and key activity nodes is a decisive factor in shaping actual uptake and modal shift to UAM.

Santos et al. (2018) and Taylor et al. (2020) expand the concept of accessibility to include spatial justice, using participatory mapping and traffic demand modeling to identify neighborhoods at risk of exclusion and to inform planning that is both inclusive and responsive to real needs. Li (2023) further advocates for explicit policies to ensure that vulnerable and low-income populations are not left behind in the roll-out of new infrastructure.

The integration of accessibility metrics - both quantitative (distance, time, cost) and qualitative (perceived utility, equity, public acceptance) - into GIS-based planning models is thus critical for ensuring that UAM does not become a privilege for the few, but a genuinely transformative component of urban mobility.

1.6. SYNTHESIS: THE NEED FOR A CRITERIA-BASED SITING METHODOLOGY

The integration of UAM infrastructure, particularly vertiports and corridors, represents one of the most promising but complex challenges for modern urban development. As the preceding sections have established, positioning these assets requires an integrated and multidisciplinary approach that considers technical, environmental, economic, and social criteria.

This challenge is framed by high-level policy. Strategic roadmaps, such as Italy’s *National Strategic Plan for Advanced Air Mobility* (AAM) and the European Commission's “A Drone Strategy 2.0”, establish the foundational goal: achieving a “synergistic integration” of UAM with existing urban development plans and transport networks.

These frameworks, along with insights from pilot projects like Medifly in Hamburg and SkyGate in Turin, converge on a clear set of siting criteria necessary for this integration:

- **Integration with Urban Structures:** Vertiports must be sited to mitigate risks from interactions with densely populated areas and critical infrastructure. This requires balancing functionality against negative externalities, such as noise and visual impacts.

- **Alignment with Local Plans:** Siting must align with local urban planning instruments, such as Sustainable Urban Mobility Plans (SUMPs), to ensure spatial coherence and regulatory compliance.
- **Accessibility and Multimodality:** A recurring factor for success is proximity to existing multimodal transport hubs (e.g., railway stations, ports, or airports) to ensure efficient connectivity.
- **Airspace Management:** Planning must extend beyond the ground footprint to include the design of the surrounding airspace, adopting concepts like dynamic corridors and integration with UTM/U-Space systems.
- **Social Acceptance:** Public acceptance is fundamental. This requires participatory planning, transparency, and early community involvement to build public consensus.

Both ENAC and the "Drone Strategy 2.0" recognize that the selection of suitable areas must be based on **rigorous methodologies** that consider environmental, social, and economic factors. Key criteria include analysing population density, accessibility to multimodal transport nodes, and minimizing noise disturbances. **Additionally, the strategy suggests reutilizing existing infrastructure, such as heliports and small airfields, to reduce costs and territorial impacts.** European pilot projects, such as CityAM, have demonstrated that **spatial analysis tools (GIS)** are the key method for this evaluation. GIS platforms enable planners to systematically assess diverse factors – such as land use, population density, environmental constraints, infrastructure proximity, and regulatory compliance – in an integrated manner.

This review of the state of the art confirms a clear **methodological gap**: while policy identifies *what* criteria to consider, a **standardized and replicable spatial methodology is required** to assess *where* these criteria are met. This thesis addresses this gap directly. Compared to the approaches reviewed in Section 1.5, the main novelty of this thesis is not the introduction of additional criteria, but the development of a single, transparent GIS workflow that (i) separates hard constraints (exclusion masks) from soft criteria combined through MCA, (ii) applies a distinct siting logic for nodes and links (vertiports vs corridors), and (iii) operationalizes heterogeneous information (regulatory constraints, risk, noise, connectivity and socio-economic indicators) into standardized spatial layers that can be inspected and revised. In this sense, the proposed framework is meant as a decision-support process for planners and authorities, rather than as a fully optimized network design solution.

The following chapter details the specific GIS-based Multi-Criteria Analysis (MCA) framework developed to operationalize these siting criteria, providing a transparent and evidence-based approach for identifying suitable locations for vertiports and corridors.

2. METHODOLOGY

The selection of suitable areas for integrating UAM infrastructure necessitates a structured and adaptive planning methodology that accounts for the challenges outlined in the previous chapter – most notably spatial, social, and regulatory considerations. This requires a multi-step process that aligns new infrastructures with existing land use plans and transport strategies to ensure seamless integration with the urban fabric, maximize connectivity, and user accessibility.

Planning must concurrently account for multiple aspects, including logistical factors like electrical grid connectivity and social parameters like noise and visual impacts. This entails a multi-layered analysis implemented within GIS. As demonstrated in the literature review (see **Section 1.5.2**), the **GIS-based Multi-Criteria Analysis (MCA)** technique is an effective tool for systematically integrating these diverse factors into the planning process. MCA provides a **transparent and replicable framework** for evaluating the relative suitability of different locations.

Importantly, it also offers a visual and easily interpretable output, which can significantly empower local administrations to engage with other stakeholders, including national authorities. By simplifying the understanding of complex impacts and providing a clear evidence base, MCA strengthens the negotiating power of municipalities in discussions with higher-level entities, permitting a more equitable decision-making process.

This chapter details the methodological workflow.

- **Section 2.1 (General Line)** provides the high-level overview of the 3-step process, outlines the key input parameters (drone characteristics and vertiport ontology), and defines the criteria and data sources used.
- **Section 2.2 (Processing Factors for Suitability Layers)** describes the operational process of transforming these criteria into standardized, rasterized GIS layers for the MCA.
- **Section 2.3 (Processing for Positioning Refinement)** explains how hard constraints and *a priori* restrictions (such as AIP rules, obstacles, and protected areas) are processed to validate and refine the final siting analysis.

2.1. GENERAL LINE

This section details the methodological workflow developed to identify suitable areas for UAM infrastructure. It bridges the conceptual foundations of Chapter 1 with the operational workflow by presenting a transparent, replicable, and auditable GIS-based process. Rather than delivering a deterministic verdict, the methodology provides a spatial screening that local administrations and stakeholders can interrogate, adapt, and refine.

It is important to clarify the scope of the workflow: in its current form, it does not solve a facility-location optimization problem (e.g., selecting an “optimal” number of vertiports under cost constraints). Instead, it produces spatial suitability surfaces and a shortlist of candidate areas that can support scenario-based planning. The final number and type of infrastructures are therefore treated as a planning decision, to be refined with additional operational and stakeholder inputs.

The entire process is structured into three macro-steps, as illustrated in the workflow diagram (Diagram 1) below:

1. **Step 1: Data Preparation and Criteria Selection.** The process begins by identifying and processing the key spatial factors required for the analysis. These factors are derived from the six foundational domains identified in the literature review (see Section 1.6). Each factor is processed into a standardized GIS layer. The specific layers used in this thesis, grouped by domain, are summarized in Table 4.
2. **Step 2: Airspace Suitability Analysis.** This step analyses the entire airspace to determine flight feasibility. It uses a dual logic:
   - **Eligibility (MCA):** “Soft” or “variable” criteria (e.g., noise, mobile coverage, ground risk) are normalized and combined using a Multi-Criteria Analysis (MCA). This produces a **suitability surface**, a continuous map illustrating *where* it is convenient to fly. In the baseline implementation presented in this thesis, criteria are combined using equal weights to keep the workflow reproducible and to avoid introducing subjective priorities without a formal elicitation process; alternative weighting strategies (e.g., stakeholder-driven weights) can be integrated in future applications.
   - **Exclusion (Subtraction):** “Hard” or “absolute” criteria (e.g., permanent AIP flight restrictions, protected natural areas) are applied as filters to mask out areas where flight is prohibited.

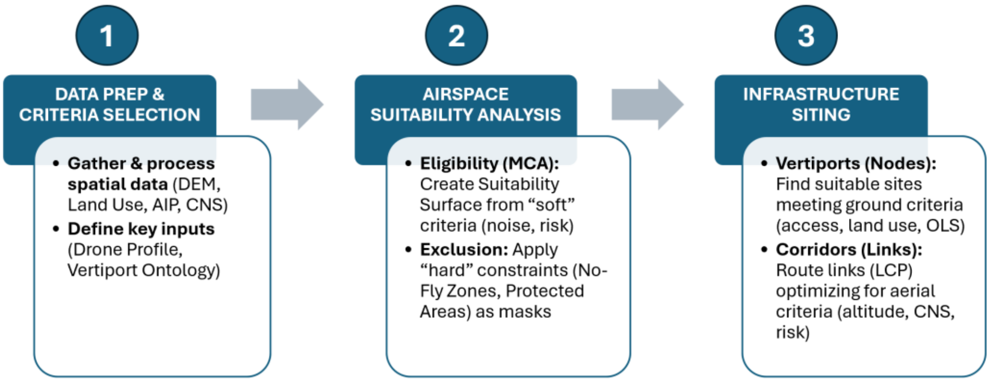

Diagram 1. Workflow: 3-Step Positioning Process

3. **Step 3: Infrastructure Siting (Nodes and Links).** The final step uses the outputs from Step 2 to identify specific infrastructure locations. This methodology distinguishes between the siting logic for nodes (vertiports) and links (corridors):
   - **Vertiports (Nodes):** Are positioned by identifying high-suitability patches that meet specific criteria, primarily **horizontal/ground-level factors** like horizontal noise limits, land-use compatibility, electrical grid connection, and accessibility to multimodal transport nodes.

  - **Corridors (Links):** Are routed to optimize for **vertical/aerial factors**. This often involves using Least Cost Path (LCP) analysis over the suitability surface, prioritizing criteria like altitude-dependent effects, obstacle clearance, energy consumption, and the continuity of CNS coverage.

Table 2. Key layers and correspondent data sources

Foundational Domain	Key Layer Used in Analysis	Data Source(s) (by Case Study)
Safety (Risk)	SORA Ground Risk (iGRC)	Population (ISTAT, INE) + Land Cover (Sentinel-2)
Safety (Airspace)	AIP Flight Rules / No-Fly Zones	Italy (D-Flight) / Spain (ENAIRE Drones)
Safety (Obstacles)	Obstacle Limitation Surface (OLS)	DSM / Building Heights (IGM, Valencian Geoportal)
Social Acceptance	Noise Exposure (Horizontal/Vertical)	DEM (TINITALY, Valencian Geoportal) + Land Use
Social Acceptance	Privacy / Visual Impact	Building Geometry (IGM, Valencian Geoportal)
Drone Performance	CNS (Coverage & Positioning)	Mobile Antennas (Spanish Ministry) - *Valencia Case*
Drone Performance	Energy Consumption (proxy)	Terrain Roughness from DEM
Infrastructure	Electrical Network Access	High Voltage Lines (OpenStreetMap)
Infrastructure	Multimodal Access	Transport Nodes / Land Use (Regional Geoportals)
Accessibility	Socio-Economic Factors	Real Estate Value (Idealista), Spending Capacity (INE)
Environmental	Protected & Natural Areas	National/Regional Geoportals (Emilia-Romagna, ENAIRE)
Environmental	Meteorology & Climate	Weather Station Data (ARPAE, AEMET)
Environmental	Bird Migration Areas	IBAs (MITECO) + Mountain Passes (OSM)

This structure – moving from criteria selection to suitability analysis and finally to infrastructure-specific siting – forms the core of the methodology. The following subsections are structured as follows:

- Section 2.1.1 specifies the reference drone characteristics and risk scenarios, anchoring parameters to concrete operational profiles.
- Section 2.1.2 formalizes the vertiport ontology, clarifying the functional and spatial requirements used in the analysis.
- Section 2.1.3 distinguishes between exclusion constraints (*hard* regulatory bans) and eligibility factors (*soft* criteria for the MCA), defining how layers are applied.

- Section 2.1.4 draws the necessary methodological distinction between vertiports (nodes) and corridors (links), explaining how factors are interpreted differently for each.

In the introduction to this chapter, I further summarized the process to better understand it, starting with a simplified description and identifying the various parts of the process. At the same time, to better understand the sequence of the process, Table 2 provides a summary. In the data preparation phase, factors are first identified and grouped into domains consistent with the decision logic (safety and regulation; technical/CNS; environment and climate; energy and grid; access and socioeconomics). Together with diagram 1 presents this grouping for our analysis, explaining why each factor sits in its domain and pointing to the layers effectively used. This also serves to simplify conceptually at the same time because it is important to consider a certain factor. Each factor is then operationalized as a GIS layer, harmonized to a common spatial reference and working grid (e.g., 50 m resolution), and transformed into a standardized suitability score based on factor-specific response functions and expert rules detailed in Section 2.1. Data capture and provenance for the two study areas are documented in Sections 3.1.2 and 3.2.2; for instance, meteorological records sampled every 15 minutes were aggregated to hourly summaries to match the temporal resolution required by the workflow. Where a dataset exists for one case study only, its use is explicitly scoped to that area and flagged as such in the layer list (see 2.1.1 and the data sections of Chapter 3).

The whole-airspace analysis builds two complementary products. First, a weighted MCA surface (Section 2.3) aggregates the standardized factors into a continuous cost/impedance field that answers, “where is it advantageous to fly?” - with lower impedance indicating preferable volumes due to, for example, CNS continuity, stable meteorology, terrain favorability, and lower expected energy demand. Second, a set of a-priori exclusions (Section 2.4) encodes “where cannot we fly?” by applying hard constraints such as AIP no-fly rules, protected/natural areas, and other non-negotiable bans. Subtracting the exclusions from the MCA canvas yields a feasible airspace in which subsequent infrastructure decisions are made. This two-track logic - soft aggregation for convenience vs. hard subtraction for prohibitions - keeps the analysis transparent and auditable for public authorities and stakeholders.

Within the planner’s objectives, nodes (vertiports) come first. Candidate patches are screened on the shared evidence base for land-use compatibility and noise acceptability during TOL (Take-Off and Landing), compliance with obstacle-limitation surfaces around FATO/TLOF (via DSM/OLS checks), proximity to the electrical grid for charging and turnaround services, and accessibility to multimodal transport nodes. These pad-level requirements operate on top of the MCA-derived feasible airspace and are paired with post-MCA validations to confirm operational feasibility before shortlisting (see Sections 3.1.4 and 3.2.4 for the site-selection steps).

Corridors are then derived to connect the shortlisted nodes. Using the MCA surface as a cost field, the routing/connectivity procedure (Section 1.5.4) traces least-cost alignments across low-impedance cells while respecting altitude-dependent constraints. Where available (e.g., in the Valencia case), CNS layers and positioning-quality proxies - such as 4G/5G continuity and positioning accuracy - reinforce link robustness and flag segments where micro-rerouting or altitude policies mitigate overflight impacts on protected or densely populated sectors. In practice, the corridor step privileges continuous, obstacle-aware, communication-supported paths between selected vertiports; case-specific applications are reported alongside node results in Sections 3.1.4 and 3.2.4.

Practical sequence:

i. construct a robust least-cost canvas and carve out a feasible airspace.
ii. shortlist vertiport candidates by enforcing service and safety requirements on suitable ground patches.
iii. extract corridor candidates that interconnect those nodes using the routing method in Section 1.5.4.

The choice introduced in Section 2.1.2 - the reference vehicle and performance envelope - is the outcome of staged exploration. We initially considered a long-distance logistics scenario with a small generic UAV, as it offered a simpler basis for reasoning about positioning and costs. We subsequently examined the feasibility of passenger-carrying drones (see Section 3.3), an option that is methodologically more demanding due to the number of interacting factors and, above all, ground-risk management. While the SORA method - introduced in Chapter 1 - provides a compliant framework for the Specific category (and is potentially extensible to Certified under proper justification and so practice still requires careful argumentation for this last category. Therefore, for the passenger-carrying, we adopted a pragmatic approach to the risk dimension: we computed the potential number of people that could be affected in a worst-case impact footprint as an indicative constraint (3.3). Ultimately, due to the complication explained before, the research core refocused on commercial transport UAVs, for which parameterization is more mature. Anchoring the parameters to a concrete vehicle profile in 2.1.2 keeps the downstream scoring and thresholds reproducible.

In terms of cross-references and execution flow across chapters: raw data acquisition and provenance are in 3.1.2/3.2.2; factor engineering, scoring, and standardization rules are consolidated in 2.2; non-aggregated exclusion criteria are specified in 2.3; the transformation into eligibility (soft) and ineligibility (hard) layers for each case is reported in 3.1.3/3.2.3; corridor extraction and vertiport shortlisting are discussed in 3.1.4/3.2.4 and connected through the routing method referenced in 1.5.4.

Finally, we note two scope conditions that inform interpretation of the results. First, when a layer is available in one study area but not the other (for example, telecom datasets enabling coverage/positioning proxies), it is used only where documented and is not generalized outside its domain of validity; this is flagged in 2.1.1 and reiterated in the data sections. Second, while the MCA provides a transparent, replicable screening, it is not intended as a deterministic verdict: it produces evidence-based shortlists of corridors and sites that local administrations and stakeholders can interrogate, refine, and progressively de-risk through regulatory, technical, and social assessments in subsequent design stages. This separation - advantages to fly vs. places where flight is not admissible, and links for continuity vs. nodes for serviceability - underpins the structure of Sections 2.2–2.3 and guides the case-study results presented in Chapter 3.

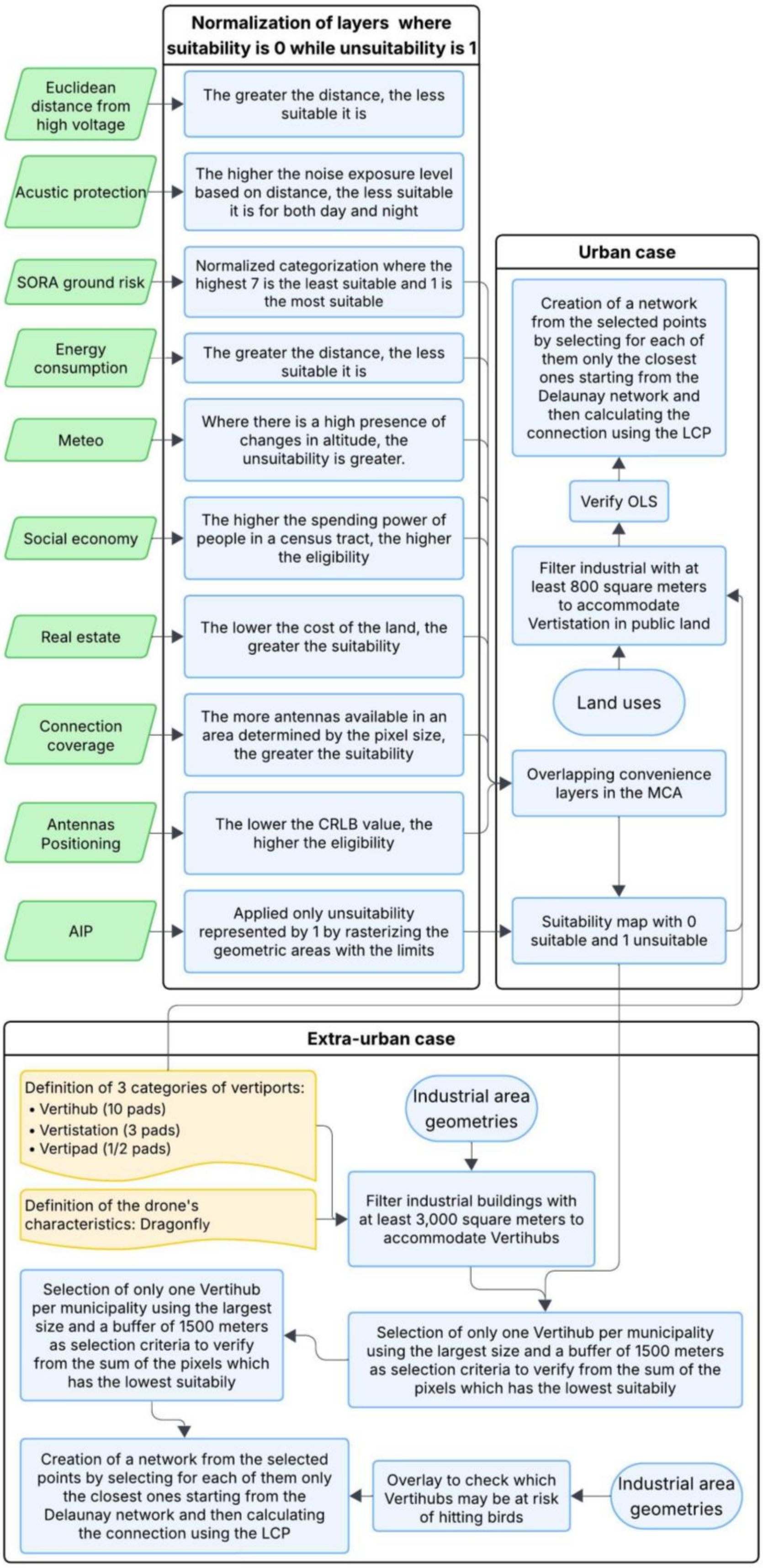

Diagram 2. Process Overview for Site Suitability Across Both Case Studies

2.1.1. Drone characteristics

Figure 1. Dragongly Drone Overspace

Dragonfly DS-1 (Figure 1), developed by Overspace Aviation Srl[1], a dynamic Italian startup based in Prevalle (BS) and Milan that emerged from four years of collaborative research in fluid dynamics, mechanics and structures with the University of Brescia, is a lift-and-cruise VTOL fixed-wing unmanned aerial system featuring a patented three-surface configuration with six rotors - four vertical-lift units mounted on semi-wing supports and two rear horizontal-thrust units - enabling vertical takeoff and efficient airplane-mode cruise and equipped for 2D/3D mapping missions through optional CMOS and LiDAR sensors as well as RTK (Real-Time Kinematic) GNSS (Global Navigation Satellite System) kits for centimeter-level navigation (Overspace Aviation, 2023). Supporting a maximum takeoff weight of 25 kg with a 5 kg payload and engineered for BVLOS/autonomous flight, it delivers up to 200 km of range and two hours of endurance at a cruise speed of 97 km/h, climbing and descending at 3 m/s, resisting winds up to 10 m/s, operating from -20 °C to +45 °C and reaching a service ceiling of 4,500 m. Its advanced ground control station offers up to 50 km of encrypted AES-256 telemetry across customizable 2.4/5.8/1.4 GHz links, with a 15″ IPS 1 000 cd/m² monitor, 10″ multitouch display and 4-axis joystick in a weather-resistant, portable enclosure.

Applications range from medical deliveries - exemplified by the January 2025 BVLOS flight carrying biological samples between Iseo hospital and Monte Isola under Programma Philotea, in collaboration with Carpitech and FlyScabris - to search and rescue with RGB/thermal sensors, large-scale infrastructure inspection and autonomous monitoring missions, with public demonstrations of safe hover-to-cruise transitions showcased online

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[1] Thanks to the company for providing us with information on the technical characteristics.

(ASST, 2025). Since June 2023, Overspace has been incubated at PoliHub in Milan's deep-tech accelerator.

The technical characteristics of the drone are summarized below:

- General Performance
  - Flight range: up to 200 km
  - Endurance: 2 hours (≈ 120 min)
  - Batteries: 2 × 27 Ah 12S LiPo
  - Max tested speed: 160 km/h (45 m/s)
  - Standard cruise speed: 97 km/h (27 m/s)
  - Max climb rate: 3 m/s
  - Max descent rate: 3 m/s
  - Service ceiling: 4 500 m
  - Tested wind resistance: 15 m/s
  - Operating temperature: -20 °C to +40 °C
- Weights & Payload
  - Empty weight (with batteries): 20 kg
  - Max Take-Off Weight (MTOW): 25 kg
  - Max payload: 5 kg
- Airframe & Propulsion
  - Configuration: lift-and-cruise VTOL (4 vertical + 2 forward-thrust motors)
  - Structure material: full carbon-fiber
  - Dimensions (aircraft): 1 980 × 2 000 × 480 mm
- Positioning Accuracy
  - GPS: ± 1.5 m horiz., ± 0.5 m vert.
  - RTK: ± 0.05 m horiz., ± 0.10 m vert.
- Comm & Video
  - Standard link: 15 km range @ 1080p HD
  - Extended link: up to 150 km mesh network
  - Video downlink: 1080p Full HD, 2.4 GHz ISM

2.1.2. Vertiport ontology

Once the suitability analysis (MCA) has identified candidate areas for vertiport siting, it is necessary to verify that each resulting parcel is large enough for the intended vertiport type. Several studies classify vertiports into distinct typologies; in this work we adopt the taxonomy of (Lineberger et al., 2019) , distinguishing Vertistation, Vertiport, and Vertihub, but we changed in order as: Vertipad, Vertistation and Vertihub, giving the meaning in table 6. This is because Vertiport is used as a generical term.

The primary regulatory framework is (EASA, 2022), which addresses manned VTOLs; for unmanned drones we draw on summary references such as (Preis, 2023; 2021) and, in particular on (Kotwicz Herniczek et al., 2024).

Since “Vertiport” has become a generic term for all such facilities, we decided to introduce a slight modification: we will keep “Vertihub,” but replace “vertiport” with “Vertistation,” which better evokes the idea of a transport station - much like a train station - and aligns with Lineberger’s original intent. We then pair “Vertistation” with “vertipad. Vertiport is kept as generical term (Table 3).

Table 3. Vertiport ontology

Category	Primary Function	Typical Connections
Vertipad	Lightweight embarkation/disembarkation point, designed as a “feeder”	• To vertiports and vertihubs • To other vertistations
Vertistation	Local urban-peripheral nodes	• Intra-city routes (neighborhoods ↔ city center/metropolitan)
Vertihub	High-capacity regional hub (10+ pads) with full infrastructure (MRO, parking, passenger services)	• Intercity routes • Regional airport shuttle services

In the selected references, various studies explore vertiport geometries - where to locate parking versus departure areas, schemes for arranging multiple pads in series, and so on. For our purposes, we chose to generalize a single form by extracting from literature the minimum dimensions prescribed for each vertiport category and then validating those dimensions based on the intended number of pads. Accordingly, each vertiport is represented in the GIS of area A and radius r, where:

$$r = \sqrt{\frac{A}{\pi}}$$

To account for the protective airspace above the FATO - OLS or Approach/Take-off Climb Surface - we apply a lateral divergence buffer of 7D approximately 16.26 m for a Vertipad, 26.82 m for a Vertistation, and 47.60 m for a Vertihub. In GIS, these buffers are generated about each pixel centroid: any pixel whose centroid lies within r_{out} of a vertiport center is classified as sufficiently large; others are excluded.

From (Kotwicz Herniczek et al., 2024) we calculated table 4.

Table 4. Area footprint per vertiport type

Category	Pad	Area footprint(m²)	$r_1 = \sqrt{(area/\pi)}$ m	$r_2 = r_1 + 14$ m
Vertipad	1	16	2.26	16.26
Vertistation	3	516	12.82	26.82
Vertihub	10	2 184	26.37	40.37

2.1.3. Setting exclusion and eligibility parameters

In the context of the spatial analysis conducted for vertiport and corridor siting, it is essential to distinguish between layers that serve as absolute exclusion criteria and those that contribute to a suitability score within the MCA. Additionally, some layers are used at a later stage to validate the areas previously identified as potentially suitable. Some layers act as strict exclusion filters. These include flight restrictions defined in the AIP, natural and protected areas, and land use categories that are incompatible with drone operations. For example, areas designated for hospitals, schools, or dense residential functions are excluded from the outset to avoid conflicts with existing land uses and ensure compliance with legal and safety constraints.

Other layers are used within the MCA to determine the degree of suitability of a given location. Among these, energy consumption, especially for corridors, influences the range and efficiency of drone operations. Similarly, the level of mobile network coverage plays a crucial role in ensuring reliable connections during flights. Meteorological conditions and noise exposure vary over the year. Together with visual/privacy impacts, property values, and local spending power, they shape the siting index - reflecting technical feasibility as well as social acceptance and economic viability.

A further group of layers is used in the final phase of the analysis to validate the areas initially selected. The presence of vertical obstacles, for example, is not included in the MCA scoring but is used to verify that the candidate sites meet the safety requirements associated with the Obstacle-Free Surface (OFS) above the FATO. Only those locations where the volume required for safe take-off and landing is free of obstructions can be confirmed as viable vertiport sites.

Some layers may take on different roles depending on the context. The SORA ground risk model, for instance, may lead to total exclusion in high-risk areas, while moderate-risk zones may simply be penalized in the scoring. Similarly, the presence of bird migration areas may either contribute to exclusion or be included in the MCA weighting depending on whether the site is a resting zone or a transit area. The identification of transport nodes, while not an exclusion criterion, directly improves the suitability score for vertiports by enhancing accessibility and multimodal integration.

2.1.4. Distinctions between vertiports and corridors analysis

The spatial analysis aimed at identifying suitable areas for vertiports and corridors requires a methodological distinction, as the two elements respond to different priorities and planning logics. While some layers are relevant to both, many others specifically influence only one or must be interpreted differently depending on whether the focus is on take-off and landing infrastructure or aerial transit routes.

The integration of transport drones into urban and extra-urban environments introduces distinct challenges and considerations, shaped by the unique characteristics of these settings. A comparative analysis highlights the differences in environmental impact, infrastructure needs, safety requirements, social acceptance, and operational efficiency, providing a comprehensive framework for decision-making in drone deployment strategies in the two different contexts.

Starting from a basic selection of data, this analysis has considered factors that can impact at least one of the key areas identified in literature. The contrasting nature of urban and extra-urban traffic requires tailored approaches, as the constraints and requirements differ significantly. Urban traffic is subject to much stricter conditions, necessitating more advanced solutions to mitigate challenges such as noise, safety, and spatial limitations. On this side, extra-urban settings could provide a more flexible foundation for planning drone operations, serving as an initial focus for infrastructure development in this study.

The envisioned infrastructure for drone traffic mirrors the hierarchical structure of terrestrial transportation networks. Extra-urban airways can be conceptualized as "highways of the sky", linking major nodes of high traffic, such as large cities or logistics hubs. These highways would facilitate the efficient movement of goods over long distances. Primary routes would connect these major nodes to secondary distribution centers, typically located in smaller towns. Finally, secondary routes would penetrate urban environments, corresponding to local roads that enable "last-mile" deliveries.

Environmental impact remains a critical consideration in both contexts. In urban areas, noise pollution is a predominant issue, with amplified sound reflections from buildings exacerbating the problem. Visual intrusions often draw resistance from residents, emphasizing the need for specific regulation and transparent community engagement to plan the network. Extra-urban areas, while less densely populated, present challenges related to environmental conservation. The potential disruption to wildlife habitats and natural ecosystems necessitates careful route planning to minimize ecological impact.

Infrastructure availability and adaptability differ significantly between urban and extra-urban areas. Urban environments already benefit from well-established telecommunications, power networks, and transport connections, facilitating the implementation of vertiports and corridors.

However, space constraints demand innovative solutions, such as utilizing rooftops or multi-purpose urban infrastructure. In contrast, extra-urban regions offer ample space for new infrastructure but often lack basic utilities, necessitating additional investments in foundational facilities like power supply and road access.

Safety is a paramount concern, particularly in urban settings where high population density amplifies the risks associated with drone operations. Advanced traffic management systems, collision avoidance technologies, and clearly defined aerial corridors are essential to ensure safe operations. Extra-urban regions, while less populated, face challenges such as varied terrain and natural obstacles, requiring robust systems to maintain operational safety in remote and potentially inaccessible areas.

The social acceptance of drones also varies between these environments. Urban populations are more likely to express concerns about privacy, noise, and safety, highlighting the importance of transparent communication and regulatory compliance. Extra-urban communities, although potentially more receptive, may raise objections related to environmental impacts or interference with local activities like agriculture or recreation.

Operational efficiency further distinguishes the two contexts. Urban areas offer higher economic returns, optimizing last-mile logistics, having higher population density. However, the complexity of navigating congested air space increases operational costs and technological requirements to avoid risk of collision. Extra-urban routes, characterized by open skies and longer distances, enable streamlined operations but face reduced delivery density, which can impact economic viability.

Layers primarily relevant to corridors:

- **Coverage and positioning analysis using mobile antennas**: currently, the calculate coverage in this work provided by mobile network antennas is mainly effective at altitude, making it a key factor for the stability of connections along flight paths. On the ground, coverage tends to be less reliable.
- **Energy consumption**: closely linked to flight distance and environmental conditions, this layer is essential for planning efficient and safe corridors.

Nevertheless, it also indirectly influences the placement of emergency vertiports in case of battery failure or other malfunctions.

- **Noise**: for corridors, noise has a predominantly vertical component, related to cruising altitude and overflight of sensitive areas.
- **Obstacles presences**: critical to ensuring safe flight by avoiding collisions with tall structures such as buildings, towers, or antennas, making it highly relevant to corridor planning.

Layers primarily relevant to vertiports:

- **Electrical network connection**: essential to ensure drone charging capabilities and the energy autonomy of the infrastructure.
- **Identification of key transportation nodes and connections**: integration with existing transport networks and mobility plans is crucial for maximizing vertiport accessibility and intramodality.
- **Land use** helps assess the compatibility between land use types and the installation of take-off and landing infrastructures, identifying regulatory or functional constraints and opportunities.
- **Real estate value distribution** useful to evaluate the potential economic impact of the intervention and the feasibility of the investment.
- **Spending capacity distribution** provides insights into the potential demand for drone-related services, based on the local population's purchasing power.
- **Noise**: in the case of vertiports, noise takes on a horizontal dimension, related to proximity to residential or sensitive areas.

Layers shared by vertiports and corridors:

- **Flight rules from AIP** apply to both corridors and vertiports, as airspace restrictions also affect the feasibility of take-off and landing zones.
- **Ground risk - SORA model** used to identify high-risk areas in case of failure or emergency, influencing both infrastructure types.
- **Key bird migration areas and resting sites** from both an environmental and safety perspective, it is crucial to avoid interference with bird migratory routes and resting sites.
- **Meteorology and climatology** weather conditions affect both flight safety and infrastructure durability. Strong winds, fog, or precipitation can compromise operations in the air as well as maintenance on the ground.
- **Natural and protected areas** these impose strict limitations on the placement of any infrastructure due to environmental protection regulations.
- **Privacy and visual impact** are a transversal issue, as both drones and vertiports may raise concerns related to visual pollution or perceived privacy intrusion, especially in urban and peri-urban areas.

2.2. PROCESSING FACTORS FOR SUITABILITY LAYERS

This section presents the transformation of all factors considered to be integrated into MCA. The process includes the conversion of data into raster format when vector data is unavailable, ensuring compatibility for subsequent spatial computations. Each dataset describes different phenomena - ranging from drone characteristics and positioning accuracy to environmental constraints and socio-economic variables - thus requiring normalization to a common scale (e.g., 0 to 1 or 1 to 10). This normalization is essential for aggregating and comparing their relative impact on the suitability of potential sites for drone infrastructure.

The following subsections explore the encoding of diverse inputs into GIS-compatible formats. The analysis is based on a reference drone model weighing less than 25 kilograms, capable of VTOL, with a typical cruising altitude of 120 meters. This configuration reflects a common class of drones envisioned for short- to medium-range urban and peri-urban operations. Starting from this assumption, the selection and processing of layers were tailored to reflect the operational needs and regulatory constraints associated with such vehicles. For the theoretical passenger-transport case, a different drone is used; it is introduced in the paragraph describing that case.

Corridors are presented first because the MCA’s cost surface primarily encodes where it is feasible and advantageous to fly. Corridor design therefore emphasizes the continuity of low-impedance paths by aggregating altitude-dependent constraints, CNS signal availability and continuity (e.g., GNSS and 4G/5G proxies), obstacle fields and buffer distances, expected energy demand, meteorological stability, and environmental sensitivity. This combination guides least-cost routing and supports micro-rerouting or altitude policies that maintain safe, continuous links while limiting overflight of protected areas or densely populated sectors.

Vertiport siting then applies node-specific requirements to the same evidence base. In addition to shared exclusions and safety constraints, eligible locations must demonstrate land-use compatibility and noise acceptability during TOL phases, adequate obstacle limitation surfaces (e.g., FATO/TLOF clearances and approach/departure paths), proximity to the electrical grid for charging and turnaround services, and convenient access to multimodal transport nodes. These criteria determine whether a candidate site can reliably host operations and integrate into the surrounding mobility system. In practical terms, the workflow first produces a robust, least-cost canvas for air corridors; it then identifies vertiport candidates by enforcing pad-level siting and service requirements on top of that surface.

The layers processed include a wide array of aspects. Technical and infrastructural considerations are addressed by analyzing mobile antenna coverage to ensure signal continuity and positioning accuracy, and by mapping the electrical network to verify energy availability. Operational feasibility is further assessed through avoiding areas that could have a higher energy consumption and regulatory constraints extracted from national aeronautical AIP. The SORA methodology was used to evaluate ground risk, integrating land use and population density data to reflect varying levels of exposure.

Additional layers focus on spatial integration, such as the identification of transportation nodes and commuting flows, which were compared with official planning documents to assess their compatibility. Ecological sensitivity was considered by identifying areas of bird migration and nesting, while climatic suitability was derived from the spatial interpolation of meteorological station data. Urban and environmental quality were addressed by incorporating layers on natural and protected areas, ambient noise conditions, and privacy exposure derived from building morphology.

Lastly, socio-economic dimensions were included by mapping real estate values and local spending capacity, which provide insight into potential demand and societal acceptance.

2.2.1. Coverage and positioning analysis using mobile antennas

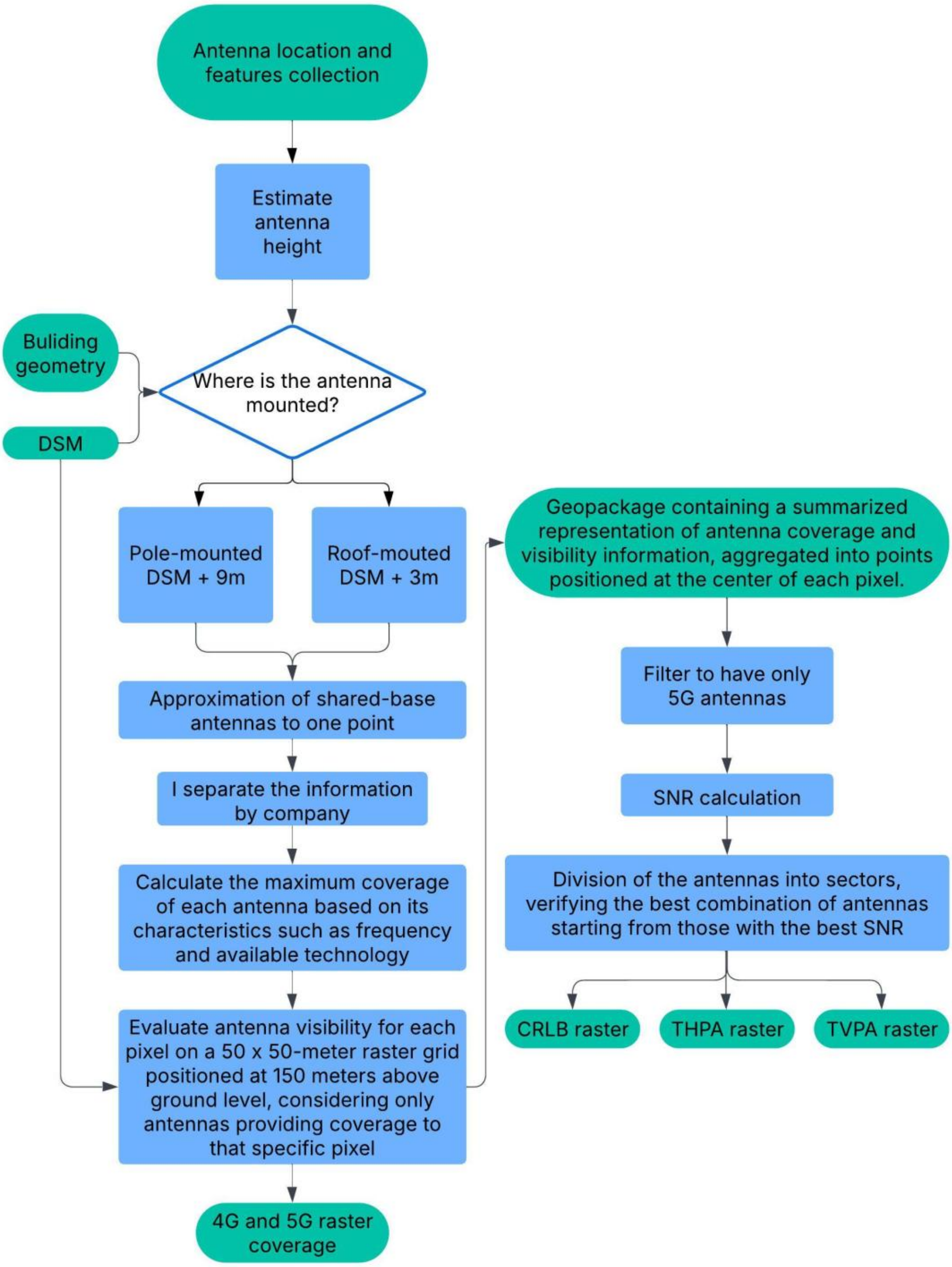


Diagram 3. Connection and coverage workflow

The communication and precise positioning of drones - particularly in urban environments - are essential to ensure maximum safety during flight. While satellite systems, such as GNSS, are currently the primary choice for positioning, especially for amateur drones, they are not sufficiently reliable in the case of automated flight operations. To enhance safety, it is crucial to implement redundancy by integrating alternative technologies that can serve as backups in case of system failure.

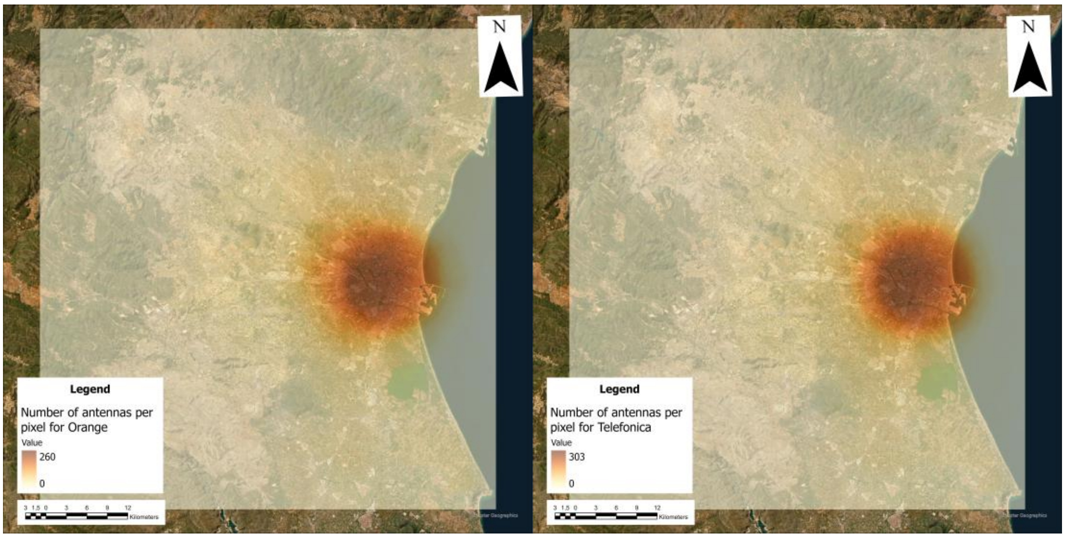


Figure 2. Number of antennas for Orange (left) and Telefonica (right)

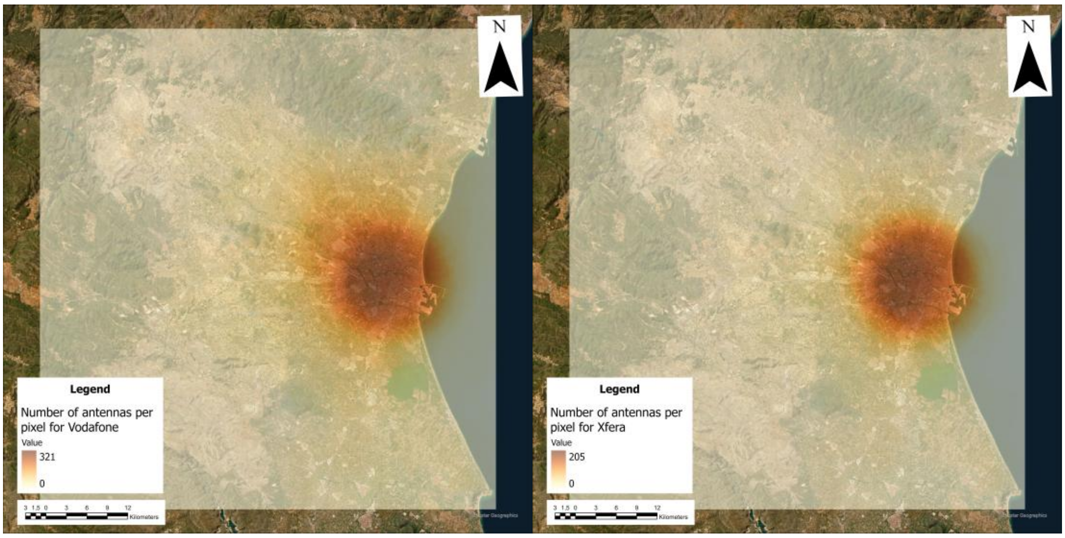


Figure 3. Number of antennas for Vodafone (left) and Xfera (right)

One promising alternative involves leveraging mobile communication networks. These networks offer the advantage of being widely available, as they are part of existing infrastructure, and are well-suited to support drones on densely populated and closely spaced drone operations. 4G networks, and even more so 5G networks - with discussions of 6G already underway - provide extremely high data transfer rates, low latency, and the ability to handle many connected devices simultaneously (Hongyuan Gao et al., 2019). As highlighted in the paper "*Advances in Secure 5G Network for a Nationwide Drone Corridor*" (Bhuyan et al., 2022), many existing infrastructures - such as mobile network antennas - are primarily designed to serve devices located on the ground. Consequently, they are not optimized to provide reliable coverage at altitude, which is essential for aerial platforms like drones.

In our case, information on the location of antennas was only available openly for Spain, and therefore the analysis was conducted exclusively for the Valencia case study. A key part of the work involved obtaining data on the spatial distribution of antennas and their technological characteristics, which was the base for evaluating network coverage in the context of drone operations (Diagram 3).

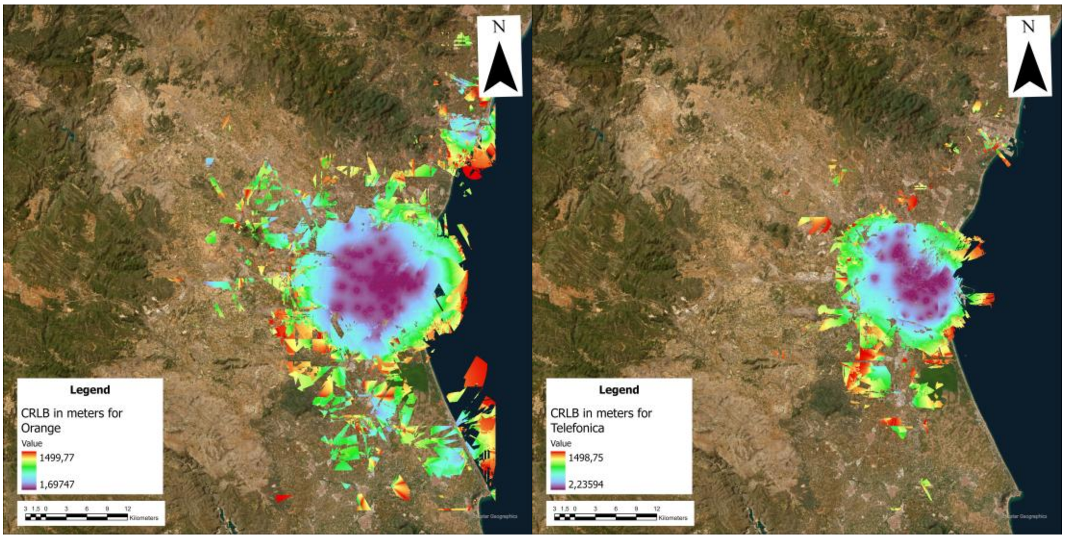


Figure 4. CRLB in meters for Orange (left) and Telefonica (right)

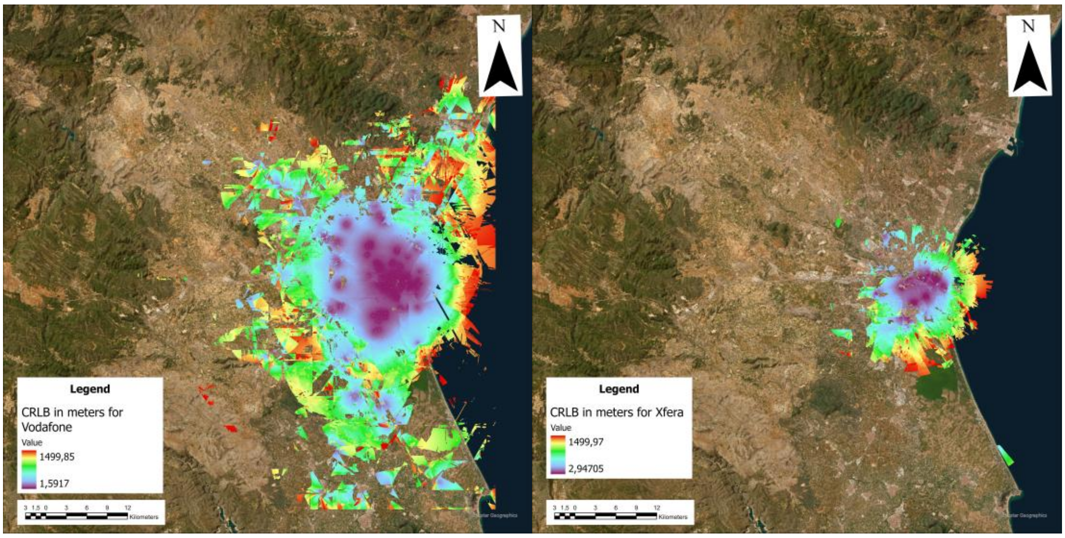


Figure 5. CRLB in meters for Vodafone (left) and Xfera (right)

The communication layer shows areas with adequate network coverage, ensuring stable communication between drones and their operators. Both 4G and 5G antennas were analyzed separately due to their distinct technical characteristics, providing a comprehensive understanding of coverage across the study area. The process began with the acquisition of telecommunication infrastructure data, including the location, height, and technical specifications of antennas. Using a Digital Terrain Model (DTM) and a Digital Surface Model (DSM), line-of-sight calculations were performed to evaluate signal strength at an operational altitude of 150 meters above ground level. This analysis incorporated factors such as transmission power, antenna gain, and receiver sensitivity to determine the extent of each antenna's signal reach and the quality of coverage. The results were summarized in a vector file, with data represented as points corresponding to the centroids of a 50 x 50-meter raster grid. This resolution was selected as a balance between computational efficiency and spatial detail. Each point in the vector file contained detailed information about the visible antennas - those without obstacles in their line of sight - and their respective signal reach (Figure 2 and 3).

Once the communication layer was completed, it provided the necessary base for the creation of the positioning layer. The positioning layer aims to minimize errors in determining the location of drones within the coverage area. Using 5G antennas exclusively, this layer employs techniques such as multilateration, leveraging Time-Difference-of-Arrival (TDOA) and Angle of Arrival (AOA) measurements to calculate positioning accuracy (Monzonís Melero, 2022). The methodology includes evaluating the best configurations between the visible antennas within the coverage area, applying the Cramér-Rao Lower Bound (CRLB) to estimate theoretical positioning errors. Antennas were analyzed for their spatial distribution and technical specifications to identify optimal configurations for precise drone localization (Figure 4 and 5).

2.2.2. Electrical network connection

The deployment of vertiports to support electric VTOL operations entails substantial energy demands, especially due to the need for rapid recharging. In many respects, the power required for charging eVTOLs (Electric Vertical Take-Off and Landing aircraft) can be compared to that of high-performance electric vehicles. For instance, the Porsche Taycan, when connected to an 800-volt public fast charging station, can reach a peak power draw of up to 270 kW, allowing a charge from 5% to 80% in approximately 22.5 minutes under optimal conditions (Wikipédia, n.d.; Kane, 2021). To put this into perspective, the average power consumption of a typical U.S. household ranges between 1 and 2 kW at any given time. Therefore, a single Taycan in fast charging mode can draw the equivalent power of over 100 average homes.

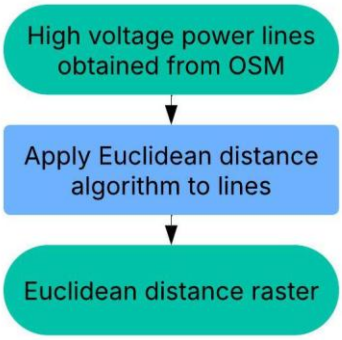


Diagram 4. Euclidean distance from high voltage power lines workflow

This analogy provides a tangible reference point for estimating the impact of eVTOL recharging infrastructure. Passenger-carrying drones, depending on the design and range, are typically expected to use battery capacities ranging from 60 kWh to over 100 kWh, with power delivery rates potentially exceeding 200 kW to ensure short turnaround times. In contrast, cargo drones limited to 25 kg payloads generally operate with smaller battery systems, often in the range of 5 - 15 kWh (Charge Cube, 2025). Nevertheless, the cumulative demand from multiple smaller drones operating concurrently can still represent a significant load, particularly in urban environments with high traffic frequency. In terms of electrical infrastructure, current fast-charging systems for eVTOLs - such as those developed by BETA Technologies - require a three-phase 480 V AC input and deliver between 800 V and 950 V DC output, indicating that vertiports will typically need medium - to high -voltage connections to the power grid (Florida Department of Transportation, 2022).

According to system-level analyses in (Kohlman et al., 2018), the introduction of a fully electric UAM fleet may strain the current grid infrastructure. To support such networks, infrastructure upgrades including new transformer banks and dedicated substations may be required, with estimated costs ranging from $3 million to over $80 million depending on the network size and local grid conditions. In the study (Ahn et al., 2022), the authors suggest that a single vertiport serving up to 500 eVTOLs could necessitate as many as 160 high capacity charging stations, further exacerbating the load on the urban power grid.

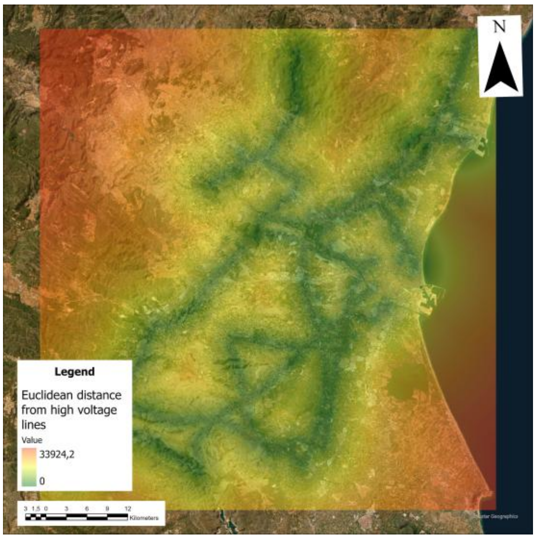


Figure 6. Euclidean distance from high voltage lines

In addition, the (McKinsey & Company, 2021) identifies access to robust electric infrastructure as one of the most critical criteria for vertiport siting, together with location accessibility and land use compatibility. These insights underline the need for an integrated planning approach that encompasses not only airspace design and urban regulations, but also energy forecasting and smart grid coordination. Properly anticipating the energy profile of vertiports - both in peak and average conditions - is essential to ensure the feasibility and resilience of future urban air mobility systems.

In this case we went to check which areas were closest to the high voltage grid using data downloaded from Open Street Map (Figure 6 and Diagram 9).

2.2.3. Energy consumption

The energy consumption of drones will have a profound impact on their operational feasibility and environmental footprint, making energy-efficient route planning essential not only for cost reduction but also for minimizing emissions. (Poikonen et al., 2021) shows that several authors calculate energy consumption based on the distance traveled and the specific mission profile - a perspective further supported by insights in (Figliozzi, 2017). Moreover, (Hong et al., 2021) demonstrates that flight autonomy does not solely depend on increasing battery capacity; rather, adding more battery increases weight and, consequently, the energy required to maintain altitude, with environmental factors such as wind also significantly affecting consumption. This paper introduces a TD3-based method that continuously learns and adapts flight paths, integrating onboard camera data for obstacle avoidance. Similarly, (Yu Wu et al., 2021) present an algorithm that pre-assesses energy requirements by segmenting the flight route into a three-dimensional “AirMatrix” using k-means clustering. By continuously monitoring and updating the drone’s battery status, the system checks whether actual consumption aligns with predictions and, if not, dynamically adjusts the flight trajectory - both to optimize energy use and to avoid potential conflicts with other drones. Complementing these studies, (Liu et al., 2017) develops a theoretical model - validated by experiments on a quadcopter IRIS - that decomposes energy consumption into induced power, profile power, and parasitic power, thereby providing an accurate estimation of power usage during steady-state flight.

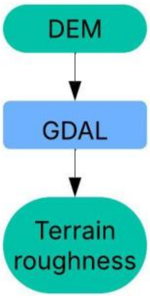


Diagram 5. Terrain roughness workflow

Finally, it should be noted that “energy consumption” in the UAV literature may refer to different components, depending on the application. While many works focus on propulsion power (i.e., the energy required to sustain flight), other studies address communication/network power when UAVs act as aerial base stations. In this latter context, Mozaffari et al. (2016) show that jointly optimizing UAV locations and service-area boundaries can reduce network power consumption by up to 20 times compared with a Voronoi (nearest-node) baseline, where each user is associated with the closest UAV and service regions are defined by a Voronoi tessellation. This result is reported here only to highlight that spatial allocation and demand distribution can strongly affect energy-related objectives; however, communication-network power modelling is outside the scope of this thesis, but part of the PhD research. Furthermore, safety and contingency planning - such as ensuring the availability of alternate vertiports along the route in case of emergencies - can further impact energy consumption, as alternative routes and extended flight times must be factored into the planning algorithms. These studies underscore that a holistic approach integrating energy modeling, adaptive route planning, and safety considerations is essential for the sustainable and reliable implementation of drone systems.

Currently, there is a lack of widely available, standardized data on energy consumption from various drone manufacturers, making it challenging to precisely quantify the energy demands across different systems. To address this gap, we use a simple indicator aimed at identifying areas where drones are likely to experience fewer energy-intensive events - particularly frequent altitude changes. This method involves processing a Digital Elevation Model (DEM) using a sliding window filter to compute roughness, defined as the standard deviation of elevation values. Regions with lower terrain roughness are expected to require fewer altitude adjustments, thereby reducing energy consumption (Figure 7). The approach is implemented in Python with libraries such as rasterio, SciPy (Diagram 5), and matplotlib, and outputs a normalized rugosity map that serves as a proxy for identifying low-energy consumption corridors.

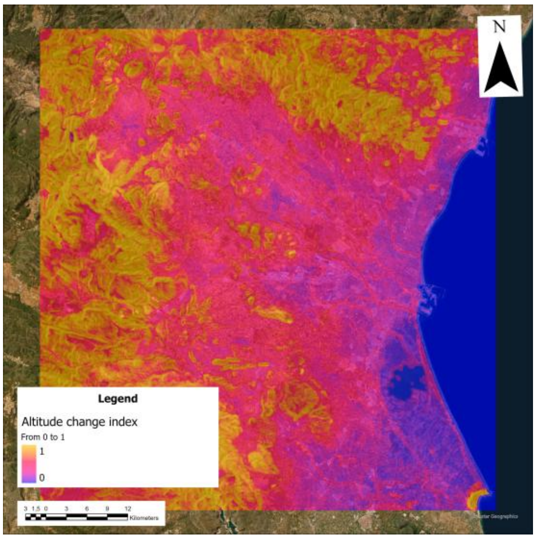


Figure 7. Altitude change index - roughness

2.2.4. Ground risk: SORA model

To operationalize the SORA framework within this research, a custom Python-based methodology was developed, specifically aimed at automating the calculation of the iGRC through spatial analysis. This implementation combines theoretical foundations from JARUS (Joint Authorities for Rulemaking on Unmanned Systems) Annex F with practical geospatial processing techniques to generate detailed, raster-based ground risk maps suitable for urban drone operations. The approach supports scalable analysis and reproducibility, allowing for flexible adaptation across different operational contexts and drone configurations.

A central component of the methodology involves the use of functions from the open source casex package, which was developed under the guidance of JARUS to support the quantitative implementation of the SORA model (Diagram 6). The casex library includes computational models for ballistic descent, critical area estimation, and friction coefficients, all tailored to the requirements of Annex F. These pre-built functions were integrated and extended within a broader Python-based workflow to ensure that drone-specific dynamics - such as glide behavior, impact energy, and sliding distances - could be accurately represented.

The computational process begins with the estimation of drone-specific physical parameters. These include the horizontal distance traveled before impact and the size of the critical area affected by the drone in the event of a failure. These parameters are determined through a ballistic descent model, namely the "BallisticDescent2ndOrderDragApproximation", which simulates descent trajectories under the influence of aerodynamic drag. Key inputs such as the drone's mass, wingspan, cruise speed, and operational altitude are used, along with contextual characteristics including material type, surface composition, and estimated friction coefficients at the potential impact location. The model also accounts for the angle of impact and sliding behavior after ground contact, offering a realistic representation of the drone's footprint in emergency scenarios.

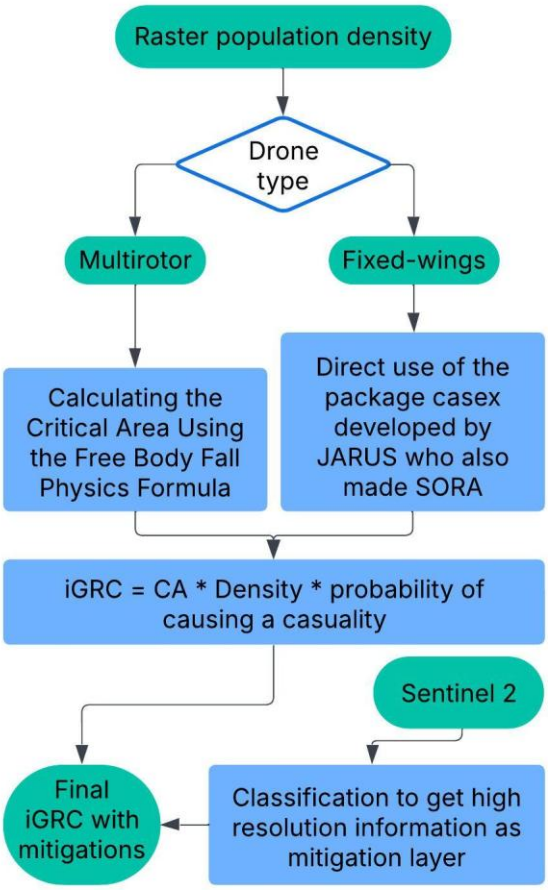


Diagram 6. Ground risk workflow

Once the physical parameters are calculated, the risk radius is derived by summing the horizontal distance before impact and the radius of a circle equivalent to the critical area. This radius defines a circular footprint used as a moving window for spatial filtering on population density rasters. The iGRC is computed on a per-pixel basis by combining local population density values with the drone's critical area, using the mathematical formulation proposed in Annex F of the SORA guidelines. To improve the fidelity of the results, an optional sheltering raster can be integrated to reflect the presence of natural or built structures that may reduce effective risk on the ground.

To capture conservative estimates, a maximum spatial filter is applied over the circular footprint defined by the risk radius, ensuring that the highest risk values within each buffer area are recorded. If sheltering mitigation is included, a minimum filter is also used to represent localized risk reduction. The final output is a georeferenced raster file in GeoTIFF (.tif) format. This file contains floating-point values that represent the iGRC - an index quantifying the intrinsic ground risk associated with each pixel in the study area. Each value corresponds to a combination of drone characteristics and the population density at that location, thus providing a spatially explicit assessment of the risk posed to people on the ground in the event of a failure.

The entire process is encapsulated within a modular Python workflow composed of reusable functions. These include routines for raster reprojection, sheltering layer alignment, physical parameter computation, risk footprint generation, and raster export. The sheltering layer was derived by classifying a one-year Sentinel-2 time series, since no available land-cover product could reliably distinguish trees, grass, buildings, and other classes. How we built this layer allows transparency and supports reproducibility across multiple scenarios. In addition, the code can be extended to accommodate further data sources - such as high-resolution 3D urban models or real-time population estimates - thereby improving accuracy and regulatory applicability. The result is a robust, data-driven approach that aligns with the quantitative risk modeling principles introduced in SORA 2.5 and offers a practical foundation for ground risk assessment in support of U-space and integrated urban air mobility planning (Figure 8).

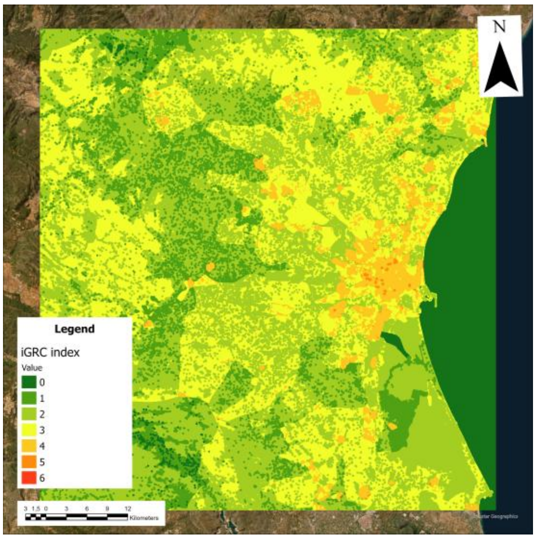


Figure 8. iGRC index

2.2.5. Meteorology and climate

Weather conditions represent a major challenge for UAM operations. Unlike conventional aircraft, drones - particularly small electric models weighing less than 25 kg - are permitted to operate at lower altitudes and are therefore significantly more vulnerable to environmental conditions (Mozhou Gao et al., 2021). In addition to natural phenomena, it is necessary to pay attention to the influence of the built environment, such as the aerodynamic effects generated by buildings and urban structures, especially in relation to wind modeling. Factors such as strong winds, turbulence near the ground, precipitation, fog, and temperature fluctuations can considerably affect drone stability, flight endurance, and overall operability (Chodnicki et al., 2022; Crespi et al., 2021).

Electric drones powered by lithium-ion batteries are particularly vulnerable to temperature extremes. In hot environments, batteries may overheat and degrade faster, reducing both flight time and long-term reliability. In cold conditions, energy efficiency drops sharply, potentially compromising flight autonomy (Alihosseini et al., 2021). This sensitivity makes drones especially exposed to delays and cancellations, an issue that poses logistical challenges for on-demand services like emergency response or package delivery.

These meteorological constraints must be addressed both in strategic planning - through the identification of areas frequently affected by critical weather - and during real-time operations, which require accurate weather forecasting. Following the conceptual distinction outlined by (Thibbotuwawa et al., 2019), long-range mission planning can benefit from historical weather records to avoid seasonally hazardous zones, while tactical decision-making must rely on current weather data to adjust routes and mission timing based on the drone’s autonomy and capabilities.

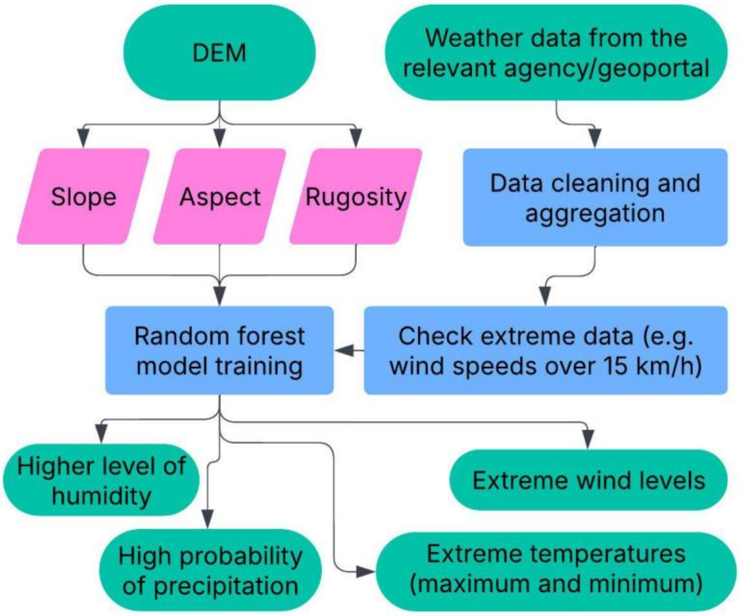


Diagram 7. Meteo workflow

This research takes inspiration from the methodology developed in (Crespi et al., 2021), adapting its structure to generate a series of high-resolution raster maps covering multiple weather variables - including wind, humidity, temperature extremes, thermal excursion, and precipitation - for the region of Valencia.

These maps were created through a machine learning pipeline based on Random Forest regression models trained with data from weather stations, enriched with topographic features derived from a high-resolution DEM. These features include elevation, slope, aspect, and rugosity, all known to influence localized weather patterns. Each predicted raster layer provides spatialized insight into a single meteorological variable and is calibrated using station-based values and cross-validation. The following steps summarize the process (Diagram 7):

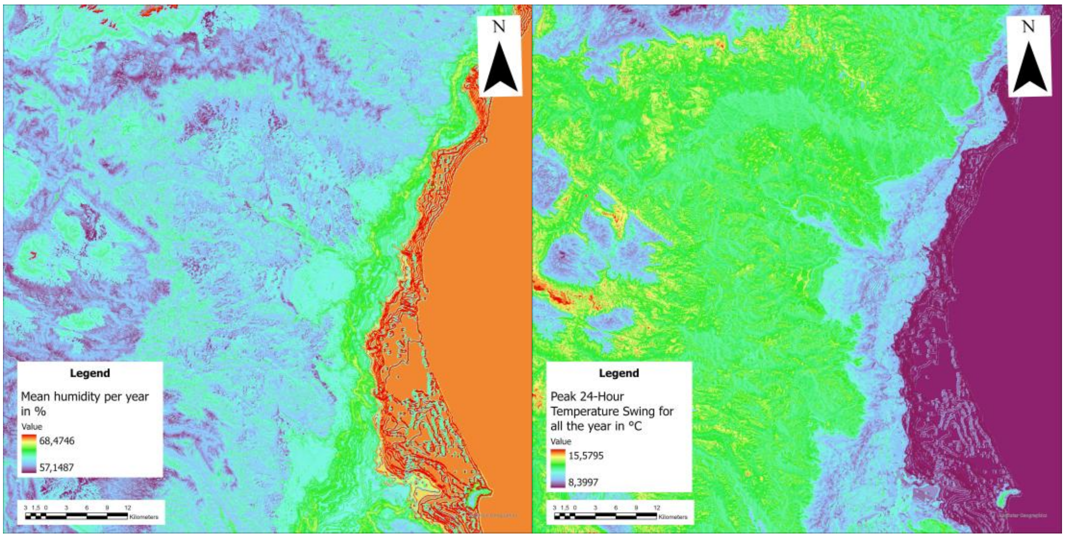


Figure 9. Mean humidity per year in % (left) and Peak 24-hour Temperature Swing for all the year in °C (right)

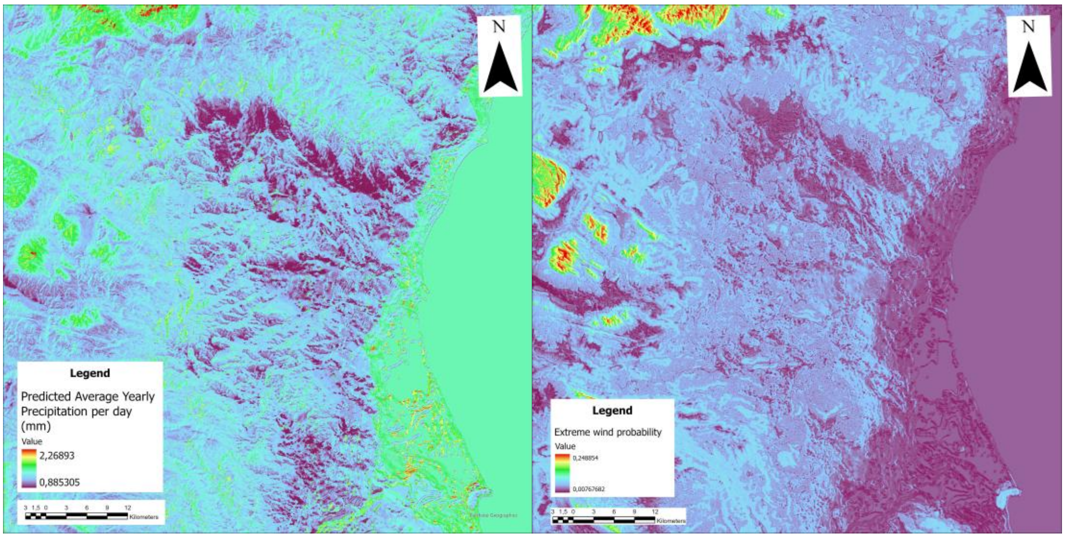


Figure 10. Avarage Yearly Precipitation per day (left) and Extreme wind probability (right)

- **DEM processing**: it was used to derive secondary topographic variables such as slope, aspect, and rugosity (standard deviation in a 9×9 moving window).
- **Weather data integration**: hourly weather time series and georeferenced station metadata were combined and reprojected to EPSG:25830, ensuring spatial alignment with raster layers.
- **Orographic feature extraction**: for each station, values of DEM, slope, aspect, and rugosity were extracted to enrich the training dataset.

- **Feature engineering and prediction**: for each target variable (e.g., wind, humidity, max/min temperature), Random Forest models were trained using a grid search to optimize parameters and used to generate continuous raster predictions across the study area.
- **Output generation**: final raster files were saved for each variable, providing spatial weather predictions that support both strategic and real-time drone mission planning (Figure 9 and 10).

2.2.6. Noise

The integration of drones into urban and rural environments requires careful consideration of noise, a factor that significantly influences their societal acceptance and operational feasibility. Research has demonstrated that noise generated by drones is often perceived as more intrusive than other sources, making it a critical element in planning and deploying drone operations.

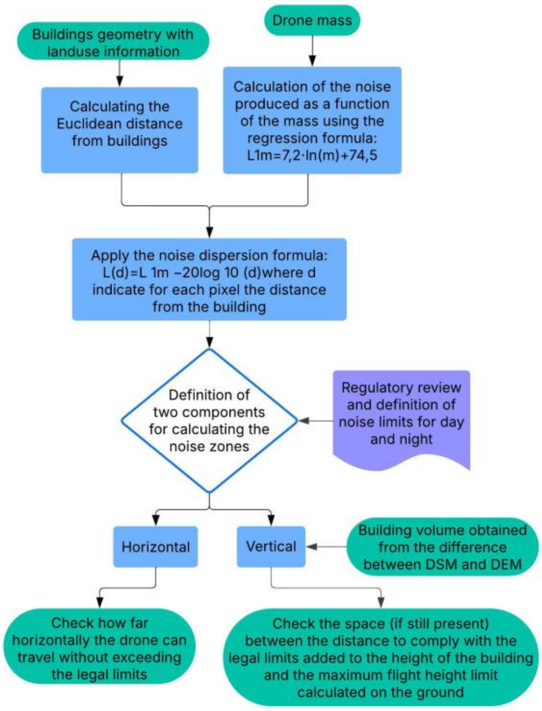


Diagram 8. Noise emission workflow

Noise is a fundamental determinant of the commercial success of drones, as highlighted by (Straubinger et al., 2020). Their analysis revealed that drone noise should ideally remain 15 dB below that of conventional helicopters to gain broader acceptance. However, the specific tonal qualities of drone noise make it inherently more challenging to tolerate, emphasizing the need for innovative noise mitigation strategies.

To operationalize this principle, the methodology presented in (Brunelli et al., 2022) proposes a multi-criteria approach for siting vertiports. Factors considered include population vulnerability (e.g., proximity to schools), perceived noise levels, infrastructure availability, and potential for intermodal integration. Scenarios that prioritize noise mitigation over route length, for example, have shown to reduce the number of residents exposed to noise by up to 76.9% compared to the shortest-route scenario. This underscores the importance of strategic positioning based on broader socio-territorial variables.

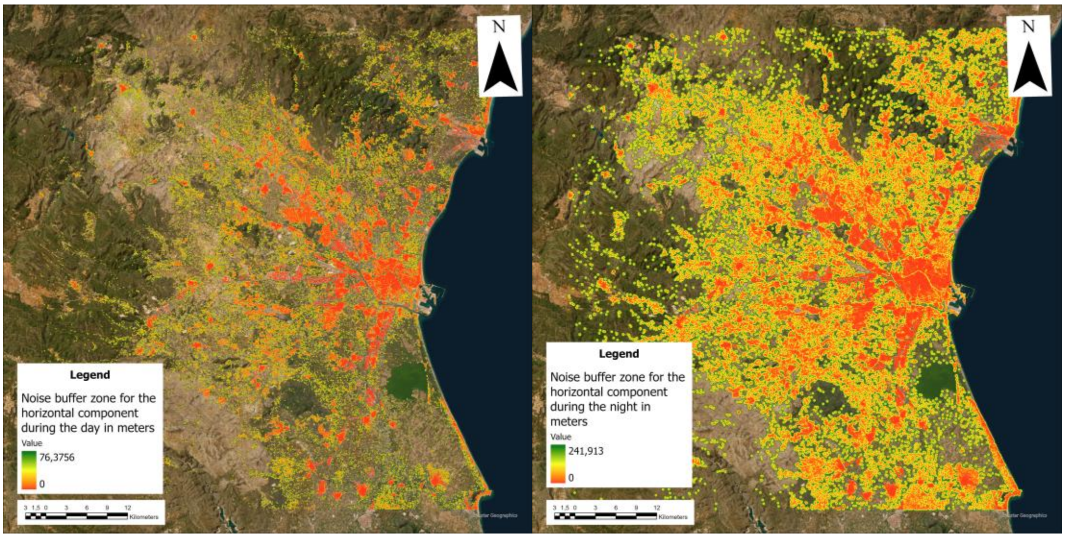


Figure 11. Noise buffer zone for the horizontal component during the day (left) and night (right)

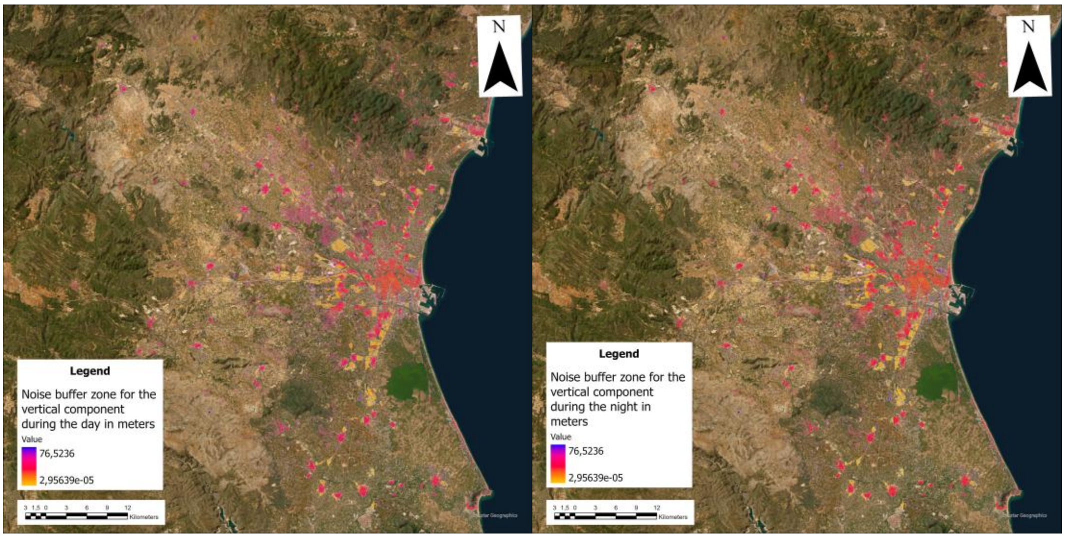


Figure 12. Noise buffer zone for the vertical component during the day (left) and night (right)

In this context, guidelines such as those outlined by the Provincia autonoma di Bolzano - Alto Adige (2019) and the Sardinia Region's framework (Pisu et al., 2008) provide valuable insights. These documents propose acoustic respect zones and noise thresholds that can be integrated into GIS-based planning tools. By defining noise-sensitive areas and incorporating these constraints into spatial analyses, planners can optimize the placement of drone routes and operational hubs.

McKinsey & Company (2021) adds to this discourse by establishing that acceptable drone noise levels should remain below 60 dB to avoid significant disturbance. However, proximity to residential areas poses a challenge, particularly for landing and takeoff points, where noise levels often exceed acceptable thresholds. Acoustic zoning and adherence to regional noise plans can play a crucial role in addressing this issue.

Emission limit value - Leq db(A) - D.M. 14/11/97 **Land use acoustic zone**	**Day 6 a.m. to 10 p.m Leq dB(A)**	**Night 10 p.m. to 6 a.m. Leq dB(A)**
Area Class I - Particularly protected areas: territories where the "quiet represents a priority characteristic": hospitals, schools, areas dedicated for relaxing and recreation, public parks, residential rural areas, more sensible urban planning areas, etc.	50	40
Area Class II - Areas mainly dedicated to a residential use, characterized by local road traffic, low population density, low presence of commercial activities and absence of industrial and handcrafted activities	55	45
Area Class III - Mixed areas: areas characterized by local and crossing road traffic, by medium density of population, presence of commercial activities, offices, low density of handcraft activities and absence of industries; rural areas characterized by the presence of machinery	60	50
Area Class IV - Intensive human activities areas: busy road traffic, high density of population, high presence of commercial activities and offices, presence of handcraft activities; areas close to main road traffic and railway infrastructures; ports; areas with a presence of factories	65	55
Area Class V - Mainly industrial areas: presence of factories and a low presence of residential buildings	70	60
Area Class VI - Exclusively industrial areas: the areas belonging to this zone are interested exclusively by industrial activities	70	70

Table 5. Noise class by land uses in Italy

Further emphasizing the unique characteristics of drone noise, (Schäffer et al., 2021) conducted a systematic review of its acoustic and health impacts. They found that drone noise is not only perceived as more annoying due to its tonal properties but also varies significantly based on factors such as age, gender, and familiarity with the sound. For instance, their study noted that a DJI Phantom 3 Advanced drone operating at 25 feet generates approximately 70 dB, while a larger delivery drone would likely produce noise levels comparable to helicopters. This underscores the need to account for drone size and payload in noise assessments, as larger drones with more propellers typically generate higher decibel levels. The work of Schäffer et al. (2021) also highlights the importance of considering environmental and demographic variables in noise analysis. The review points to the differential impact of noise based on local conditions, including structural barriers that can mitigate sound propagation and the potential effects on animal welfare. Additionally, their findings draw attention to the limited research on the long-term health implications of drone noise, suggesting that this area warrants further exploration. Research into the correlation between drone design and noise emission provides actionable insights for GIS-based analyses. For example, it was identified a 6 dB difference between drones weighing 0.11 kg and 11 kg, with the number of propellers also influencing noise levels. Such data can be incorporated into GIS tools to model and predict noise dispersion, enabling planners to design routes and infrastructure that minimize acoustic impact.

Finally, the systematic review by Schäffer et al. emphasizes the broader implications of noise, advocating for it to be a primary focus in drone deployment studies. While much attention has been given to issues like crime and privacy, noise remains a pressing concern that directly affects public acceptance and regulatory frameworks. Developing clear guidelines and integrating noise considerations into GIS analyses are essential steps for ensuring the sustainable implementation of drone technologies.

The procedure followed for developing the layer aimed at identifying the most appropriate areas in compliance with noise bands was based on the formula (1) proposed by Schäffer et al. (Diagram 8):

$$L_{1m} = 7.2 \ln(x) + 74.5 \quad (1)$$

This approach, which is more thoroughly explained in a paper I co-authored and presented at the Quiet Drones 2024 conference held in Manchester (UK), employs the formula to determine the distance at which the noise limit is respected, in accordance with applicable regulations (Cunietti, Sammarco Chiara, et al., 2024), such as Table 5.

For instance, considering a daytime noise limit of 50 dB in Class I areas, the maximum noise generated is first estimated using the proposed formula. Subsequently, the noise propagation formula is applied to determine the distance at which the noise level falls below the specified threshold (Figure 11 and 12).

2.2.7. Real estate value distribution

The integration of vertiports into urban environments is not only a technical and regulatory challenge but also a deeply spatial and socio-economic one. As highlighted in recent literature, the presence of these infrastructures may lead to profound changes in the value and function of urban fabric. Some studies predict that property values in proximity to vertiports might increase due to improved accessibility, especially in areas where travel time to central business districts is significantly reduced (Tomaszewski et al., 2022). However, this positive externality is not guaranteed: noise pollution, perceived risk, and changes in land use may produce the opposite effect, particularly in residential or historically sensitive areas.

In parallel, real estate dynamics are intimately tied to land acquisition strategies. Research suggests that constructing vertiports in high-demand central zones may be economically unsustainable due to exorbitant land prices (Tomaszewski et al., 2022). This economic constraint, combined with the need to mitigate negative externalities, supports the strategy of locating vertiports in areas where the spatial and economic impact is relatively lower.

A limitation related to socio-economic layers is the Modifiable Areal Unit Problem (MAUP), which occurs when variables are available only as aggregates over administrative units rather than as continuous surfaces (Fotheringham et al., 1991). In this study, indicators such as real-estate values and spending capacity are computed at the census-section level; when rasterized, all pixels inside the same unit inherit the same value. This hides variation within each district (e.g., street-level differences) and creates sharp boundaries that may interact with higher-resolution layers (e.g., DSM/DEM-derived variables, distance surfaces, and CNS/positioning rasters). As a result, local suitability values - especially near census-section borders - can be partially sensitive to the chosen spatial partition. This does not invalidate the screening logic, but it suggests interpreting these indicators as area-level tendencies. Where feasible, future refinements may reduce this effect by using smaller reporting units, applying spatial disaggregation (e.g., dissymmetric mapping), and/or testing sensitivity to alternative zonation.

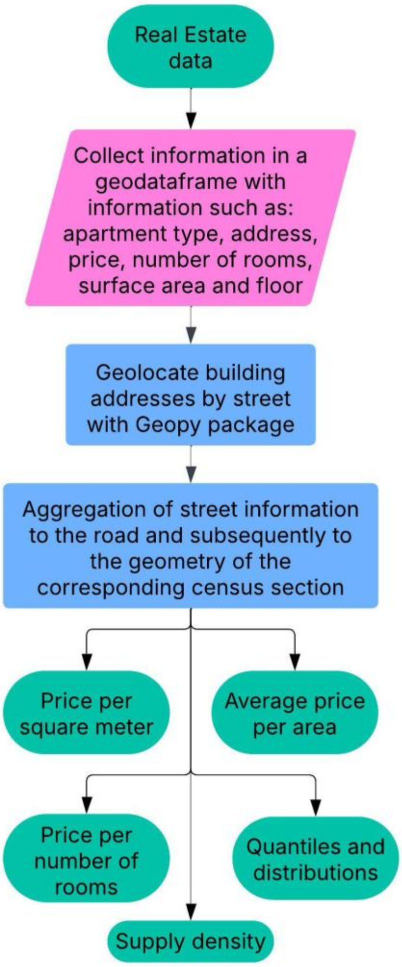


Diagram 9. Real estate value distribution workflow

In the context of the present study, a dedicated spatial layer was developed to examine the spatial distribution of property values in the metropolitan area of Valencia, Spain

(Diagram 9). Data were collected through a custom scraping pipeline built for Idealista.com, one of the Spain's leading online real estate platforms. The scraping process retrieved detailed listings for residential properties, including price, surface area, and number of rooms, and geocoded them using the address extracted from each listing's title.

Once georeferenced, the property data were spatially clipped to the project's bounding box and subsequently joined to OpenStreetMap road segments. This join enabled the aggregation of price information along the road network, which was then intersected with census section polygons to calculate area-based statistics, such as mean, median, and standard deviation of price per square meter (€/m²). The final spatial layer includes aggregated indicators such as average property value, number of rooms, and average floor area at the census section level, providing a robust proxy for land market dynamics across the metropolitan fabric.

This granular layer not only allows for the identification of areas with lower real estate values - therefore more suitable for vertiport deployment from an economic perspective - but also serves as a valuable component for future integrated MCA. By linking economic cost with social vulnerability, environmental exposure, and infrastructure availability, this approach aims to guide the strategic placement of UAM infrastructure toward locations that balance efficiency with public acceptability and long-term sustainability (Figure 13).

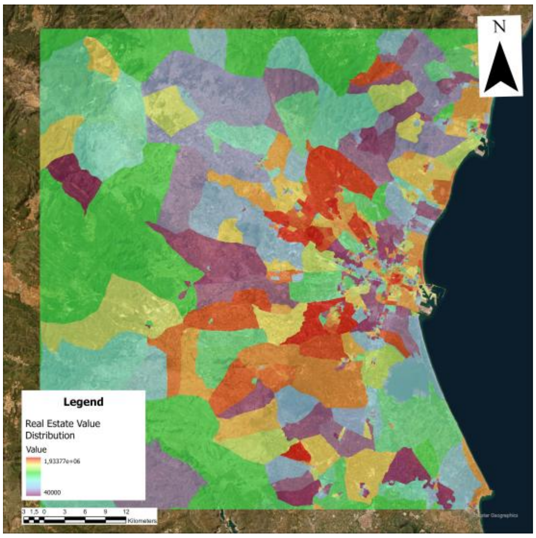


Figure 13. Real estate value distribution

2.2.8. Spending capacity distribution

As previously discussed, one of the most critical factors for the implementation of passenger drones - particularly during the early stages - will be the economic availability of potential users. It is likely that the first UAM services will be accessible only to a limited and affluent segment of the population. Over time, however, as technological development progresses and production scales up, the costs are expected to decrease, allowing for broader accessibility. This diffusion pattern is consistent with what typically occurs in the deployment of emerging technologies: the more the technology is developed and deployed, the faster its costs drop.

Several studies indicate that the initial users will likely be younger individuals with medium-to-high incomes, who are more inclined to use UAM services for non-daily travel purposes (e.g., leisure or special occasions) rather than for regular commuting (Chodnicki et al., 2022). This introduces a significant risk of social exclusion: the benefits of fast and convenient aerial mobility could initially be reserved for a minority, while the burdens - such as noise pollution or airspace occupation - might be distributed across the wider population (Chodnicki et al., 2022). Such a disparity could undermine the social acceptance of UAM, especially if public authorities do not actively work to ensure equitable access.

Cost projections from early commercial experiments reinforce this notion. For example, Uber Copter charged between $200 and $225 per passenger for short routes, while services like BLADE and Voom reported prices around $195 per ride or approximately $10 per passenger-mile, respectively. Although Uber Elevate anticipates future cost reductions to $1.84 per passenger-mile, such levels will likely only be achieved in the medium term, making these services initially unaffordable to the majority (Brunelli et al., 2022).

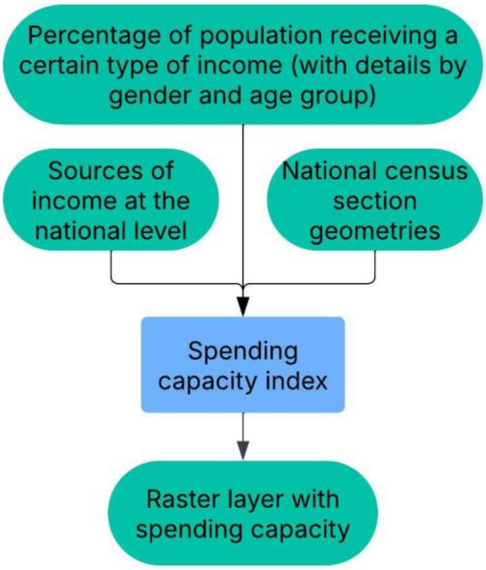


Diagram 10. Spending capacity index workflow

Additionally, spatial inequalities are expected to play a role: studies suggest that low-income populations, blue-collar workers, and certain age groups will have below-average access to vertiports, further limiting their ability to benefit from UAM services during the early stages of deployment (Tomaszewski et al., 2022).

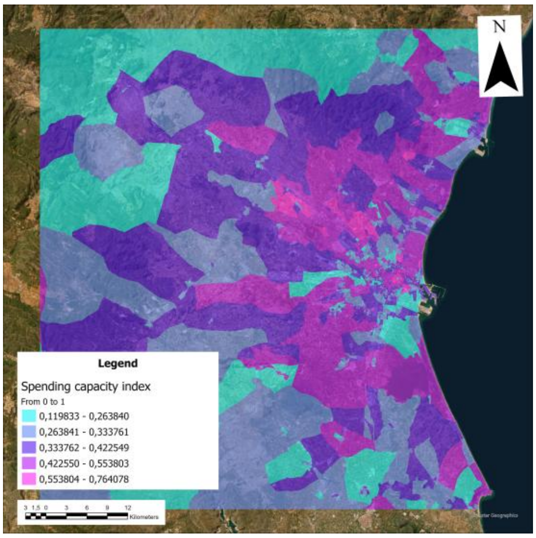


Figure 14. Spending capacity index

To explore this issue within a real-world context, a socio-economic spatial analysis layer was developed for the metropolitan area of Valencia, Spain - chosen due to the availability and consistency of relevant data at the census section level (Diagram 10). The process involved the integration of two primary datasets: one containing average gross personal income, and another indicating the proportion of the population earning more than 200% of the national median income. These were spatially joined with census section boundaries clipped to the metropolitan bounding box, creating a foundational geospatial layer.

Subsequently, additional demographic and educational data were incorporated - specifically the proportion of working-age individuals (18-64 years) and the share of the population with higher education qualifications. After standardizing all variables using Min-Max normalization, a composite index of purchasing capacity was calculated, assigning weights of 50% to income, 30% to working-age population, and 20% to education level (Mazziotta et al., 2016). The resulting geospatial output was exported as a shapefile, providing a spatial representation of areas where residents are more likely to afford and adopt early UAM services (Figure 14).

2.2.9. Visual pollution and privacy

UAM integration into urban and rural landscapes presents not only an engineering and regulatory challenge, but also a deeply socio-spatial one. The spatial distribution of vertiports, the economic accessibility of aerial transport, and the resulting impacts on privacy, visual experience, and property value are all factors that condition the social acceptability of this new transport system.

Multiple studies have shown that drones and eVTOLs could be often perceived as intrusive, especially when operating in proximity to residential areas. Even in the absence of actual data collection, the mere presence of aerial vehicles can trigger a sense of being watched. This psychological dimension of privacy is increasingly recognized as a major obstacle to public trust (McKinsey & Company, 2021). In the survey, it is confirmed that privacy is one of the most cited concerns. 86% of respondents feared privacy violations, secondly to the misuse of drones for criminal activity. Similar findings are echoed in technical and planning studies, which note that public resistance is amplified when drone operations are perceived as opaque or indiscriminate (Brunelli et al., 2022).

The regulatory response has been varied. In Europe, the General Data Protection Regulation (GDPR) establishes strict boundaries for data collection, while in the United States, the Drone Aircraft Privacy and Transparency Act has been proposed to mandate transparency in data practices. The Federal Aviation Administration's (FAA) Remote ID regulation incorporates data minimization and risk mitigation procedures, acknowledging that privacy risks must be assessed as part of operational planning (Chodnicki et al., 2022).

Further complexity arises when considering the purpose of the drone operation. Studies indicate that UAM used for emergency services or medical deliveries tends to be viewed more favorably, while commercial and surveillance applications are met with skepticism (Bueddefeld et al., 2021). In some cases, even camera-less drones are associated with privacy threats simply due to their altitude and flight proximity (Nakamura, Harada, Oura, et al., 2018).

In addition to privacy, the visual impact of drones and vertiport infrastructure presents a significant concern, particularly in heritage-sensitive or high-density urban areas. The literature frequently highlights that aerial vehicles flying at low altitudes generate negative visual stimuli: they cast shadows, clutter the sky, and interfere with the established aesthetic continuity of the urban landscape (Brunelli et al., 2022).

Surveys conducted by major aerospace companies report that up to 45% of respondents are concerned about visual pollution, particularly in cities with strong architectural or cultural identity. Respondents frequently cited fears that UAM might alter the skyline, degrade urban views, or contribute to a dystopian atmosphere (Tomaszewski et al., 2022).

Media representations have also played a role in shaping these fears. The image of congested skies filled with autonomous flying vehicles has become a common trope in speculative fiction and dystopian visual media. This "aerial saturation" narrative, even if not grounded in current technical capabilities, contributes to real-world apprehension and symbolic resistance (Brunelli et al., 2022).

To mitigate these effects, some planning frameworks have proposed flight corridors that avoid visually sensitive areas, prioritize routes above highways or industrial zones, and restrict drone activity near cultural heritage sites. Furthermore, the integration of visual impact assessments into airspace planning is increasingly seen as a necessary step toward sustainable UAM deployment.

2.3. PROCESSING FOR VERTIPORT AND CORRIDOR POSITIONING REFINEMENT

This subsection turns the MCA outputs of Section 2.2 into actionable locations and links, refining the initial suitability surfaces into a shortlist of vertiport candidates and a set of indicative corridors. The logic follows the node - link distinction introduced earlier: at nodes (vertiports), feasibility hinges on pad-level checks - OLS from the DSM, horizontal noise stand-off consistent with land-use limits, access to electricity and interchange quality - while along links (corridors) the decisive levers are vertical separation above rooftops, compliance with airspace and protected-area rules, and continuity of CNS (GNSS and 4G/5G) along the route.

Operationally, refinement proceeds in four stages. First, we threshold and denoise the suitability rasters to isolate contiguous “eligible” patches for vertiports and corridors, rank them by size and context, and intersect them with settlement, land-use and transport-node layers to generate an initial set of pad candidates. Second, we apply post-MCA gating at the site scale: hard exclusions (e.g., protected areas under the default Open-category ≤120 m AGL - Above Ground Level), DSM-based OLS clearance around the FATO/TLOF, horizontal stand-off for TOL noise, and basic serviceability checks (grid connection, access). Third, we build connectivity between surviving nodes by skeletonizing inter-node relations (e.g., Delaunay/k-NN) and tracing least-cost paths over the corridor surface with penalties for airspace and environmental constraints, altitude-floor policies, obstacle fields and CNS deficits; candidate links are then simplified and segmented for subsequent assessment.

Because planning instruments and data differ across contexts, the pipeline accommodates two modes: in Emilia-Romagna the MCA is split upstream into vertiport- and corridor-oriented layers, whereas in Valencia a single urban surface is produced, and the vertiport/corridor differentiation is applied downstream through the site- and link-specific checks above. In both cases the output of 2.3 is a traceable shortlist - pads with OLS/noise/regulatory attributes and corridors with altitude/CNS/constraint metadata - that feeds the case-study results in Chapter 4 and supports subsequent policy reading and pilot design.

2.3.1. Flight rules from AIP

Data related to the AIP in Italy (accessible via D-Flight) and in Spain (through Enaire Drones) can be retrieved through programmable queries. In the case of Italy, the map interface and regulatory framework appear simpler. Conversely, in Spain, it is not possible to download full datasets of all restricted areas, which are significantly more numerous and detailed. These include protective zones within urban settlements, along riverbanks, railways, and other infrastructural corridors (Figure 25).

Following a consultation via email with representatives from Enaire Drones, I was informed that such restrictions are expected to be revised as drone implementation expands to include commercial and passenger transport. This is because current limitations significantly constrain overflight possibilities and complicate the planning of optimal, direct routes.

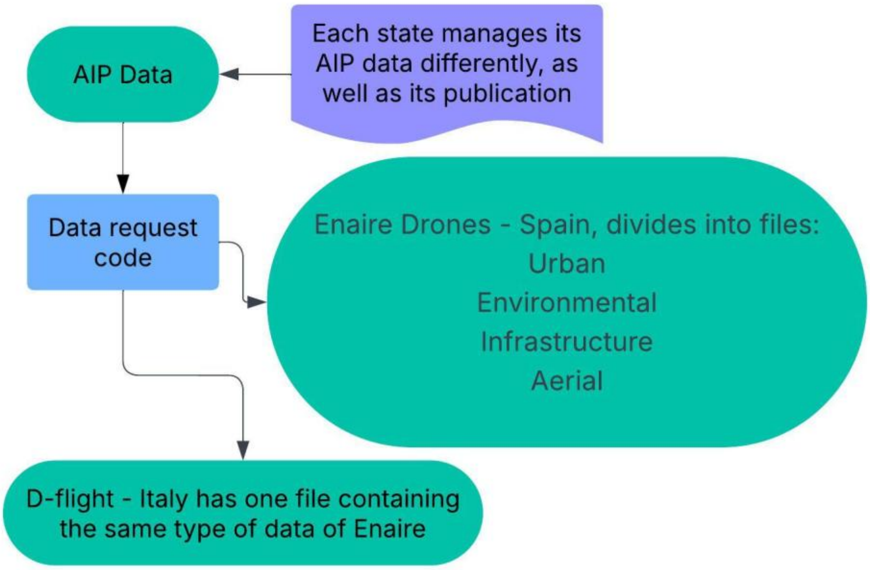


Diagram 11. AIP data extraction

For Italy, D-Flight also shows a high density of restricted zones even across relatively small areas, further limiting operational flexibility. However, as future aims to integrate U-Space with conventional civil aviation airspace, some of these restrictions are expected to be relaxed. Coordination between manned and unmanned traffic management systems is anticipated to enable smoother integration, making certain current no-fly zones less rigid in practice (Diagram 11 and Figure 15).

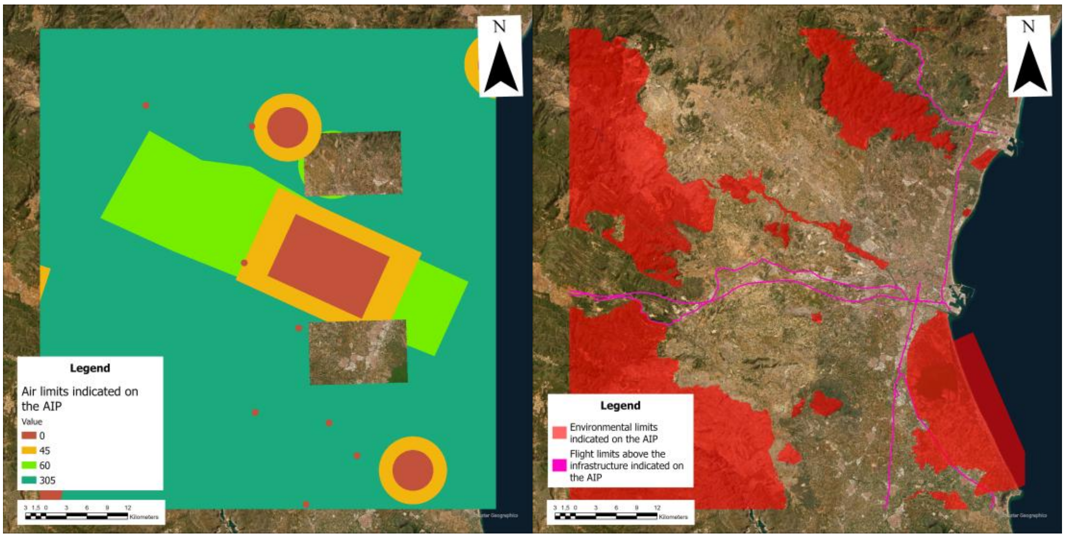


Figure 15. Air limits Enaire Drones (left) and enviromental and instructure limits (right)

2.3.2. Obstacle presence

In the context of vertiport siting, one of the fundamental requirements is the presence of an OFS) or, as defined in several regulations, an OLS above the FATO. This safety volume is essential to ensure that take-off and landing maneuvers can be carried out without interference from vertical obstacles that might pose a risk to flight operations. While in traditional aviation this concept is well established, its application to drone vertiports - especially in urban or complex environments - requires careful spatial analysis and an adapted methodology.

In our approach, the evaluation of obstacle presence is conducted after the initial identification of areas potentially suitable for hosting vertiports. Once these areas are selected based on broader criteria - such as accessibility, compatibility with land uses, and energy infrastructure - we proceed with a more refined verification that considers the three-dimensional clearance above each candidate location. This phase is crucial, as the presence of tall buildings, towers, or other elevated elements could invalidate otherwise promising sites.

The analysis consists of simulating a virtual cone or volume above the FATO, corresponding to the geometrical parameters defined by EASA or derived from existing SESAR-funded projects. Within this volume, no obstacle should be present that might interfere with the drone's vertical trajectory during the critical phases of approach and departure. This layer thus provides a spatial constraint that filters the initially selected areas and narrows down the final list of viable vertiport locations.

The importance of this analysis lies not only in meeting safety standards but also in supporting the design of a network that is both operationally efficient and compliant with aviation regulations. A vertiport that fails to meet OFS/OLS criteria may require structural adaptations or operational limitations, reducing its attractiveness and scalability, or excluded.

2.3.3. Key bird migration areas and resting sites

The presence of birds around airports poses significant risks to flight safety, as bird strikes can lead to severe accidents or operational disruptions. To mitigate these risks, airport safety planning includes a range of measures aimed at managing bird populations and their habitats, particularly within defined zones of influence around the airport.

Airport safety plans classify surrounding areas into distinct zones, such as Zone A, B, and C, each with specific regulations and restrictions to reduce bird activity. These zones are designed to manage land use and minimize activities that might attract birds. For instance:

- Zone A (closest to the runway): strictly controlled to prevent any activity that could attract birds, such as water bodies, waste disposal sites, or agricultural practices that produce food sources.
- Zone B and C (further from the airport): allow limited activities but still enforce restrictions on land use to discourage bird congregation.

One of the key strategies in bird management is identifying areas that serve as habitats, migration corridors, or resting points for birds. Natural areas, including wetlands, forests, and agricultural lands, are often hotspots for bird activity. Regular monitoring programs are established to track bird presence, flight paths, and seasonal patterns. Tools such as radar systems and on-site observation are used to gather data, enabling airports to predict and mitigate potential risks effectively.

Habitat modification is a primary method to deter birds from frequenting airport vicinities. This includes:

- **Eliminating or modifying water bodies**: Draining or covering ponds and lakes to reduce access for waterfowl.
- **Vegetation control**: Removing or altering vegetation that provides food or nesting sites.
- **Managing waste and food sources**: Strict regulations on waste disposal and the use of landfill sites near airports to prevent scavenging birds.

Urban and suburban planning within the zones of influence also considers bird risks. For example, **housing developments and industrial operations near airports are restricted or adjusted to avoid creating conditions conducive to bird attraction**.

Airports employ a range of deterrents to keep birds away from runways and surrounding areas. These include:

- **Auditory deterrents**: Devices emitting high-frequency sounds or predator calls.
- **Visual deterrents**: Lights, reflective surfaces, and decoys to scare birds.
- **Physical barriers**: Netting and other physical structures to block access to critical areas.
- **Falconry**: Using trained birds of prey to naturally deter other birds from entering the airport vicinity.

While safety is a priority, managing bird populations near airports must also account for environmental and conservation considerations. Protected areas, such as wildlife refuges or designated natural reserves, often overlap with airport zones. In these cases, collaboration between airport authorities, conservationists, and urban planners is essential to balance ecological preservation with operational safety.

Regulations from bodies such as ENAC guide airport operators in implementing bird management strategies. These include:

- Setting clear guidelines for activities allowed within safety zones.
- Conducting risk assessments to identify high-risk areas and activities.
- Coordinating with local governments to align urban planning with airport safety needs.

The Italian regulation concerning the construction of a new airport, specifically outlined in Chapter 5 - “Risk of Bird and Wildlife Strikes” in (Giuntini et al., 2023), provides operational guidelines and legal obligations for managing the risks associated with collisions involving birds and other wildlife. It mandates the implementation of a comprehensive environmental and ecological study, which must span a minimum of twelve consecutive months. This study aims to identify the species present, assess their monthly abundance, determine the habitats they utilize, their activity patterns, and identify areas of concentration as well as bird migration routes. Furthermore, the study must locate any potential attractants for birds and other wildlife within the airport grounds and in surrounding areas and assess their potential risk to aviation safety. When a potential hazard is identified, an in-depth assessment must be carried out to determine the actual level of risk and whether it can be prevented or reduced. This includes the establishment of a dedicated organizational structure responsible for risk management. If the location is deemed suitable for the construction of an airport, this structure must report to ENAC all incidents occurring within the airport or in its surrounding areas. An annual report must be submitted, including detailed analyses of recorded events, wildlife monitoring data, and the mitigation measures implemented. Furthermore, specific activities that may attract birds and other wildlife must be carefully regulated or, when necessary, explicitly authorized. These include:

- Landfills, open water bodies, or other wetlands that may serve as attractants for birds.
- Industrial operations are likely to attract avifauna, such as food processing or manufacturing plants.
- Agricultural activities and livestock farming could encourage the presence of wildlife.
- Practices involving the release of animals into the environment, such as game reserves, wildlife repopulation zones, pigeon breeding, and hunting dog training areas.
- Structures or installations with reflective surfaces, photovoltaic systems, misleading lights, laser emissions, or smoke, which may interfere with aircraft operations or attract wildlife.

These guidelines may also have valuable applications in the field of drone operations, where, similarly, bird migration represents a considerable challenge, both in terms of safeguarding natural ecosystems and ensuring the safety of passengers transported by drones. To identify the areas most at risk, a specific layer was developed by adapting the methodology proposed by (Tattoni et al., 2019), which aims to approximate avian migration routes based on flight behavior. Key factors considered include the availability of stopover sites for feeding and resting, the shortest and least energy-demanding paths, and flight altitude depending on the species.

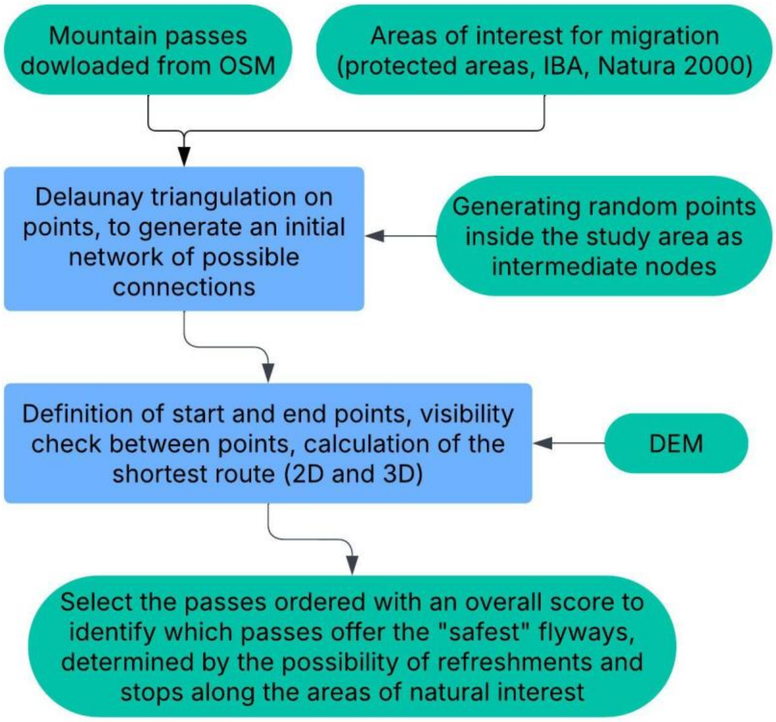


Diagram 12. Bird migration routes workflow

However, the migratory routes of many bird species are still not fully known. In several cases, data are not publicly shared by researchers, as they are the result of long-term studies and are therefore considered sensitive or proprietary. Typically, bird migration routes are reconstructed through bird banding, where individuals are tagged with rings and subsequently identified by both professionals and enthusiasts upon re-sighting. This process allows researchers to infer the trajectories followed.

GNSS trackers are used only on larger birds, as their weight and size make them suitable for carrying such devices. Nevertheless, the number of tracked individuals remains limited, and even in these cases, gaps in coverage may occur. Currently, researchers are also experimenting with the use of small radar systems to detect bird presence and movements more comprehensively.

The adopted methodology involved identifying major migratory corridors, such as mountain passes, and ecologically significant areas designated as Important Bird and Biodiversity Areas (IBAs). This analysis was carried out over a spatial extent broader than the actual study area, as migratory routes can span large territories. Once the key transit zones were recognized, random points were generated to simulate potential paths followed by birds, based on behavioral patterns and topographic constraints derived from a DEM. For instance, the model assumes that birds tend to select routes requiring less physical effort, favoring paths with minimal slope variation and reduced uphill segments. To implement this approach, random points within the study area related to known ecological interest sites, defining plausible origin and destination pairs according to Tattoni et al. (2019). The algorithm not only assessed the morphological characteristics of each route but also evaluated point-to-point visibility to determine the most likely next node along the path. Additionally, it considered the presence of suitable stopover areas within species-specific maximum flight distances, verifying their visibility from the nodes. Migratory birds typically travel in stages, requiring rest and foraging opportunities between flights.

The entire simulation was repeated at different altitudes to reflect the behavior of various bird species based on their size. According to (Giuntini et al., 2023), most species adopt flight altitudes of approximately 500 meters for take-off and landing. Conversely, Tattoni et al. (2019) reports that smaller birds tend to migrate at altitudes around 700 meters (Diagram 12).

Figure 16. Bird migration routes

The flight range of a bird can vary depending on its speed and fat storage capacity. Small migratory species, such as swallows, are generally capable of covering distances of up to 200 km, while larger species can exceed 500 km. Although most drones - particularly smaller models - are likely to operate below typical bird flight altitudes, the primary concern lies in the potential overlap between flight zones, especially in the buffer areas where birds may fly below or intersect the drone’s operational altitude. According to (Hedenström et al., 1992), birds typically ascend or descend at an angle of approximately 6°. This implies that a bird would require about 2 km to reach an altitude of 200 meters and around 5 km to reach 500 meters. Consequently, in regions identified as high-density migratory corridors, particular attention must be paid to these buffer zones, where the risk of interaction is more pronounced due to the transitional flight phases of birds (Figure 16).

2.3.4. Land uses

The success of UAM deployment is intricately linked to urban planning policies and land-use governance. Adapting existing tools - or developing new, more flexible instruments - is essential to enable a planning environment where vertiport siting is not merely reactive but proactively integrated into the urban development process. The shift toward this integration also marks an opportunity: to shape new forms of aerial mobility that are not only technologically feasible but also spatially coherent and socially equitable.

The implementation of UAM infrastructure - particularly vertiports - requires not only technological readiness and regulatory clarity, but also a profound alignment with existing urban planning instruments and land-use regulations. As highlighted by several studies, the integration of vertiports into dense urban fabrics is often hindered by outdated planning tools and rigid zoning systems that were not designed to accommodate emerging aviation technologies (Tomaszewski et al., 2022).

A key challenge lies in the scarcity of available land parcels that are both physically suitable and compatible with current land-use designations. In many metropolitan areas, central zones are characterized by high land values and rigid zoning codes, making the establishment of new aerial infrastructure economically and legally complex. For instance, in cities like San Francisco or Washington DC, property costs can reach up to 40 million USD per acre (circa €83.86 M/ha), and the presence of restricted airspace - such as the P-56 zone around Washington - precludes most forms of aerial activity without federal approval (Tomaszewski et al., 2022).

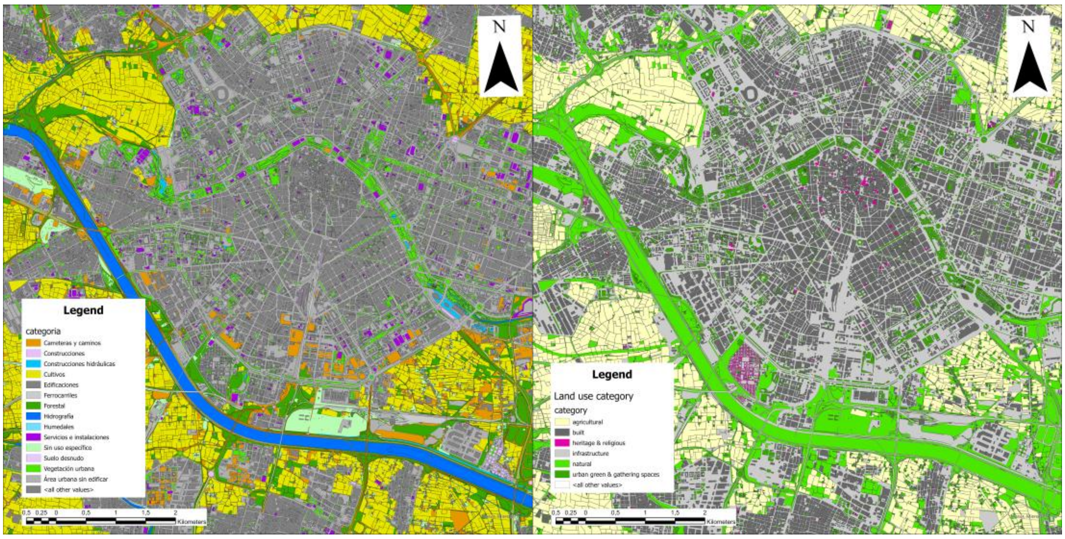


Figure 17. Land use categories zoom original (left) and synthesis (right)

Zoning ordinances and building codes further influence vertiport siting by imposing constraints related to building height, fire safety, noise exposure, and environmental impact. Local governments may already enforce rules governing acoustic emissions or conditional land-use permits for transportation facilities, which are often not yet adapted to the operational characteristics of UAM (Brunelli et al., 2022). Moreover, the inclusion of vertiports in urban plans may require a full revision of master plans and coordination between multiple layers of governance - local, regional, and national as we underlined in (Cunietti et al., 2023).

Beyond these constraints, planning tools also hold the potential to support UAM integration. Some proposals advocate for the development of an integrated framework that connects land-use planning, real estate dynamics, environmental regulations, and social acceptability criteria. For example, spatial multicriteria analyses have been used to identify areas with low population exposure and minimal economic friction, allowing for the strategic placement of vertiports in underutilized or industrial zones while ensuring connectivity with public transport (Brunelli et al., 2022).

International regulatory authorities such as the FAA and EASA emphasize that vertiport projects must align with environmental assessments, noise abatement procedures, and local urban development plans. Without alignment, even well-designed infrastructure may face strong opposition or legal barriers during implementation phases (Bueddefeld et al., 2021).

The Geoportal of the Valencian Region provides a land-use layer. As shown in Figure 17 (left), the data are disaggregated by category, following the original classification. In contrast, Figure 17 (right) illustrates the consolidated schema I devised specifically for this study.

2.3.5. Natural and protected areas

This issue is relevant not only for bird migration (Section 2.3.3) but also as an operational constraint for UAS planning. The areas shown in Figure 18 for environmental limitations are generally treated as no-fly for low-altitude drone operations and are therefore implemented here as exclusion constraints within the GIS-based spatial analysis. Although some airspace restrictions may allow overflight above a given altitude (often above 500 m for conventional aviation), this work focuses on low-altitude UAS scenarios; consequently, those altitude-conditioned permissions are applicable to the analyses developed in this thesis.

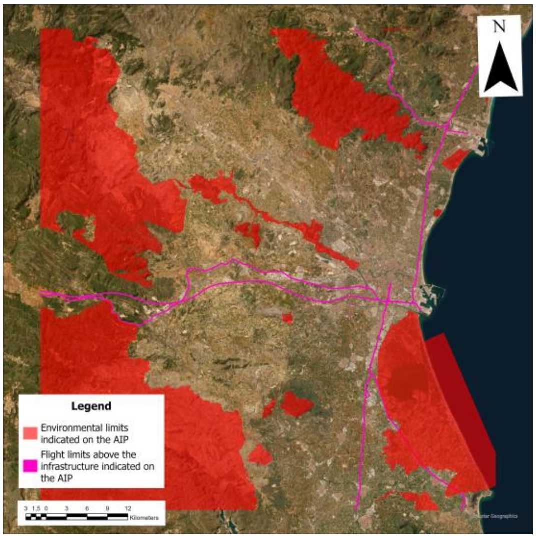


Figure 18. Natural areas and flight limits on infrastructures from AIP

3. CASE STUDIES

This chapter operationalizes the methodology set out in Chapter 2 across two contrasting contexts - an extra-urban, logistics-oriented case in Emilia-Romagna and a dense urban case in Valencia - to test transferability and make explicit how regulatory, morphological, and data conditions shape results. This work builds upon the methodology for positioning U-Space infrastructures proposed in previous studies, expanding the scope to include a multi-criteria spatial analysis. The study focuses on drones with a maximum take-off mass of 25 kg for the logistic case study and 900 kg for the passenger transport. In extra-urban environments, industrial rooftops and logistics compounds as potential vertiport locations, considering safety, noise, and access to electricity. In urban environments, more articulated reading is required, accounting for traffic density, the harmonization of noise with existing soundscapes, and safety through structured infrastructure planning. The spatial analysis aims to optimize airspace for drone operations so that vertiports and corridors are placed for efficiency while minimizing impacts on people and the environment.

To preserve comparability, both applications adopt the same GIS settings and normalization choices and the same distinction between nodes (vertiports) and links (corridors): pad siting is verified with OLS clearance and horizontal noise stand-off, whereas corridor feasibility hinges on vertical separation above rooftops, airspace rules, and CNS continuity. Methodological differences reflect local instruments and data: in Emilia-Romagna, the availability of an integrated landscape/heritage plan allows an upstream split between vertiport- and corridor-oriented layers; in Valencia, where no equivalently integrated urban plan at the same scale is available, a single MCA surface is produced, and the vertiport/corridor differentiation is applied downstream through post-selection checks. Conversely, information on antennas was available for the second case study but not for the first. In both cases, hard constraints (e.g., protected areas under an Open-category ≤ 120 m AGL envelope) are treated as exclusions unless altitude-conditioned permissions are explicitly tested; soft factors are aggregated in the MCA and in a real decision process, it could be revisited as stakeholder deliberation progresses. Each layer represents a factor that either facilitates inclusion (e.g., proximity to multimodal interchanges, grid connection) or constrains it (e.g., obstacle/DSM fields, noise-sensitive land uses).

The chapter is organized to move from context to evidence. Section 3.1 delineates the Emilia-Romagna study area (intercity UAS cargo), describes data sources and preprocessing, and reports the eligibility patterns for vertiports and corridors under the regional constraint set. Section 3.2 does the same for the Valencia metropolitan area (urban UAS cargo), starting with the delineation of the study area and the identification of transport nodes already outlined in local mobility plans, then assessing their eligibility against the unified suitability map and applying post-MCA checks. Section 3.3 presents a theoretical case study on passenger transport in the metropolitan area of Valencia, previously published as a scholarly contribution, whereas Section 3.4 offers a short theoretical concept on how to reduce the isolation of residents in peripheral areas, such as mountainous regions.

3.1. CASE STUDY: INTERCITY UAS CARGO

The initial objective of this work was to identify suitable areas for the deployment of infrastructures serving both vertiports and drone corridors. The original idea was to rely on information derived from literature to develop a series of thematic layers - after first verifying the availability of relevant data for the study area - each classified along a continuum ranging from unsuitability to suitability. These layers were then intended to be integrated through an overlay process to produce a composite suitability assessment.

This methodology was initially presented in the first publication included in the proceedings of the SESAR Innovation Days 2023, where we attempted to apply this approach to sub-25 kg drones intended for long-distance cargo transport. According to the reviewed literature, industrial zones - particularly the rooftops of warehouses - were frequently identified as the most feasible points of departure and arrival for larger drones.

The analysis focused on identifying warehouses with a minimum area of 2000 m^2 that could potentially serve as take-off and landing sites. As mentioned, this study assumed of long-distance transport, which implies different infrastructural requirements compared to those needed for so-called “last mile” delivery operations near residential areas. The aim was also to begin with a relatively straightforward case study to initiate a broader reflection on the integration of such infrastructures into the urban and extra-urban fabric.

3.1.1. Definition of the study area

When defining the research objective, the selection of the study area was guided primarily by the availability and accessibility of relevant datasets for the factors identified as critical in the analysis. Among these factors, meteorological conditions emerged as a central element in the early stages of assessing the suitability of potential areas. For this reason, particular attention was dedicated to the possibility of acquiring historical climatological data with adequate spatial and temporal resolution.

A comparative assessment was carried out across several Italian regions to evaluate the completeness, accessibility, and consistency of available datasets. The Piedmont region provides a large amount of data, including meteorological information, which is accessible through an intuitive system. However, the data are organized on a station-by-station basis, making large-scale processing less straightforward. By contrast, the Emilia-Romagna region, although more complex in terms of downloading some descriptive territorial data, offers real-time meteorological records over extended temporal intervals, thus enabling a more comprehensive climatological analysis.

Figure 19. Location of Emilia-Romagna within Italy (source Wikipedia)

Considering these aspects, Emilia-Romagna was ultimately selected as the study area, as its datasets better aligned with the requirements of the research framework, particularly regarding the integration of meteorological variables into the multi-criteria analysis.

Emilia-Romagna is a region in northern Italy, with Bologna as its capital city. Geographically, it is bordered by the Po River to the north, the Apennine chain to the south, and the Adriatic Sea to the east, while its central portion opens toward the Po Valley (Figure 19). From a morphological perspective, the region can be described through four main zones: the Apennine, the foothill, the plain, and the coastal areas.

The settlement pattern is characterized by a markedly polycentric urban system, distributed along the historical Via Emilia axis. This corridor is structured around a sequence of medium- and large-sized cities by Italian standards - administrative capitals and major industrial hubs - with interconnected and partially overlapping catchment areas. As a result, settlement density is relatively high along the Po Valley corridor, while it decreases in the Apennine areas and in the more dispersed coastal contexts.

The regional transport system is strongly reinforced by the presence of primary infrastructure corridors, including the A1, A13, and A14 motorways, as well as the Milan - Bologna-Florence high-speed rail line, in addition to the port of Ravenna and Bologna International Airport. This combination of factors makes Emilia-Romagna particularly well connected both nationally and internationally.

The polycentric configuration of medium-to-large urban centers - each surrounded by its own network of smaller municipalities and located at relatively short distances from one another - provides an ideal context for testing interurban connectivity solutions. For this reason, the region offers favorable conditions for comparative analyses between urban and extra-urban contexts, which represented one of the initial objectives of this research.

3.1.2. Data source

The Emilia-Romagna Region provides access to a wide range of datasets through its Geoportal, although the downloadable extent is often subject to spatial limitations. Most of the data used in this research was obtained from this source, but not exclusively. As will be discussed in the following sections, data availability constitutes a critical factor in the development of a standardized analysis for assessing the risks associated with the integration of drone infrastructures. In fact, for the extra-urban case study, not all the information employed in the subsequent urban scenario was accessible, highlighting a disparity in the completeness of the datasets across different spatial contexts.

- For the noise layer, the information used included land use, and the DEM.
    - Land use data represents the geometry of buildings and was initially obtained from the Emilia-Romagna regional geoportal. In the meantime, the Italian Military Geographic Institute (IGM) released a geodatabase containing the same information, along with building heights, which proved particularly useful for assessing noise in the vertical dimension (Istituto Geografico Militare, 2025). Furthermore, for Emilia-Romagna, no DSM was available; therefore, the DEM was employed. To generate a proxy DSM, building heights were added to the DEM.
    - The DEM was obtained from the TINITALY portal (Istituto Nazionale di Geofisica e Vulcanologia, 2023), curated by the National Institute of Geophysics and Volcanology (INGV), which provides open access to the dataset divided into multiple sections to facilitate downloading. After acquiring all the tiles covering the entire region, it was necessary to merge them into a single continuous dataset.
- To identify the areas most exposed to extreme climatic events, two main data sources were used: historical climate records provided by ARPAE (Regional Agency for Environmental Protection of Emilia-Romagna - Agenzia Regionale per la Protezione Ambientale Emilia-Romagna) and the DEM. The prediction over the entire study area was carried out under the assumption that climate variability was primarily influenced by local phenomena. ARPAE provides the historical series of all meteorological stations across the region in JSON format, covering the period from the activation of each station. The dataset is considerably large, and since the information is delivered in real-time format without prior processing, substantial data handling is required to extract usable values. For this reason, the entire historical record was not employed; instead, a ten-year period from 2011 to 2021 was selected.
- For the calculation of impact probability, the primary information required was population density. In the Italian context, and specifically for Emilia-Romagna, this can be derived from census section geometries, and the corresponding population counts provided by (ISTAT, 2011). Since these datasets are made available separately, they must first be joined and subsequently processed to compute population density values.
- Protected environmental areas are provided as official datasets through the regional geoportal.
- The areas regulated by the regional landscape plan are made available through the regional geoportal.

3.1.3. Suitability layers

In an MCA, the composite cost (or suitability) surface is derived by comparing and combining multiple heterogeneous factors. To ensure commensurability, each factor is first normalized onto a common scale so that its values become directly comparable despite differing units and ranges. In this thesis, factors are rescaled to [0,1], where 0 denotes higher suitability (lower cost) and 1 denotes unsuitable (higher cost) since in the next step it will be necessary to use the LCP the cost derives from 1.

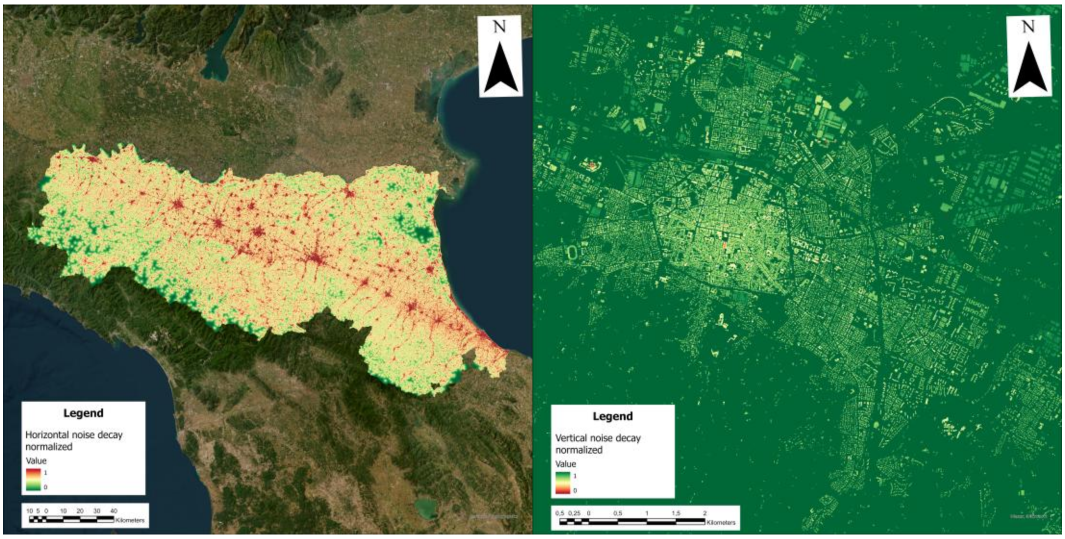


Figure 20. Horizontal (left) and vertical (right) noise decay normalized

When a factor behaves as a cost (e.g., slope steepness), a monotonically decreasing transformation is used; when it behaves as a benefit (e.g., accessibility), increasing transformation is applied. This orientation step prevents any factor from exerting undue influence merely because of its measurement units or dynamic range.

ArcGIS Pro has a tool to calculate a suitability map with a factor orientation and normalization (linear, piecewise, and fuzzy-like transforms), weighting and map algebra for aggregation, and constraint masks and diagnostic plots.

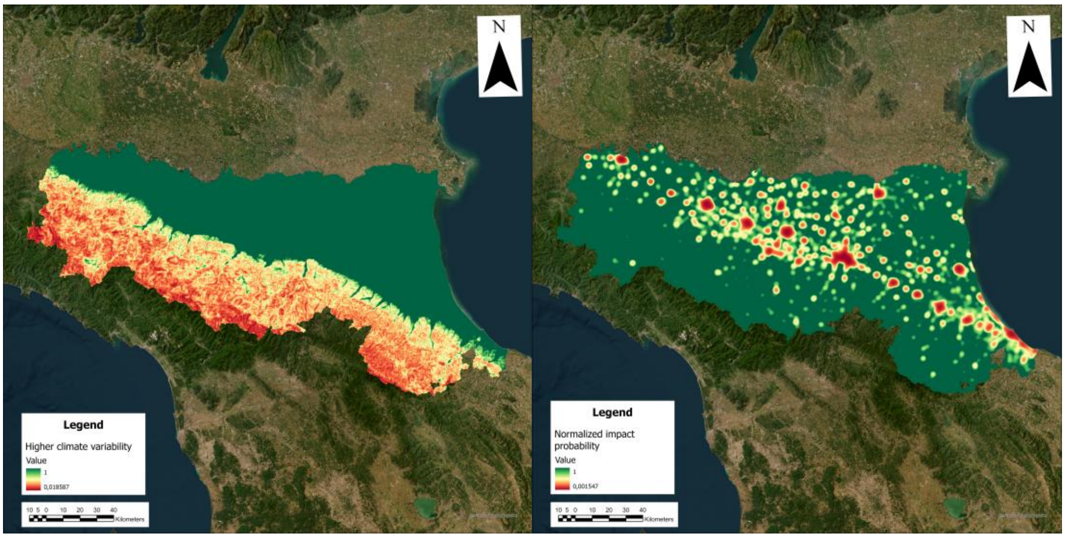


Figure 21. Higher climate variability and normalized impact probability

In the composite maps, the red-yellow-green ramp encodes decreasing risk/increasing suitability: areas in red denote the highest risk (lowest suitability), transitioning through yellow to green for the most suitable locations. Not all layers were incorporated into the MCA as weighted criteria; in several cases they acted as hard constraints - fully excluding areas from consideration (see Figure 22). Where layers entered the MCA as soft criteria, the resulting spatial patterns align with domain expectations: the impact probability surface (Figure 21, right) highlights red clusters where population density is greatest; the indicator of extreme climatic phenomena (Figure 21, left) peaks along the main mountain ridgelines; and noise-sensitive areas (Figure 20) naturally coincide with inhabited zones.

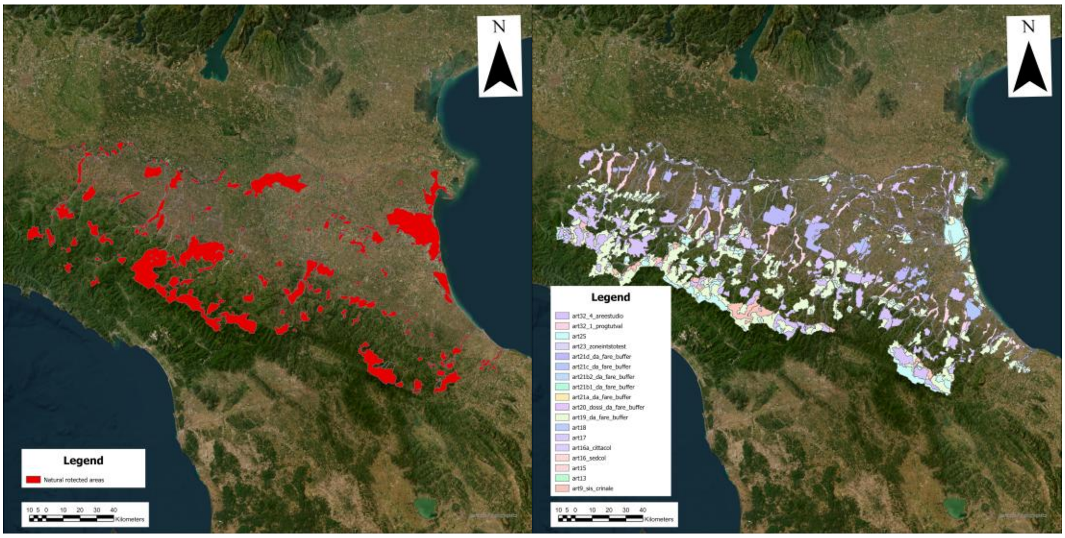


Figure 22. Natural protected areas and areas with landscape restrictions

For the vertical component of noise, a zoomed view is provided to visually illustrate the outcome. The model outputs two practical quantities: (i) the minimum stand-off distance required to remain within statutory limits, and (ii) the footprint of airspace currently permitted for UAS operations in the Open category. Both quantities can be recalibrated as regulatory thresholds or scenario assumptions are updated.

3.1.4. Vertiport selection criteria

For the Emilia-Romagna case study, we focused on what we defined as a logistic extra-urban scenario, while in the subsequent section we examine an urban logistic application. The rationale is that commercial and industrial centers - particularly those located in large-scale areas - require continuous flows of goods, whether for delivering products, exchanging materials, or sourcing inputs for production.

To operate this scenario, industrial complexes were identified from the regional land use dataset available through the regional geoportal. These were subsequently filtered to retain only industrial buildings with sufficient surface area on the roof to accommodate logistics activities, including drone storage and continuous cargo exchange. The spatial requirements were defined by assuming a facility capable of hosting approximately ten landing and take-off pads, together with an equivalent number of parking areas, in addition to maneuvering spaces for both drones and ground vehicles, as well as pedestrian circulation.

The resulting sites were further evaluated using MCA, to exclude unsuitable locations and retain only those meeting the defined thresholds of suitability. From these, representative cluster areas were delineated, with the possibility of user-defined aggregation. In this case, at least one cluster was considered per municipality whenever an eligible area was identified, although it should be noted that some municipalities did not contain any suitable vertiport sites.

Finally, Delaunay triangulation was applied to the filtered nodes, enabling the construction of a network that connects the identified locations and provides the basis for subsequent connectivity analysis (Diagram 13).

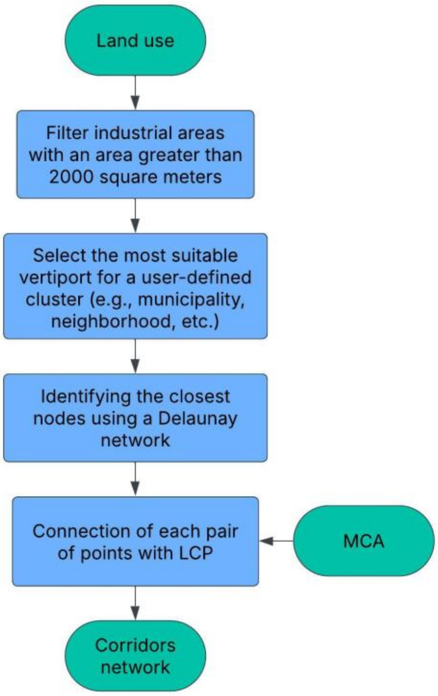


Diagram 13. Workflow for vertiport selection in extra-urban

3.2. CASE STUDY: URBAN UAS CARGO (LAST MILE DELIVERY)

This section adapts the general methodology to a dense urban environment, where operational constraints, social acceptability, and multimodal accessibility play a larger role than in the extra-urban logistics scenario. Building on the same MCA framework used in Emilia-Romagna, the Valencia case emphasizes last-mile logistics (with an exploratory note on passenger services) and aligns the spatial scope with the Metropolitan Mobility Plan of Valencia so that candidate sites can be assessed against existing interchange hubs and priority corridors identified by local planning instruments.

Methodologically, urban application requires a finer representation of the built form (DSM/building heights), stricter noise and visual-impact checks, and tighter airspace and obstacle constraints, while maintaining comparability of the core layers (antennas coverage/CRLB, grid connection, meteo/climatology, ground-risk iGRC, protected areas, and socio-economic proxies such as real-estate values and spending capacity). These layers are standardized and combined to produce suitability maps that guide the definition of selection criteria tailored to urban vertiports and corridors and, in an exploratory subsection, to potential passenger operations. The section is organized as follows: (3.2.1) defines the metropolitan study area consistently with the mobility plan; (3.2.2) details data sources and standardization choices; (3.2.3) presents the urban suitability layers; (3.2.4) specifies vertiport selection criteria in the city context; (3.2.5) outlines an exploratory passenger-transport scenario.

3.2.1. Definition of the study area

The definition of the study area within the metropolitan region of Valencia was primarily influenced by the start of an exchange period with the Universitat Politècnica de València. Given this context, it was more appropriate to develop a case study that was geographically closer to my academic supervisor there during the exchange period.

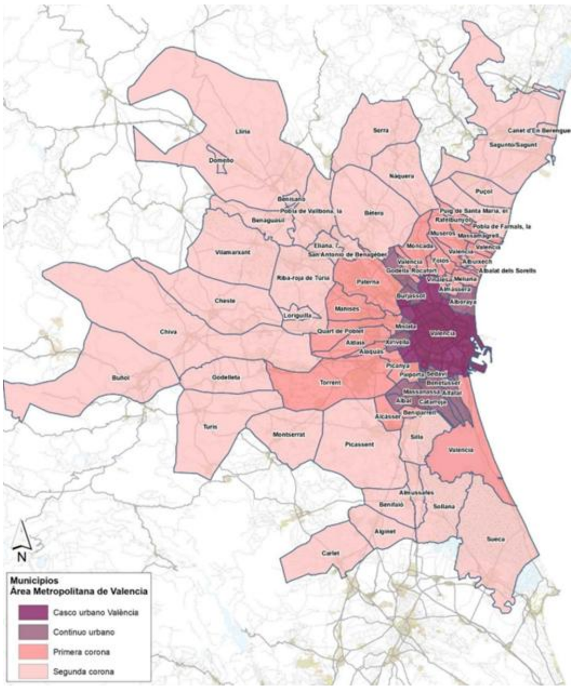


Figure 23. Municipalities within the Metropolitan Area of Valencia Mobility Plan (2018)

The delineation of the boundaries was subsequently guided by the objective of proposing a methodology consistent with the existing urban and regulatory planning frameworks. Within the transport sector, several plans have been developed that include analysis aimed at identifying key transport routes and major nodes of interchange between different modes of mobility. For this reason, the Metropolitan Mobility Plan of Valencia was selected as the main reference for the spatial scope of the analysis (Figure 23).

3.2.2. Data source

The initial idea was to develop a type of analysis that could be standardized and thus applicable across different contexts. However, when transitioning to a new study area, it became evident that data availability poses a significant limitation to such standardization. Therefore, if the goal is to implement a comparable methodology across all EASA member states, it will be essential to ensure that countries make the necessary data accessible to achieve consistent and comparable outcomes throughout the region.

Data collection represented a crucial component of the work, alongside the identification of relevant literature to inform the development of a methodology capable of generating a suitable level of information. This information should be able to represent the full spectrum of suitability - from maximum suitability to complete unsuitability - with respect to the factors identified as most relevant for the integration of vertical ports and corridors.

The main data sources used for the development of each layer are as follows:

- **Electrical network connection**: The data were obtained from OpenStreetMap, which allows access to geographical information through customized queries. A dedicated script was developed to download high-voltage power line networks available in the OSM database.
- **Coverage and positioning**: The processing of this layer was among the most complex, particularly due to the difficulty in acquiring detailed information on the location and technical characteristics of telecommunications antennas. These data are made publicly available by the spanish *Ministerio para la Transformación Digital y de la Función Pública*, and several third-party platforms extract and publish them online (2024b). A tailored web scraping script was implemented to extract the relevant data specifically for the area under investigation.
  In addition, further data - including the Digital Surface Model (DSM), the DEM, and the building footprints with height attributes - were obtained from the geoportal of the Valencian Community (2024a). In cases where the elevation above ground level for certain buildings was not available, an average height value based on surrounding buildings was assigned.
- **Energy consumption**: In this case, the DEM previously acquired was reused, as it was the only dataset required for this layer.
- **Flight rules from AIP**: the Spanish AIP, managed by ENAIRE, makes its data available not only through an online portal but also via WFS queries to its geographic database (ENAIRE, 2025). A dedicated script was developed to identify the layers available for download and to retrieve them accordingly.

- **Ground risk**: The evaluation of ground risk was conducted in alignment with the Specific Operations Risk Assessment (SORA) methodology, focusing on two primary data components: population density and land cover characteristics.
    - Population Density: Data pertaining to population distribution were sourced from the Instituto Nacional de Estadística (INE), which provides detailed census information, including the number of inhabitants per census section. This granularity facilitated an accurate assessment of population exposure within the operational area.
    - Mitigation Layer via Land Cover Classification: To account for environmental features that could mitigate the impact of a drone in the event of a ground incident, a land cover classification was implemented. Recognizing that existing land use datasets lacked sufficient detail - particularly in identifying features like tree canopies - Sentinel-2 satellite imagery was utilized. Monthly images were acquired from the Copernicus Open Access Hub, and a Random Forest classifier was trained to categorize land cover types. Training samples were derived from true-color composites, enabling the differentiation of various surface features, including vegetation and built structures.

  This classification informed the development of a mitigation layer, wherein areas with features such as dense vegetation or robust building structures were considered to offer a degree of protection, potentially reducing the severity of ground impact. For instance, tree-covered regions might attenuate the force of a descending drone, while rooftops could absorb impact energy, depending on their construction and the drone’s specifications.
- **Migration routes**: Geospatial data were obtained from two primary sources. Mountain passes were identified using OSM data, extracted through the Overpass API, which allowed for precise querying and retrieval of relevant geographical features. These natural corridors are critical for avian migration across mountainous regions. Additionally, Important Bird and Biodiversity Areas (IBAs) were sourced from the Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO) of Spain (SEO/BirdLife, 2020). These areas are designated as critical habitats for the conservation of bird populations and biodiversity. By integrating the spatial data of mountain passes and IBAs, the study aimed to model potential migratory pathways, identifying key transit points and habitats essential for avian species during their migratory cycles.
- **Land uses**: Available on the Geoportal of the Valencian Region; used to identify the areas most suitable for vertiport placement.
- **Meteorology and climate**: Data were obtained from the Spanish State Meteorological Agency (Agencia Estatal de Meteorología, AEMET), which provides access to historical meteorological data through a queryable API. This API allows for the retrieval of daily statistical data per station, including maximum and minimum values for various meteorological phenomena. However, it does not provide hourly data. Additionally, the previously mentioned DEM was utilized in the analysis.
- **Natural and protected areas**: These are provided by the national AIP website Enaire drones.

- **Noise**: For this layer the DEM and the DSM previously mentioned. Additionally, land use data were obtained from the geoportal of the Valencian Community. These datasets were instrumental in delineating noise buffer zones in accordance with land use regulations. The land use information facilitated the classification of areas based on their predominant functions - such as residential, industrial, or recreational - which is essential for determining permissible noise levels and implementing appropriate mitigation strategies. By integrating topographical data with land use classifications, the study aimed to accurately model noise propagation and assess its impact across different zones within the region.
- **Obstacle presences**: Evaluated during the vertiport site-selection phase by testing compliance with OLS. Using the previously computed DSM, we detect potential conflicts (e.g., buildings, masts, terrain ridges).
- **Real Estate Value Distribution**: conducted by extracting property transaction information from Idealista, one of the most prominent real estate platforms in Spain. A custom script was developed to specify the geographic area of interest and systematically retrieve relevant property listings. The extracted data were then processed and saved in a GIS-compatible format, facilitating spatial analysis and integration with other geospatial datasets.
- **Spending Capacity Distribution**: Conducted using the same census section geometries previously mentioned. The INE provides economic information for each of these sections, including indicators such as average and median income levels. This data enabled a detailed spatial analysis of the population's economic capacity across different areas.

3.2.3. Suitability layers

Compared with the extra-urban case, the set of factors considered is substantially larger and more comprehensive, and several variables exhibit greater complexity. The key methodological challenge is to handle these heterogeneous inputs jointly and make them comparable. Consistently with the map legend, green values approaching 1 denote the most suitable areas, whereas red values approaching 0 indicate unsuitable zones, in line with the convention adopted for the other layers. The suitability tool available in ArcGIS Pro typically normalizes factors by assigning the highest values to the most suitable areas, thereby giving greater weight to locations that contribute positively to the overall outcome.

The result was then inverted with 1 being the least suitable and 0 being the most suitable and then inserted into the LCP.

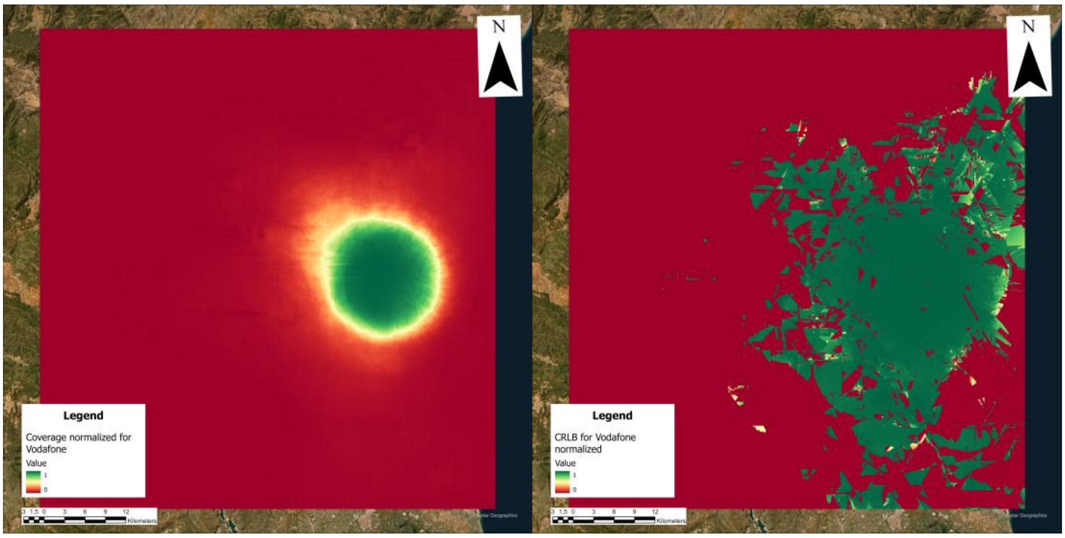


Figure 24. Coverage (left) and CRLB for Vodafone (right) normalized

Following normalization, Figure 24 shows that coverage is adequate predominantly within built-up areas, whereas rural and peripheral zones remain under-served. This pattern reflects the legacy prevalence of 2G/3G sites - which favor long-range coverage and are typically not densified where populations are sparse - while our analysis purposefully considered only 4G and 5G infrastructure. Under these assumptions, acceptable positioning was defined as a planimetric error ≤ 25 m: this threshold is widely met across large portions of the urban fabric, but less so outside it. In dense urban contexts, positioning reliability is thus markedly higher, whereas in peripheral areas larger errors may remain operationally acceptable depending on the use case.

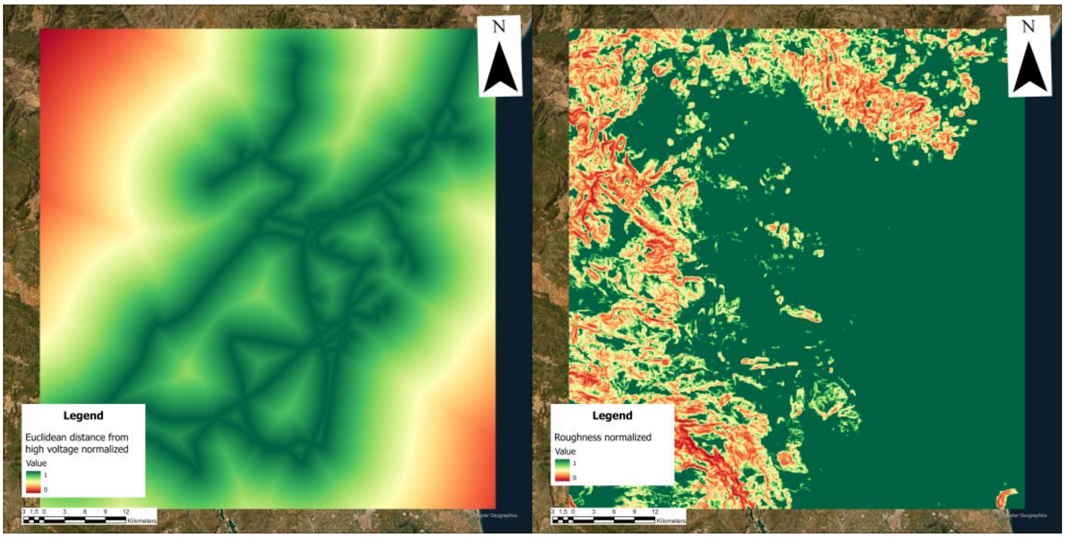


Figure 25. Euclidean distance from high voltage (left) and roughness (right) normalized

Figure 25 reports two straightforward indicators: (left) distance to linear corridors (e.g., major transport or utility lines) and (right) terrain rugosity. The distance layer is normalized through a monotonic, proportional mapping of the geometric distance, such that suitability decreases with increasing distance from the lines (areas farther from corridors are treated as less suitable). Rugosity expresses the repeated variation in elevation over a given baseline distance (i.e., local relief variability within a moving window) and is normalized so that smoother terrain yields higher suitability, whereas highly variable relief yields lower suitability.

Spatially, the main urban core is predominantly flat, while the peri-urban belt exhibits greater elevation contrasts. This pattern points to a key operational challenge: entering and exiting the city along interurban links toward inland settlements is likely to incur higher energy expenditure due to more frequent climbs/descents and obstacle avoidance over rugged terrain. By contrast, for coastal cities, seaward routing may offer an alternative with gentler relief interactions and potentially lower energy costs.

In the case of AIP, the initial approach was to treat its permanent restrictions as hard constraints applied at the end of the MCA, thereby excluding non-permissible areas. We then tested an alternative in which AIP is integrated directly into the MCA by representing permitted flight-altitude limits as a graded penalty (Figure 26, left): lower permissible heights reduce suitability, whereas fully permitted volumes retain higher scores.

As the literature and regulatory direction increasingly point toward U-space integration within conventional airspace, the modelling choice requires nuance. Some AIP elements are legally non-negotiable (e.g., permanent prohibited or restricted areas) and should remain hard excluded. Others are procedural or time-dependent and may be operationally manageable in a U-space environment (e.g., via strategic deconfliction) and are therefore better represented as soft penalties rather than absolute masks.

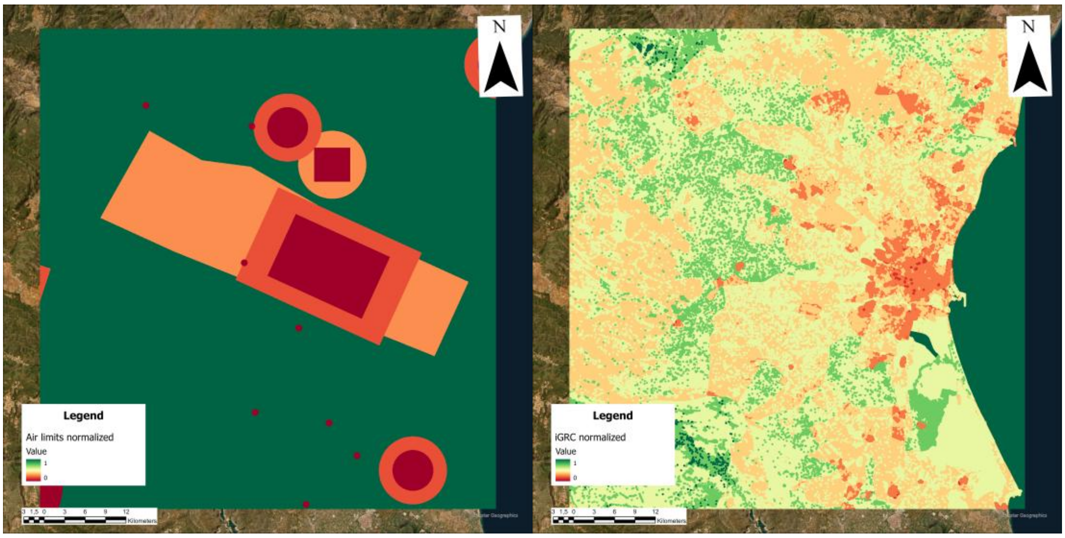


Figure 26. Air limits (left) and iGRC (right) normalized

To make these assumptions transparent, we report results under three configurations: (i) a baseline in which AIP is enforced as hard masks; (ii) a transitional setting where AIP-derived altitude ceilings enter the MCA as a normalized cost; and (iii) an integrated U-space setting in which only immutable AIP elements remain masked while the rest are modelled as graded penalties. This separation preserves legal compliance, supports reproducibility, and enables sensitivity analysis on how siting decisions evolve under progressive U-space adoption. In the interurban logistics case, the impact hazard was approximated using only a subset of SORA inputs rather than the full categorical framework. By contrast, in the urban passenger case we explicitly computed the SORA Ground Risk Class (GRC, 1-7) and used it as a criterion, normalized so that higher classes correspond to lower suitability (Figure 26, right). Importantly, this normalization cannot be treated as a hard exclusion, because operations at GRC 7 may still be authorized within the Specific category when adequate mitigations are in place. The methodological shift reflects the different objectives: whereas the interurban case sought to avoid the urban fabric as far as possible, the urban case aims to minimize risk while preserving feasibility within the city.

Compared with the interurban logistics case, climatic phenomena were incorporated into the MCA as separate factors, with each dataset individually normalized (Figures 27 and 28). In the resulting maps, green areas with values approaching 1 indicate the most suitable zones, whereas red areas with values approaching 0 denote unsuitable ones, consistently with the convention applied across all other layers.

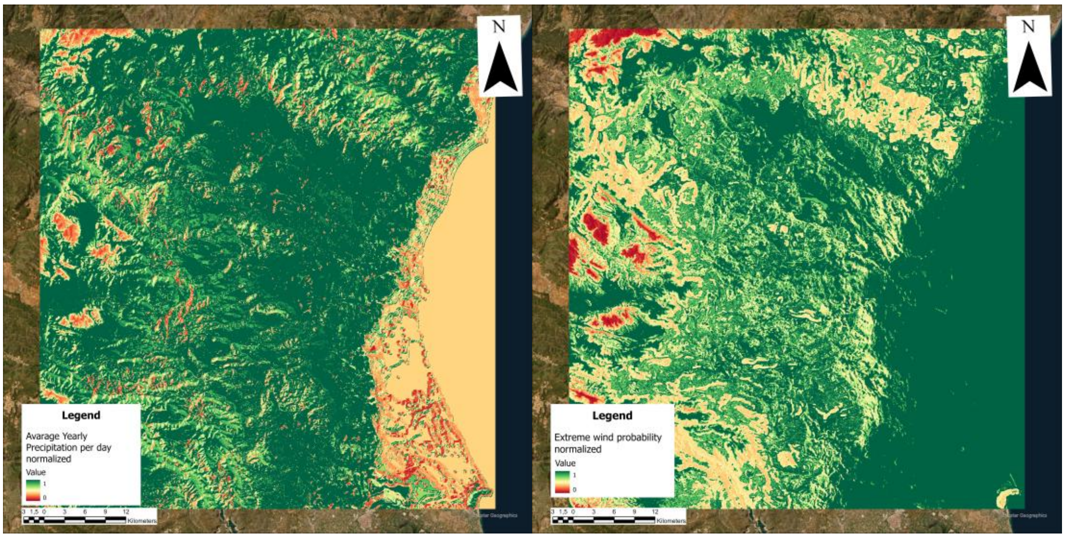


Figure 27. Average yearly precipitation per day (left) and extreme wind probability (right) normalized

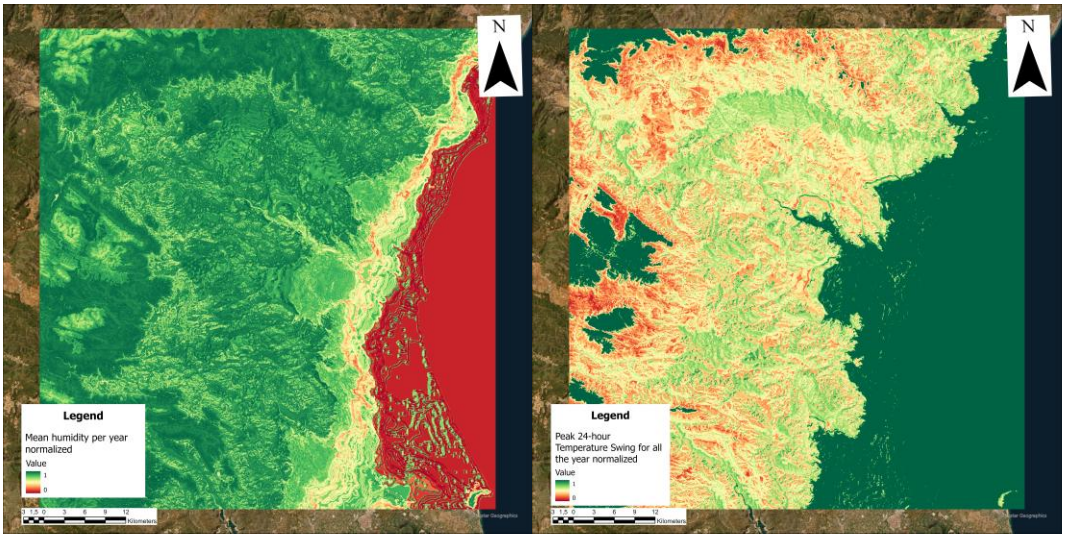


Figure 28. Mean humidity per year (left) and Peak-24-hour temperature swing on the year (right) normalized

The least suitable areas are located immediately along the coastline (Figure 44, left), which is critical considering that a substantial portion of the city lies precisely in this area. Additional unsuitable conditions also appear in higher-elevation areas, where more severe meteorological phenomena are likely to occur. As expected, the strongest winds are concentrated along exposed edges and ridgelines (Figure 44, left). At the same time, humidity levels are markedly above average along the coast, with additional peaks observable within the valleys (Figure 45, left). This factor is particularly relevant for operational planning, as high humidity combined with a saline environment is likely to increase maintenance requirements for serving the city. Conversely, temperature stability is greater in proximity to the coast, resulting in lower fluctuations and thus less impact on battery health (Figure 45, right).

These patterns highlight a methodological challenge: while some meteorological variables increase suitability, others decrease it, making the synthesis of multiple climatic indicators within the MCA more complex and less straightforward than for other factors.

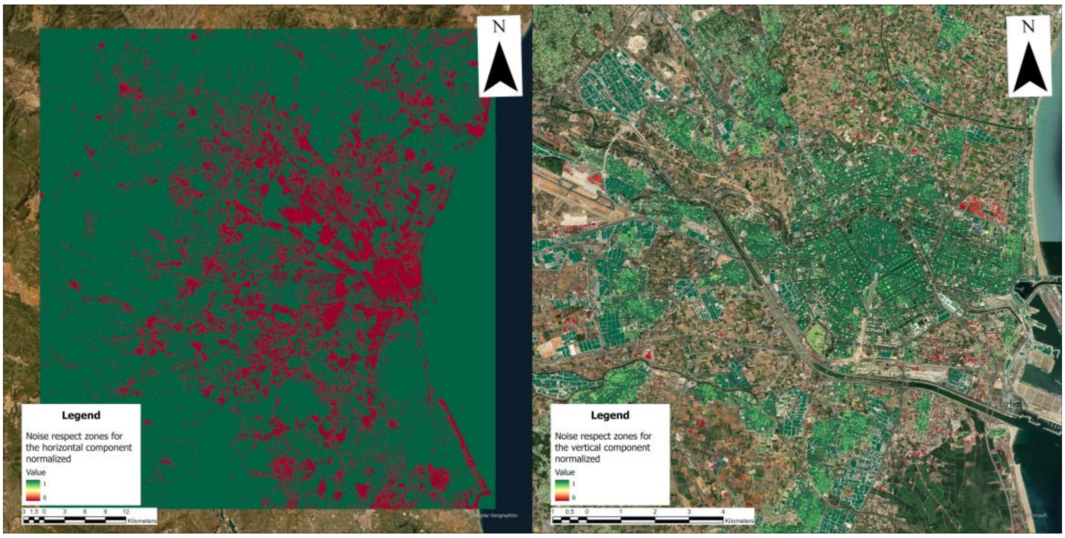


Figure 29. Noise respect zones for the horizontal (left) and for the vertical component (right) normalized

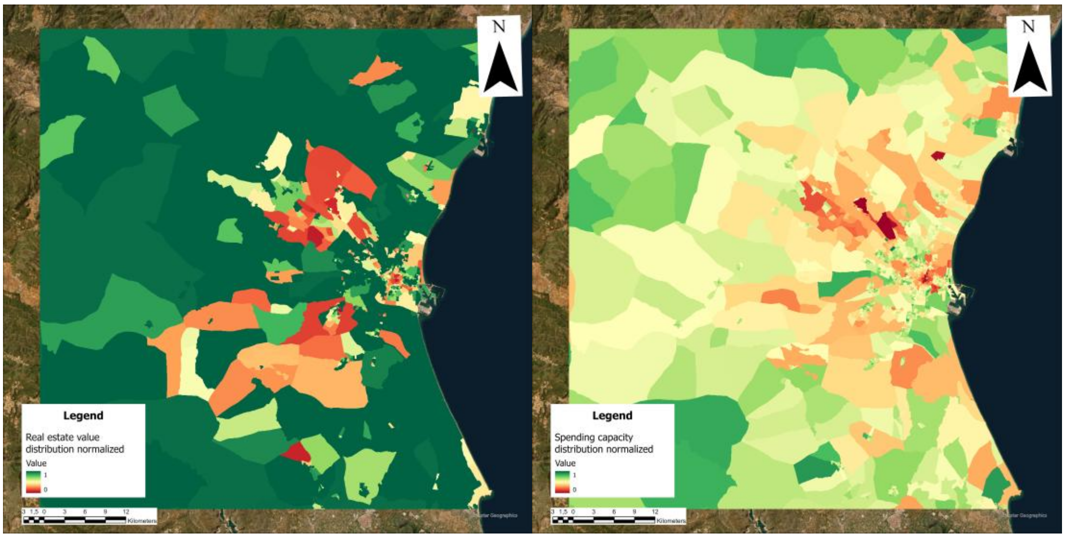


Figure 30. Real estate value distribution (left) and spending capacity index normalized (right)

From a graphical perspective, it is difficult to visualize a clear transition from red to green for the horizontal noise component when maintaining the same scale as for the other factors. From a regulatory standpoint, however, the entire band colored differently from green would be considered unsuitable. Nonetheless, we maintained the normalized scale to allow for the possibility of mitigation measures, which could vary depending on proximity and the level of noise generated (Figure 29, left). To make the distinction within the normalized buffer zone more visible, a zoomed view of the vertical component is provided (Figure 29, right).

The normalized real estate value distribution and spending capacity index simply reflects the spatial distribution of their respective values across the territory, aggregated at the census section level (Figure 30).

3.2.4. Vertiport selection criteria

Unlike the long-distance logistics case study, the urban scenario was conceived as an “last-mile” delivery model, with drone operations terminating at locations like current parcel lockers (e.g., Amazon Prime). Accordingly, candidate sites had to be publicly accessible and provide unobstructed conditions for take-off and landing (Diagram 14).

The first step consisted of identifying a suitable land-use dataset, which was obtained from the Valencia regional geoportal. The original categories were numerous and were reclassified into six macro-groups: natural areas, infrastructure, urban green, built-up areas, cultural heritage, and religious sites.

Subsequently, an algorithm was implemented to ensure that potential sites met the minimum dimensional requirements for a vertiport with three pads, each with at least 500 m^2 of surface. Identified locations were further filtered by verifying compliance with the OLS. In addition, a clustering procedure was applied using a user-defined buffer - in this case, 1,500 m - to assess whether multiple vertiports overlapped in the same catchment area. When this occurred, only the site with the highest suitability score according to the MCA was retained.

Finally, as in the interurban logistics case, the selected nodes were connected through a Delaunay triangulation, resulting in a network suitable for subsequent connectivity analysis.

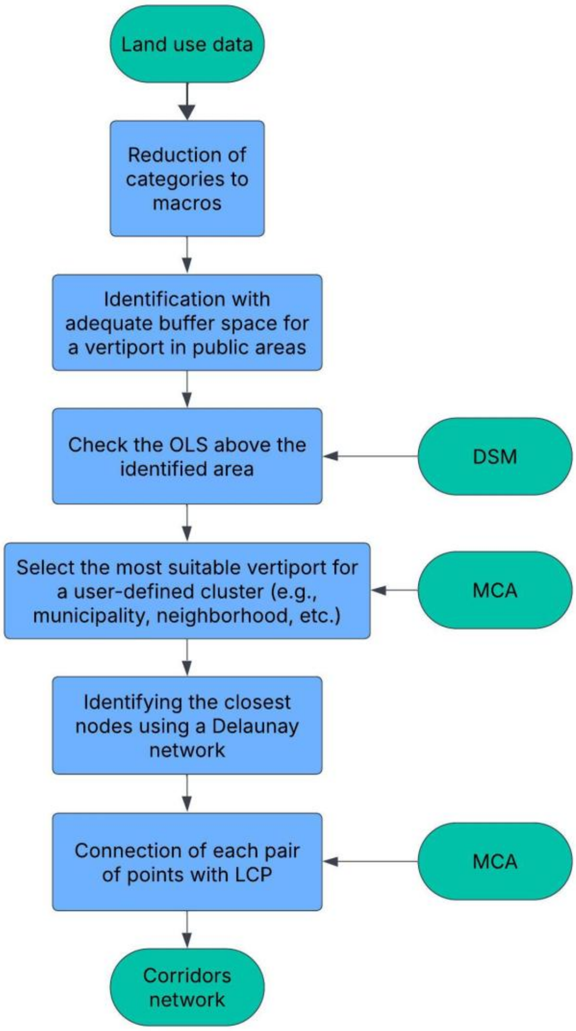


Diagram 14. Workflow for vertiport selection in urban

3.3. CASE STUDY: EXPLORATORY URBAN PASSENGER TRANSPORT

This subsection summarizes the exploratory application developed for urban passenger transport simulated with Volocity (Figure 31) with a methodology like the two logistics use cases discussed earlier. Unlike the interurban cargo scenario - where the methodological objective was to keep operations away from dense urban fabric as far as possible - the urban passenger case adopts a different stance: it seeks to minimize risk while preserving feasibility within the city. The case is intentionally more conceptual and is presented to clarify methodological implications for future implementation rather than to claim readiness for deployment. The approach builds on the methodology introduced in our earlier conference paper (Cunietti et al., 2023) - where MCA-based suitability mapping was framed as a preparatory pre-phase with respect to the strategic, pre-tactical, and tactical planning tiers - and adapts it to the specific constraints of passenger operations in dense urban contexts. Elements of this work have also been presented in a conference contribution (Cunietti et al., 2025).

Figure 31. Volocity, source (Volocopter, 2024)

The results emphasize a central challenge that also emerged in the logistics case studies: a single MCA map cannot exhaustively resolve siting decisions. In practice, locating drone infrastructures is the outcome of a multi-step process in which some layers function as hard constraints (legal prohibitions or non-negotiable safety rules that fully exclude areas), while others act as soft criteria whose influence may increase or decrease at different stages. Moreover, certain factors may be applied after an initial MCA synthesis - such as obstacle screening used as a post-filter for the final vertiport selection or revised operational assumptions - or revisited as stakeholder deliberation advances. This iterative logic accords with the role we assign to the suitability surface: a decision-support artefact to be interpreted alongside planning knowledge and expert judgement, rather than a deterministic output.

A further distinction from the inter-urban cargo scenario concerns the treatment of ground risk. In the cargo case, we employed an approximate SORA-based proxy to represent impact hazard at broad scale - permitted by the vehicle characteristics and mission profile - focusing on the ground-risk component with only a simplified check on air risk. By contrast, the present application must operate within the Specific/Certified categories, where robust mitigations are required and SORA is not totally modelled for this. This stance preserves feasibility for corridors and vertiport candidates in densely built areas, while recognizing that many locations will remain non-viable under current assumptions. From a regulatory and technological standpoint, this case remains theoretical. Under today’s legislation and technological maturity, urban passenger vertiports and corridors face stringent hurdles. Chief among them is:

i. the high residual ground risk in dense urban fabric in the event of a catastrophic failure, and
ii. the lack of fully compliant technologies across the safety stack that would be required for certification in the near term (e.g., demonstrated levels of reliability/redundancy, contingency management, and comprehensive CNS provision at VLL).

iii. The conference paper shows that the case is thus framed as a methodological exploration to structure the factors, expose conflicts among criteria (e.g., noise, risk, accessibility), and illustrate how MCA can be embedded as a preparatory layer ahead of airspace planning phases for passenger transport.

In summary, the exploratory urban passenger case contributes three insights that complement the logistics studies.

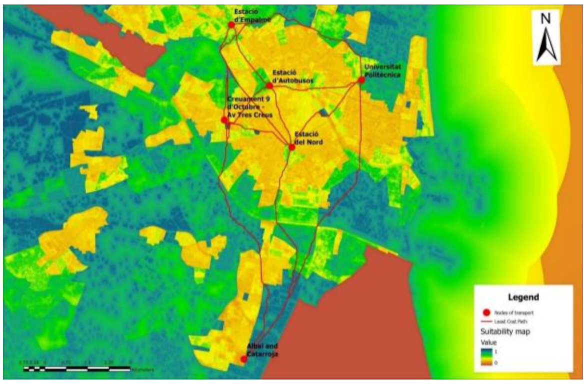


Figure 32. MCA calculation for a passenger transport drone, source (Cunietti et al., 2025)

First, MCA should be read as a staged, auditable synthesis, not as a final verdict; hard constraints and post-MCA refinements remain essential. Second, risk-related criteria dominate in inner-city contexts and must be modelled with soft-penalty mappings that preserve feasibility for subsequent, mitigation-aware design. Third, given the current regulatory/technological gap, this case is best interpreted as a conceptual reference to guide dialogue among authorities, planners, and industry while standards evolve toward U-space integration and certified operations. These conclusions are coherent with the thesis' overarching aim to provide a replicable geospatial methodology for vertiport and corridor siting that stakeholders can adapt and iterate as regulations and technologies mature.

Compared with logistics applications, accessibility - and the ease of interchange with other transport modes - is even more critical. Given that these services will initially command high rates, their introduction must be carefully targeted to maximize uptake and ensure commercial viability (Figure 32).

3.4. CASE STUDY: THEORETICAL CORRIDOR SITING FOR REMOTE-AREA CONNECTIVITY

This subsection synthesizes the conceptual reasoning presented in our study on integrating UAV infrastructures within urban and rural landscapes. It was also featured in a paper presented at the conference of the European urban planners' association, which discussed - at a conceptual level - the potential benefits of drones for remote territories (Cunietti, Sammarco, et al., 2024). Specifically, we argued that, without extensive new infrastructure, comparatively low-cost deployments could rapidly connect areas that would otherwise remain isolated.

The work is framed explicitly as a theoretical contribution: no empirical trials or operational tests were performed. Its purpose is to articulate a geospatial decision-support approach for siting vertiports and air corridors that can improve connectivity with remote areas while supporting sustainability and social inclusion. Emilia-Romagna was adopted as a reference context primarily for data availability (notably meteorological), and to anchor the discussion within Italy's multi-level planning system.

Methodologically, the paper advances a three-step spatial workflow - consistent with the previous cases - designed to identify two areas to be linked while minimizing adverse effects on local livability and the environment. Because the remote areas often could fall within protected natural landscapes and other sensitive zones, additional safeguards are considered.

The conceptual reasoning suggests two policy-relevant insights. First, integrating remote areas requires co-planning across aviation and territorial instruments (transport plans, energy networks, protected-area governance), with corridors and sites screened for both environmental compatibility and aeronautical safety. Second, even under optimistic assumptions (e.g., electric eVTOLs with zero local CO_2), siting decisions remain risk-dominated as happens in dense fabrics and coverage-dominated in sparsely populated ones - implying different priority criteria for urban versus extra-urban deployments. These insights align with - and complement - the logistics case studies presented in this thesis: while those cases operationalize the workflow on specific datasets, the present subsection preserves a purely conceptual stance to map the design space and highlight where empirical validation would be required in future work.

4. RESULTS AND DISCUSSION

This chapter reports the outputs of the GIS-MCA workflow introduced in Chapter 2 and applied to the case studies in Chapter 3, translating the composite suitability surfaces into concrete shortlists of candidate areas for vertiports and indicative corridors. For each use case, we summarize map evidence and key metrics (e.g., extent and distribution of eligible zones, population and activity served, CNS coverage quality, proximity to multimodal nodes), and we discuss post-aggregation checks that inform inclusion/exclusion - such as OLS/obstacle screening, AIP-based flight rules, protected-area constraints, and noise/visual acceptability in dense fabrics. Where relevant, we note sensitivity to alternative thresholds and operational assumptions, clarifying how the results should be read as decision-support rather than deterministic prescriptions. The chapter is organized as follows: 4.1 presents results for intercity cargo; 4.2 details results for urban cargo (last-mile delivery); 4.3 synthesis implications for public transport (inclusivity, quality-of-life, and economic/environmental/social impacts); 4.4 outlines research limitations; 4.5 sketches future research directions and potential implementation pathways.

4.1. SUITABLE AREAS FOR INTERCITY CARGO

Our initial reasoning - across both urban and non-urban settings - is that vertiports are likely to face substantially stricter ground-side constraints than aerial corridors, chiefly because landscape/heritage plans limit the insertion of visually intrusive elements. Corridors, while not exempt from such concerns, are more sensitive to operating altitude, which can attenuate visual and nuisance impacts. In addition, certain layers warrant differentiated treatment for vertiports versus corridors. Noise is illustrative: its horizontal component (lateral stand-off) carries greater weight at vertiports, particularly during eVTOL take-off and landing. If an adequate horizontal offset from buildings is maintained - so that the applicable land-use noise limits are respected - vertical separation is less binding at the pad. By contrast, for corridors the vertical component is decisive: maintaining sufficient altitude above rooftops is the primary lever to keep received noise within legal thresholds.

In our case, environmentally protected areas were, by default, treated as prohibited airspace, under the working assumption of Open-category operations (≤120 m AGL). However, certain parks stipulate altitude thresholds or permit regimes that may allow overflight above specified heights. A method is therefore needed to encode these regulatory parameters and vehicle capabilities so that, where legally and technically admissible, such areas can be rendered traversable. This need is particularly acute in Emilia-Romagna, where long stretches of coastline fall within a natural park, effectively precluding coastal approaches or along-shore routes for many kilometers under the default assumption.

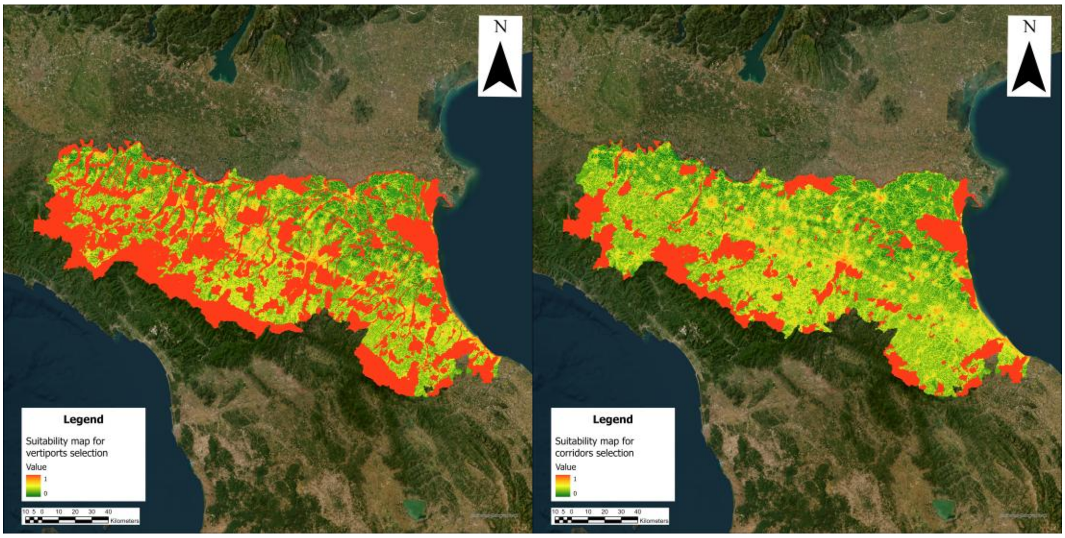


Figure 33. Suitability map for vertiport selection (left) and corridor selection (right) in extra-urban case

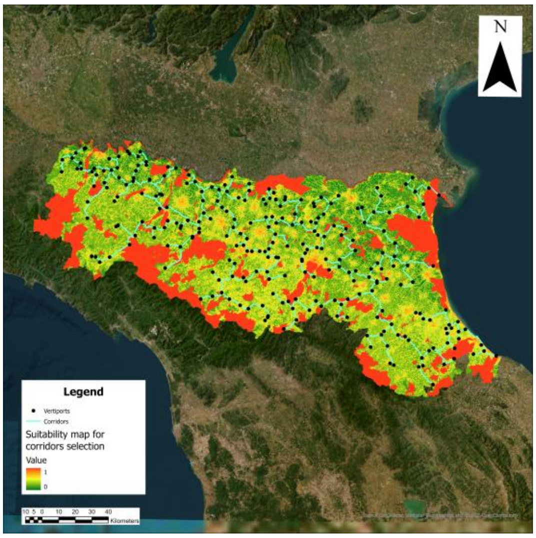


Figure 34. Corridors selection in extra-urban case

Figure 33 translates the MCA into two complementary eligibility surfaces - one tailored to vertiport siting and one to corridor continuity - and an illustrative overlay of shortlisted nodes and indicative links. A clear spatial gradient emerges: the Po Valley exhibits the highest concentration of favorable cells, while suitability decreases markedly along the Apennine ridge and across the coastal belt where protected areas dominate. This configuration reflects both morphology (flatter terrain, lower obstacle density) and planning constraints (fewer visual-intrusion limits and generally better access to electricity and road/rail nodes).

For vertiports, the "eligible" patches cluster around the Via Emilia axis (Piacenza-Parma-Reggio Emilia-Modena-Bologna-Imola-Faenza-Forlì-Cesena-Rimini) and in proximity to medium-large settlements and logistics platforms. By contrast, contiguous high-scores are rarer along the coast, where the natural park system acts as a first-order exclusion under the Open-category assumption. This supports a vertiport strategy centered on inland hubs and secondary sites near major interchanges, with coastal facilities considered only under differentiated regulatory/operational regimes (Section 2.1).

For corridors, the surface is more continuous across the plain and valley floors, indicating multiple low-cost alignments between urban/industrial clusters. Continuity weakens at mountain crossings and along the coastal strip. This is consistent with the earlier discussion: altitude can mitigate nuisance and visual exposure along corridors, but not all constraints are altitude-soluble (e.g., extensive protected areas, airspace rules, or long spans over sparsely served CNS).

From surface to candidates. Following Chapter 2, we generate a preliminary node set by intersecting the vertiport surface with settlement and logistics layers, then skeletonise inter-node connectivity with a Delaunay graph and refine arcs via least-cost paths over the corridor surface. The resulting picture (Figure 34) suggests a robust east-west trunk along the Via Emilia, several north-south feeders linking productive hinterlands to that trunk, and a comparatively weak coastal backbone under the default regulatory scenario. These patterns are coherent with freight demand geography: long-haul flows are likely to anchor on the plain, with selective cross-Apennine links only where natural passes and CNS availability align.

Post-aggregation checks. Shortlisted vertiports undergo obstacle screening (OLS compliance from DSM), verification against AIP-based restrictions and protected-area buffers, and noise acceptability for TOL phases (horizontal stand-off dominating). Candidate links are stress-tested for air-risk corridors, legal overflight above rooftops (vertical component of noise), and CNS coverage continuity (GNSS and 4G/5G proxies). Where infringements persist after mitigation (pad relocation, altitude adjustments, micro-rerouting), sites/segments are excluded.

i. Three levers meaningfully shift the picture: the corridor altitude policy (higher floors improve coastal and ridge continuity but may trade off with CNS quality),
ii. the treatment of protected areas (permit regimes or altitude-based dispensations can “unlock” coastal and delta segments), and
iii. vertiport stand-off thresholds for noise/visual impact (stricter values thin out urban-edge candidates but preserve acceptance). Read in combination with the mobility plan, the maps indicate that freight-first deployment is most credible along the Via Emilia system, with coastal connectivity contingent on regulatory accommodation.

4.2. SUITABLE AREAS FOR URBAN CARGO (LAST-MILE DELIVERY)

Figures 35 left shows the baseline suitability surface and right the same surface masked by environmental limitations. A clear gradient emerges higher scores concentrating across the coastal plain and peri-urban belt, while suitability fragments towards foothills and interior areas. Once environmental constraints are applied, large exclusion zones appear along coastal and peripheral natural areas, shrinking the contiguous high-score patches and narrowing feasible alignments.

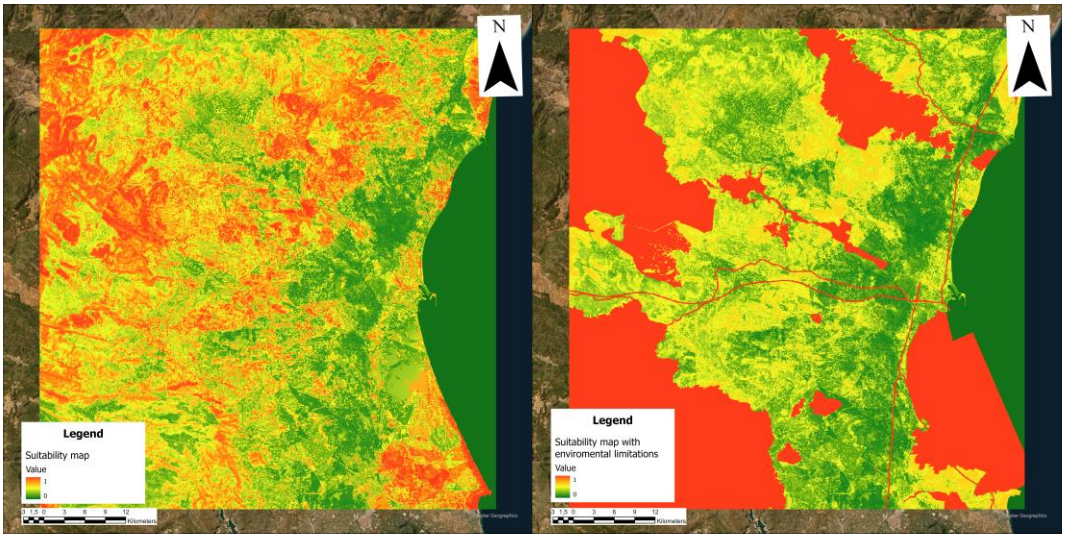


Figure 35. Suitability map without (left) and with environmental limitation (right) in urban case

Consistently with Chapter 2, the Valencia raster is produced in ETRF2000 / UTM32N (Universal Transverse Mercator Projection System, Zone 32N) from epoch 2008 and normalized with the same scheme used in the extra-urban case, but - unlike Emilia-Romagna - no a priori split was applied between vertiport-oriented and corridor-oriented layers, due to the absence of a landscape plan integrated at the same scale and level of detail as in Emilia-Romagna. The differentiation between vertiports and corridors is therefore applied downstream through post-selection checks (pad-level OLS and lateral stand-off for vertiports; altitude-dependent constraints, air-risk and CNS continuity for corridors).

Site acceptance will hinge on pad-level OLS compliance and horizontal noise stand-off during eVTOL TOL phases, especially in urban context. For corridors, the same surface indicates several potential east-west and radial linkages across the plain; however, continuity depends on maintaining adequate overflight altitudes above rooftops (vertical noise component), satisfying any local airspace rules, and preserving CNS quality (GNSS and 4G/5G) along the route. In environmentally constrained sectors, corridor feasibility may require altitude policies or micro-rerouting; where rules allow altitude-conditioned overflight, some masked segments could be partially “unlocked”.

Figure 36 depicts the **baseline eligibility surface**. The pattern aligns with the morphological and functional structure described in Chapter 3: higher values cluster across the coastal plain and the peri-urban belt where built form is more regular, obstacle density is moderate, and access to transport nodes and electricity is comparatively stronger.

Suitability becomes fragmented towards the foothills and interior sectors, where slope, relief and obstacle fields increase the cost of both pad integration and corridor continuity. The urban core displays a mosaic of medium-to-high scores interspersed with lower pockets, which is coherent with the interplay of DSM-derived constraints, noise/visual sensitivity of central fabrics, and the availability of interchange points highlighted by the metropolitan mobility framework. Figure 35 right applies environmental limitations as a mask to the same surface. Large exclusion zones appear over protected natural areas and coastal/peripheral belts, compressing contiguous high-score patches and, in places, severing otherwise promising alignments. This outcome is consistent with the Open-category working envelope (≤120 m AGL) retained from Chapter 2. As discussed there, these limitations do not necessarily preclude overflight under alternative regulatory settings; where altitude-conditioned permissions or specific authorizations exist, part of the masked swathes could be "reopened", subject to CNS quality and air-risk checks.

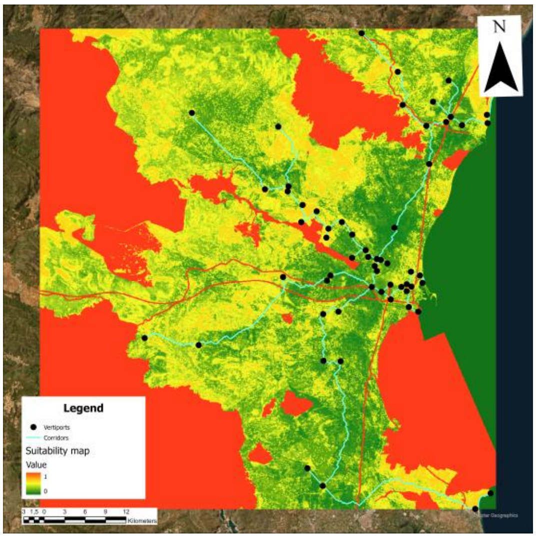


Figure 36. Corridors selection in urban case

Shortlisted cells are translated into candidate pads and links following the procedure introduced in Chapter 2:

i. vertiport candidates are screened for OLS penetrations using the DSM, environmental buffers, and pad-level noise acceptability,
ii. corridor candidates are stress-tested for altitude-dependent impacts, protected-area crossings, and CNS continuity. Results are reported with the same indicators used in Section 4.1 (share of area above threshold, number of vertiport candidates after checks, continuity of corridor segments, population/activity coverage, proportion of corridor kilometers with adequate CNS), to retain cross-case comparability.

Three levers materially shape the urban picture:

i. the altitude floor for corridors (higher floors can improve continuity over dense fabrics but may stress CNS or air-risk constraints),
ii. the treatment of environmental limitations (altitude-conditioned permissions can reopen portions of the coastal/peripheral mask), and
iii. pad-level stand-off thresholds (stricter values reduce candidates near sensitive uses but strengthen acceptance).

Operationally, we follow the pipeline established in Chapter 2. The raster in 53 right is intersected with settlement, land-use and interchange layers to generate a preliminary pad set. Each candidate is screened against OLS penetrations from the DSM, environmental buffers, and pad-level noise acceptability. Connectivity between survivors is first sketched with a Delaunay graph and then refined using LCP cover the same eligibility surface, applying altitude floors and local airspace rules where relevant. The emerging picture, which will be detailed in the subsequent subsections, anticipates a small number of peri-urban nodes of opportunity with robust access to the metropolitan transport network and a handful of east-west and radial links across the plain whose continuity hinges on altitude policy and CNS quality in constrained sectors.

To retain comparability with Section 4.1 results are reported using the same indicators: share of territory above the reporting thresholds for pads and links, number of vertiport candidates surviving post-aggregation checks, cumulative length of corridor segments satisfying continuity criteria, population and activity reachable within 10 km of shortlisted nodes, and the proportion of corridor kilometers with adequate CNS. Sensitivity tests then vary:

i. the altitude floor for corridors,
ii. the treatment of environmental limitations (default mask vs. altitude-conditioned overflight), and
iii. pad stand-off thresholds. Across these variants, the spatial ranking remains broadly stable, with re-ordering only in neighborhoods close to constraint frontiers - an expected behavior given the weight structure and normalization strategy defined in Chapter 2.

Finally, we reiterate the interpretive stance set out earlier in the thesis: the eligibility surface is a decision-support solution, not a deterministic prescription. It should be read in concert with planning knowledge and expert judgement, including local stakeholder input on social acceptability and site design.

4.3. DRONES AS NEW TRANSPORT SYSTEM

Here we read the results of Sections 4.1 - 4.2 through a public-transport lens and ask a simple question: where - and under what ways - can drones usefully complement, rather than replace, existing bus, tram and rail systems?

Consistent with the thesis' stance, the objective is public value - time savings and reliable access for underserved areas to obtain point-to-point services. Accordingly, we frame drone-PT integration around four threads that recur throughout the chapter:

i. inclusion, via periphery-first siting, universal-access design at nodes, and fare integration or PSO (Public Service Obligation)-like obligations on socially valuable links,
ii. quality of life, managed through altitude policies, quiet-hour rules, and privacy/heritage buffers tied to the same constraints used in the MCA,
iii. operational reliability, ensured by screening corridors for CNS/meteorology and publishing auditable service metrics; and
iv. economic realism, acknowledging current cost structures while identifying corridors where door-to-door performance can justify gradual, accountable pilots.

Strategies for inclusive UAM

In line with the evidence from Sections 4.1-4.2, an inclusive deployment should treat the suitability surface as a decision-support layer that is read through an equity lens rather than as a purely efficiency-driven ranking. To achieve this, the following points will be necessary:

- **Affordable access and fare integration** - To avoid premium-only service, corridor and node choices must be coupled with affordability instruments. Fares should be integrated with the regional ticketing system and capped against door-to-door public-transport comparators on the same OD pairs, with social tariffs or public-service obligations applied on corridors serving peripheral or low-access zones. Where employers or health services benefit (commuting, medical logistics), co-funding can underwrite lower user fares without compromising operational viability.
- **Universal design and interchange quality** - Inclusivity depends on frictionless first/last-mile access. Candidate pads should be sited within short walking distance of bus/rail/tram nodes and designed for universal access (step-free boarding, tactile/audible cues, sheltered waiting). In car-dependent catchments, controlled park-and-ride capacity can support access without inducing unnecessary car trips. These design choices reuse the interchange layers already employed in the MCA and make the most of the nodes highlighted in the metropolitan mobility plan.
- **Distributing externalities fairly** (noise, privacy, visual exposure) - Routing and altitude policies should minimize burdens on sensitive or disadvantaged neighborhoods. For vertiports, the horizontal component of noise governs pad siting and lateral stand-off; for corridors, the vertical component is decisive - maintaining sufficient over-roof clearance to respect legal limits while preserving CNS continuity. In protected or heritage-sensitive sectors, altitude-conditioned permissions (where lawful) may “unlock” continuity, but only where monitoring shows compliance with quiet-hour policies and privacy-by-design constraints (no persistent imaging, purpose-limited data).
- **Reliability and digital inclusion** - Equity also hinges on predictable service. Corridors shortlisted in 4.1-4.2 should be stress-tested for CNS quality and weather resilience; service-level targets (availability, cancellations) and simple booking channels beyond smartphones (kiosks, call centers) reduce digital exclusion and make the offer usable by a broader public.
- **Phased rollout and accountability** - A periphery-first phasing can be formalized with measurable commitments: minimum coverage of low-access population before CBD expansions; a share of initial kilometers located on corridors that demonstrably reduce door-to-door times to regional hubs; and publication of open performance data (noise complaints, cancellations, equity coverage). Learning loops - periodic reviews of OLS outcomes, altitude policies, and CNS performance - close the gap between the screening results and lived experience, keeping the system within social-acceptability bounds as it scales.

Evaluating the impact of UAM on urban quality of life

We found that final site selection depends on multiple factors. The most decisive are the safety dimension - namely ground-risk assessment and verification of OLS above the vertiport - the continuity of CNS services, and social acceptability, with particular attention to compliance with noise limits. What follows focuses on the three most contested dimensions - noise, risk, and affordability - and how policy levers can keep them within acceptable bounds.

- **Noise**: psychoacoustic work on eVTOLs suggests evaluating not only level but noticeability/blend with ambient soundscapes - useful where absolute levels are close to thresholds. In practice:
    - i. pick pads where horizontal offsets meet land-use limits,
    - ii. enforce corridor altitude floors to keep façade exposure compliant,
    - iii. publish exceedances and complaints to allow course-corrections.
- **Risk and safety**: from proxies to deployable operations - Our results use SORA-inspired proxies to represent GRC and airspace constraints; real operations in dense settings will fall in the Specific/Certified categories and require robust mitigations. In SORA v2.5 the operational volume plus a ground-risk buffer defines GRC, while air-risk, mitigations and the resulting SAIL drive the required safety objectives. At network level, U-space services (EU 2021/664) introduce strategic deconfliction, tracking and geofencing as baseline enablers. Policy levers consistent with our maps include altitude-conditioned permissions over constrained sectors (where lawful), geofenced avoidance of sensitive land uses, and corridor-level minima tailored to local risk pictures.
- **Economics and affordability**: credible use-cases first - Near-term unit costs for passenger eVTOLs are expected to exceed typical ground PT. Literature points to multi-dollar cost per passenger-mile (with wide uncertainty) and significant vehicle capex, making early services vulnerable to “premium-only” uptake unless supported by public-value missions and fare integration. Public debates during the Paris trials also highlighted high fares as a concern (e.g., ~€110 quoted for demonstration trips), feeding equity critiques. To align with “inclusive UAM,” deployment should target OD pairs where door-to-door time savings are demonstrable, and fares can be capped/integrated via PSO-like mechanisms or co-funded corridors (health logistics, regional-hub access).
- **Signals from public discourse** (positives and negatives) - European surveys find conditional openness - stronger for medical/emergency use and remote-area access - tempered by concerns over safety, noise, privacy, and heritage/landscape protection. Recent Paris experience shows how noise, cost, and cultural-site sensitivities can trigger legal and civic pushback, even when demonstrations proceed without passengers or at limited scale: this underlines the value of transparent criteria, auditable limits, and a “periphery-first” phasing that delivers public value early (Mandard, 2024).
- **Operational guardrails are tied back to the maps**:

  - Where to site pads should prefer industrial/peri-urban clusters and strong interchanges where horizontal stand-off is feasible (our vertiport surface hotspots in 4.1-4.2),
  - How to route corridors by enforcing altitude floors over rooftops to respect façade limits and check CNS continuity; in masked sectors, consider altitude-conditioned overflight only if legal and verifiably quiet,
  - When to operate defining quiet-hour caps per corridor and publish exceedance/complaint dashboards,
  - Who benefits first should prioritize corridors with clear public benefit (health, peripheral access), which literature links to higher acceptance.

Economic, Environmental, and Social Impacts of UAM

UAM's net impacts are not intrinsic; they depend on where, when, and for whom services are deployed, how clean the energy is, and whether social guardrails (noise/privacy/heritage) are encoded in operations. The literature and recent European experience converge on a simple lesson: if cities want the benefits (time savings, selective connectivity) without outsized externalities, they must combine targeted corridors/nodes with auditable limits and inclusive fare policies.

- **Economic** - Near-term passenger eVTOL services remain cost-intensive. Recent syntheses and case studies place early operating prices in the multi-euro/dollar per passenger-mile range (often ~US$2.5-6.25/pp-mi) depending on utilization, turnaround/charging, maintenance, and crew rules - implying premium fares unless public-value missions or cross-subsidies are used. Public demonstrations in Paris reinforced the affordability concern, with trial fares quoted around €120-140 per trip and a mixed regulatory outcome (Butterworth-Hayes, 2023). Economic upside is scenario-dependent: regional impact studies forecast jobs and induced activity if networks reach sustained demand, but results are highly sensitive to assumptions (load factors, energy prices, vertiport throughput). In inclusion-oriented deployments (4.3.1), credible levers are fare integration/PSO-like obligations on corridors that deliver public value (health logistics, peripheral access), and employer/agency co-funding on commuting or critical-services links.
- **Environmental** (climate & local exposure) - System-level climate impact hinges on electricity mix, occupancy, trip length, and mode shift. A Nature Communications study finds that for ~100 km trips with three passengers, VTOL GHG per passenger-km can be ~35-52% lower than ICE cars and modestly higher/lower vs. BEVs depending on occupancy and routing; the advantage grows with longer trips and high occupancies but shrinks if UAM displaces rail/bus rather than private cars.
- **Nature** - Newer LCA work shows context-dependent results - e.g., eVTOL may exhibit higher total emissions than ground EVs when upstream electricity and manufacturing burdens dominate, underscoring the importance of clean grids and high utilization. Operationally, routing/altitude policies can minimize local environmental exposure (wildlife interfaces, sensitive landscapes). WHO guidance on aircraft noise frames a health-protective target of ≤ 45 dB in residential areas; when UAM is planned as part of the urban system, those

thresholds should anchor corridor floors and pad siting, alongside air-quality co-benefits from electrification.

- **Social** (acceptance, noise/visuals, privacy & safety) - Europe-wide polling shows conditional openness to UAM - strongest for medical/emergency and remote-area use - tempered by concerns over safety, noise, wildlife/heritage, privacy, and fairness. EASA's pan-EU study ranks safety as the benchmark ("as safe as commercial aviation"), with noise a close second; acceptance improves with transparent limits (quiet hours, routing), familiarity of sound, and clear public value. Noise needs both level-based and psychoacoustic treatment. WHO's ≤ 45 dB recommendation remains a robust compass for residential exposure.
- **Safety & risk** - In dense fabrics, real operations sit in Specific/Certified categories under SORA, where the operational volume plus ground-risk buffer defines GRC, with air-risk and mitigations yielding SAIL-driven objectives. U-space (EU 2021/664 et seq.) introduces strategic deconfliction, geo-awareness and tracking as baseline digital services. This argues for machine-readable rules (geofencing, altitude floors, heritage and quiet-hour constraints) that regulators/operators can audit in real time.
- **Signals from public discourse** (positives & negatives) - Paris became a focal case: crewed validation flights progressed, yet passenger services during the Olympics were ultimately scrapped, and municipal/legal challenges highlighted noise, cost, safety and heritage concerns. The episode illustrates both public curiosity and organized pushback - hence the need for transparent criteria and verifiable guardrails if cities aim to proceed.

4.4. FUTURE RESEARCH PERSPECTIVES AND POSSIBLE IMPLEMENTATION

This study should be read as decision-support rather than prescription. The GIS-MCA pipeline relies on proxies and simplifying assumptions that enable cross-case comparability but inevitably constrain precision and transferability.

The first limitation concerns data availability and harmonization across the two case studies. Emilia-Romagna benefits from a landscape/heritage plan that could be encoded as spatial constraints and DSM, whereas Valencia lacked an integrated instrument at the same scale. As a result, the Emilia-Romagna workflow separated vertiport- and corridor-oriented layers upstream, while in Valencia the differentiation was deferred to downstream checks (OLS, stand-off, altitude policies). Although both rasters share the same Coordinate Reference System or CRS (ETRF2000 / UTM32N, epoch 2008), resolution, and normalization scheme introduced in Chapter 2, the heterogeneity of sources and regulatory layers affects strict comparability. More broadly, several datasets (land-use regulation, environmental designations, AIP excerpts, obstacle fields) are uneven in coverage or accessibility; this motivated the adoption of a minimum common dataset, at the cost of excluding finer local information.

Second, weighting choices were intentionally conservative. All layers were given equal weights to avoid spurious precision where stakeholder elicitation was not feasible. In an operational planning process, weights would be co-defined with sectoral experts and stakeholders (e.g., via AHP or similar), and they would likely vary by sub-area and use case. The equal-weight stance helps transparency but may under- or over-represent certain constraints in specific locales.

Third, several modelling simplifications were necessary. Noise was treated through horizontal (pad-centric) and vertical (overflight) components rather than through a propulsion- and trajectory-specific acoustic model. Our method could be used more widely for urban planning regulation by creating plans to limit noise pollution. Obstacle screening used DSM-based OLS checks that do not capture all protected surfaces or temporal obstacles. Ground/air risk relied on broad SORA-inspired proxies; airspace conflict management was not simulated. Corridor routing combined a Delaunay skeleton with least-cost paths; it is not a full traffic assignment nor an operational deconfliction model. CNS quality (GNSS and 4G/5G) was represented through raster proxies and CRLB-style indicators on a fixed grid; multipath and urban-canyon effects were only indirectly captured, and no drive-test calibration was performed. These choices are adequate for regional screening but not for final design.

Fourth, the regulatory envelope was simplified. By default, Open-category operations (≤120 m AGL) were assumed, which led to masking large, protected areas (notably along the Emilia-Romagna coastline). While the text discusses altitude-conditioned permissions that could “unlock” segments, these variants were not systematically encoded in a rule’s engine. Similarly, several local by-laws on noise, privacy, and visual intrusion were incorporated through surrogate layers rather than enforceable, machine-readable constraints.

Fifth, temporal dynamics and validation remain limited. Weather, demand patterns, and network performance were considered in static or long-term average form. No empirical validation against flight trials or operational logs was undertaken, and the sensitivity analysis focused on threshold and weight perturbations rather than on alternative normalization schemes or multi-model ensembles. Consequently, uncertainty bands are indicative rather than statistical.

Finally, the study does not cover economic and organizational viability deeply. Capital/operating costs, business models, service levels, and staffing were not modelled; nor was a structured multi-stakeholder deliberation conducted. In real deployments each thematic block (operations, safety, acoustics, telecoms, planning) would require domain experts and a negotiated decision process, which is beyond the scope here.

Taken together, these limitations justify the interpretive stance adopted throughout the thesis: the suitability surface is an analytical artefact to be read alongside planning knowledge and expert judgement. Future work (Sub-chapter 4.5) will address these gaps by standardizing input datasets, introducing expert-elicited weights, upgrading noise and risk models, encoding regulatory rules (including altitude-conditioned permissions) in a machine-readable way, and validating the routing and CNS layers against empirical evidence or high-fidelity simulators.

We plan moving from the static screening delivered in this thesis to a sharable software program (API) that operationalizes the same logic - MCA layers, the vertiport/corridor distinction (horizontal stand-off and OLS at pads vs altitude-dependent effects and CNS continuity along corridors), and environmental masks - so that cities, agencies and researchers can reuse, parameterize and audit the tool on their own data. Concretely, the API will expose services for:

i. data ingestion and normalization,
ii. demand-informed siting,
iii. risk-aware routing, and
iv. monitoring.

It will incorporate dynamic feeds already signaled in the thesis - e.g., mobile-network cells to observe where people concentrate and to prioritize nodes and time windows, weather/forecast inputs (with a view to integrating Italian providers such as MISTRAL) to assess wind and meteorology along candidate routes, and time-bounded flight restrictions to reflect temporary constraints - so that corridor availability and pad compliance can update in near-real time. The demand/siting component will complement raster eligibility with a two-step optimization pipeline that first clusters observed flows (e.g., AHC - Agglomerative Hierarchical Clustering/k-means) to nominate candidate pads and then solves facility-location problems (p-median/p-center with capacity and budget constraints) to select sites that balance coverage, access and externalities, as discussed in the thesis notes on equitable siting methods. On the routing side, we will replace static least-cost traces with risk-aware path planning that minimizes expected ground exposure and nuisance under regulatory envelopes, including a wind-dependent dynamic ground-risk map - as suggested by prior studies cited here - so that altitude policies and micro-rerouting can reconnect masked segments only where law, CNS quality and noise objectives allow. To support credible operation planning, the platform will interoperate with simulation-in-the-loop (e.g., reusing aviation simulators mentioned in the thesis, adapted to UAM) to test pad throughput, turnaround and schedule robustness under realistic demand and weather, and to quantify KPIs (noise exceedances at façades, CNS-adequate corridor-km, cancellations, complaint rates). Finally, because replication and governance matter, the API will ship with open documentation, default schemas and reference datasets, privacy-by-design options for aggregating telco inputs, and a minimal UI for publishing auditable dashboards. Modelling extensions will remain explicitly flagged as future work - namely, (i) validation of coverage and positioning layers against measurements; (ii) replacing the equal weights adopted in this work with expert-elicited and stakeholder-informed weights (e.g., via AHP/Delphi-style protocols); (iii) richer acoustic and risk models; (iv) integration of dynamic restrictions; and (v) an explicit participatory module to operationalize social acceptance, by coupling the workflow with lightweight PPGIS/WebGIS feedback (e.g., perceived nuisance and locally salient constraints) and by documenting how alternative value sets affect the resulting suitability and routing outputs through scenario and sensitivity analyses - so that the analytical artefacts presented here can be reused, extended, and scrutinized by others in a transparent manner.

As discussed in the section describing these socio-economic layers, a key limitation is the **MAUP**. Put simply, MAUP means that results based on indicators aggregated over administrative areas (e.g., census sections) can vary depending on the size of those areas and on how their boundaries are defined. In this study, both the real estate value and the spending capacity index are available only at the **census-section** level and are therefore used as areal aggregates. When these polygon-based indicators are rasterized to match the analysis grid, all cells inside the same census section receive the same value. This creates block-like patterns and sudden changes at census-section borders, while differences inside the same census section (e.g., at street scale) are not represented. This also creates a mismatch with other criteria that are available as high-resolution rasters (e.g., DEM/DSM-derived layers, positioning/coverage rasters, and distance-based surfaces). As a result, the final MCA suitability may be influenced by census-section boundaries, especially close to their edges, and the ranking of candidate sites can be partly sensitive to the chosen aggregation units. Classic MAUP studies discuss these effects in multivariate spatial analyses and show that both scale and zoning choices can affect outcomes.

5. CONCLUSIONS

This thesis develops a replicable, GIS-based MCA to support early-stage planning of drone infrastructure - both vertiports and aerial corridors - by reconciling operational feasibility with environmental, regulatory, and social constraints. The empirical design comprised four cases obtained by crossing mainly two case studies for logistic transport: one on large scale that is Emilia-Romagna and another in an urban scale in the metropolitan area of Valencia with two infrastructure types (vertiports and corridors). This keeps a constant analytic core while observing how morphology, policy instruments, and data availability reshape the resulting eligibility surfaces. The work began with a long-distance logistics corridor use case that could not be fully replicated or refined in the last-mile logistics case because of heterogeneous data conditions: in Valencia, detailed information on antenna locations/CNS proxies enabled corridor-specific continuity checks; in Emilia-Romagna, clear GIS layers from statutory plans (notably the landscape plan) supported an upstream separation of node- and link-oriented constraints. These asymmetries did not alter the method but shifted with differentiation. Since this research was initiated more than three years ago, the academic discussion on spatial planning for U-space/UAM infrastructures has expanded, moving from relatively sparse, case-specific demonstrations toward more structured and specialized contributions. Recent work has formalized vertiport location criteria and weighting procedures (Mercan et al., 2025) and mapped the evolution and emerging themes of the vertiport literature through bibliometric analyses (Lu et al., 2025). In parallel, the focus is increasingly shifting from node siting to the explicit design of network and airspace constructs: corridor planning is treated as a computationally demanding network design problem (He et al., 2025), while safety research is introducing 3D, risk-informed exclusion volumes that can be integrated with GIS-based decision support and trajectory planning (Zhenyu Gao et al., 2025). Earlier data-driven siting approaches combining clustering with noise screening (Jeong et al., 2021) also anticipate the current emphasis on coupling environmental impacts with location selection. Together, these studies corroborate the relevance of the workflow proposed here and indicate a fast-maturing research agenda in which transparent and transferable planning pipelines are becoming increasingly valuable.

Across the four cases, the results demonstrate:

i. the conditional transferability of the analytic core - under fixed CRS, resolution, and normalization choices (Chapter 2) - provided a minimum common dataset is available (DEM/DSM, land-use, protected areas and regulated buffers, noise-sensitive uses, airspace structure, and CNS proxies such as GNSS/4G/5G or antenna footprints); where this bundle is incomplete, the method remains portable but outputs degrade and some checks must shift downstream or rely on proxies,
ii. that siting and routing are a staged decision-support problem, combining hard legal/safety exclusions with soft criteria whose weight evolves with stakeholder deliberation, and we could not replicate,
iii. a robust node - link asymmetry, whereby horizontal stand-off governs vertiport siting while vertical separation and CNS quality govern corridors, and

iv. the tangible role of policy leaders (e.g., altitude floors, stand-off thresholds) in shifting feasible patterns without changing the underlying approach.

Across both contexts, the results confirm three structural insights. First, MCA functions as a modular, staged form of decision support rather than a one-shot map. A composite suitability surface cannot, by itself, settle locating or routing decisions because different constraints belong at different stages of the pipeline. Some exclusions must be applied upstream as no-go screening where legal or safety rules remove areas a priori; others are legitimately combined at synthesis as soft preferences whose relative weight changes through stakeholder deliberation; still others must be verified downstream as filters and audits that cannot be credibly embedded in the composite map - for example DSM-based OLS intrusions, pad-level acoustic acceptability, or façade exposure checks. In practice, the MCA is often reused iteratively as new information surfaces, serving as a tiebreaker among candidates. The overall process should therefore be read as an auditable sequence of decisions - some before the MCA, some within it, and some after it - rather than as a deterministic verdict from a single raster. This begins with selecting the layers to consider, deciding the weight to assign to each, identifying which ones to use as filters, and then interpreting the final MCA output by re-checking it against the most relevant individual layers. For example, for noise, if no filter can be embedded, the appropriate noise stand-off distance must be respected. This deliberative component can be made operational within the GIS-MCA developed here by treating participation as an input to the staged pipeline rather than as an external add-on. Concretely, stakeholders and affected communities can contribute to (i) co-defining policy thresholds that condition feasibility (e.g., quiet-hour windows, stand-off distances for sensitive receptors, locally relevant privacy/visual-intrusion safeguards), (ii) eliciting weights for soft criteria through structured procedures (e.g., AHP or Delphi-style convergence), and (iii) providing geographically referenced feedback via a lightweight PPGIS/WebGIS interface to capture perceived nuisance and locally salient constraints that are not fully represented by proxy layers. These inputs can then be translated into documented scenarios and sensitivity tests, making value trade-offs explicit and auditable while preserving the rule-based character of hard exclusions.

Second, building on that logic, several regulations and performance constraints need to be decomposed into components and located at the correct stage. Noise is not a single layer but splits into horizontal stand-off around nodes during take-off and landing and vertical separation along links to keep façades within legal limits, with time-of-day quiet-hour policies further conditioning feasibility. Risk likewise divides into broad ground-risk exposure suitable for early screening and route-specific air-risk and clearance checks that belong later. CNS is best treated as coverage, continuity, and integrity - spanning GNSS and 4G/5G - which together determine where altitude can be raised and whether corridor continuity can be maintained.

Third, policy levers matter, and their effects are clearest when expressed in plain operational terms. Raising a minimum corridor height can restore continuity above dense fabrics, but the gain in façade noise performance may come at the expense of CNS robustness or clash with airspace rules; enlarging lateral stand-offs and buffers around pads reduces the pool of nearby candidates yet tends to strengthen acceptance; restricting operations to specific time windows can make otherwise problematic alignments viable; and codified local step-ups in altitude over short segments can reopen masked sectors only where the legal framework and monitoring allow it. These levers turn suitability from a fixed label into a set of transparent trade-offs: altitude, distance, timing, and local adjustments act as dials whose settings shift the feasible patterns, while the underlying method remains unchanged.

The interpretive stance follows: the eligibility surface is a decision-support artefact that must be read alongside planning knowledge and expert judgement. Our limitations section explicitly underscored the conservative choices made to keep comparisons credible - equal weights in lieu of stakeholder-elicited AHP, simplified representations of noise (horizontal vs vertical proxies) and obstacles (DSM-based OLS), SORA-inspired risk at broad scale without full conflict management, proxy rasters for CNS, static least-cost routing instead of traffic assignment, and a regulatory envelope defaulting to Open-category ≤120 m AGL. These are adequate for screening, not for final design, and they justify the call for future work on data standardization, expert weights, richer acoustic and risk models, and machine-readable rules.

Within this frame, the thesis also offers a planning reading. In Emilia-Romagna, inland hubs cluster along the Via Emilia axis, with north-south feeders linking productive hinterlands; coastal continuity remains weak under the Open-category default because protected areas dominate unless altitude-conditioned permissions are considered. In Valencia, peri-urban belts and interchange-rich districts concentrate the remaining high-score patches after environmental masking; long-range continuity is feasible on the plain but becomes locally constrained near protected belts. These patterns are not merely cartographic: they reflect the interplay of morphology, visual-intrusion rules, electricity and interchange access, and the need to maintain CNS quality along candidate alignments.

The thesis’ policy angle is consistent with the emerging U-space framework. CORUS-XUAM’s updated Concept of Operations details how initial UAM operations hinge on digitized geo-awareness, strategic deconfliction and flight authorizations, progressively adding services such as dynamic conflict resolution and real-time weather integration as systems mature - a roadmap that supports incremental deployment and increasing automation. Regulation (EU) 2021/664 formalizes these services and the “common information service,” setting the stage for cities to translate static constraints into machine-readable rules that can be audited in real time. In this sense, the MCA is a pre-phase that helps define where hard rules should bind and where soft objectives can guide optimization.

Quality-of-life considerations are central. European evidence shows conditional openness to UAM - strongest for medical/emergency and remote-area uses - tempered by concerns over safety, noise and privacy/heritage. WHO guidance for aircraft noise offers a health-protective target near 45 dB in residential areas, a level that should anchor corridor altitude floors and pad siting in dense fabrics; psychoacoustic features (tonality, sharpness) also matter and argue for noise-optimised operations and vehicle design.

The public debate during the Paris demonstrations further illustrates the duality of excitement and pushback: authorizations for limited validation flights coexisted with civic/legal challenges over noise, heritage and cost, and the inability to secure full passenger certification in time for the Games ultimately curtailed ambitions - an instructive reminder that technical readiness, regulatory timing and social licence must advance together. Operationally, this also means drones will not fly geodesics between origins and destinations. Routes must respect airspace structures, protected areas, altitude policies, CNS coverage and quiet-hour constraints; even the same OD pair may require asymmetric paths outbound vs inbound depending on wind, risk and noise footprints. Our own least-cost experiments already highlighted algorithmic sensitivities (e.g., route differences observed in ArcGIS Pro's cost tools vs QGIS for the same OD under round-trip computation), reinforcing the need to validate and benchmark routing components before translating analyses into procedures. This is why future work includes both model validation and simulation-in-the-loop with existing tools (as done in EU projects like USEPE with BlueSky) adapted to UAM trajectories, winds and service rules.

The governance component is equally important. Local authorities are pivotal in aligning UAM with Sustainable Urban Mobility Plans and land-use instruments; they must interpret national/EU rules locally, assemble domain expertise (operations, safety, acoustics, telecoms, planning), and run transparent locating processes open to stakeholder scrutiny. At the same time, when drafting these plans, it is necessary to anticipate the future development of these new technologies and adapt them to the evolving context. Decision-support tools like the one developed here can raise the negotiating capacity of municipalities by making complex trade-offs legible and auditable - yet tools are not a substitute for judgement. In dense European fabrics, acceptance hinges on credible safeguards (quiet hours, geofencing near sensitive uses, privacy-by-design), equitable coverage (not a premium-only service), and verifiable service-level and complaint data. The equity-oriented strategies outlined for public-transport complementarity (peri-urban first, integrated fares, universal design at interchanges) follow directly from the eligibility patterns and are consistent with the social concerns documented in the literature.

UAM represents a paradigm shift in urban transport, introducing drones and vertical take-off and landing aircraft as a solution to congestion, inefficiency, and accessibility challenges in cities. However, the introduction of such technology requires a thorough and collaborative approach to ensure its integration is seamless and beneficial. Local authorities, particularly municipal governments, hold a pivotal role in translating national and international strategies into practical, locally adapted solutions. Their responsibilities extend beyond regulatory enforcement to include urban planning, stakeholder engagement, and the facilitation of public acceptance.

A primary responsibility of local governments is to ensure the integration of UAM infrastructure, such as vertiports, into the urban landscape. This process involves aligning these developments with existing urban plans, including Sustainable Urban Mobility Plans (SUMPs). Such alignment ensures that UAM solutions contribute to broader urban development goals and avoid conflicts with other land uses. Tools like Geographic Information Systems (GIS) are essential in this context, allowing authorities to analyze spatial constraints and identify suitable locations for vertiports. This approach minimizes disruption while optimizing accessibility to other transport nodes, such as train stations or urban hubs. Moreover, local authorities must consider the dynamic nature of urban spaces and the need to allocate land flexibly for these new infrastructures.

Beyond urban planning, municipalities are tasked with interpreting and adapting regulations established at the national and European levels. The implementation of U-space frameworks, for instance, requires close coordination between air traffic management and ground-based transport systems, ensuring safety and efficiency. Local authorities must also incorporate operational risk assessments, such as SORA, to evaluate and mitigate risks specific to their territories. This includes addressing environmental concerns, particularly noise pollution and its impact on urban communities, as well as ensuring that the operation of UAM systems adheres to ethical standards and respects privacy.

Stakeholder involvement is another critical dimension of municipal responsibility. The successful implementation of UAM infrastructure relies heavily on collaboration with diverse actors, including urban planners, aviation authorities, local businesses, and community representatives. Transparent decision-making processes are essential to building trust and ensuring that the needs of all stakeholders are addressed. Public acceptance is equally important, as societal apprehension regarding noise, safety, and privacy can hinder the adoption of UAM technologies. Municipalities can employ public acceptance toolkits to assess and address these concerns proactively, fostering a sense of inclusivity and shared benefit among citizens. Educational initiatives and awareness campaigns can further support this effort, highlighting the potential advantages of UAM, such as reduced traffic congestion, improved emergency response times, and enhanced connectivity.

Local authorities must also actively address the risks associated with UAM operations, including safety and environmental challenges. Identifying suitable flight corridors and vertiport locations is essential to minimizing conflicts with existing infrastructure and reducing risks to urban populations. Municipalities must also take steps to mitigate the environmental impacts of UAM systems, particularly in ecologically sensitive or densely populated areas. Effective noise management, for instance, is crucial to maintaining public support for these technologies. Additionally, collaboration with national and international bodies can help establish and enforce guidelines for the ethical and sustainable use of drones.

To manage these responsibilities effectively, municipalities must build institutional capacity. This involves creating dedicated units or teams within local governments to oversee UAM-related activities and ensure that policies are implemented cohesively. Decision Support Tools (DSTs) can be particularly valuable in this regard, providing a structured framework for evaluating potential vertiport locations based on multiple criteria. Furthermore, local governments should invest in training programs to equip their staff with the knowledge and skills needed to navigate the complexities of UAM governance and technology.

Local authorities play a fundamental role in bridging the gap between technological innovation and societal needs. Their efforts in urban planning, regulatory adaptation, stakeholder engagement, and capacity building ensure that UAM systems are integrated responsibly, equitably, and sustainably. As the deployment of UAM infrastructure continues to expand, municipalities must remain proactive, balancing the demands of innovation with the realities of urban life to maximize the benefits for all.

Against this background, the thesis closes with a pragmatic implementation path. The final purpose is turning the screening stack into a programme/API that others can reuse: a rules engine that encodes protected areas, heritage buffers, quiet hours and AIP restrictions in a machine-readable form; ingestion of dynamic feeds (weather and wind, CNS proxies, time-bounded restrictions - Digital NOTAM (Notice to Air Missions)/AIXM (Aeronautical Information Exchange Model) - and, under GDPR safeguards, aggregated mobile-network signals for crowding); demand-first siting that couples MCA priors with clustering and facility-location optimization; and risk-aware routing that minimizes expected ground exposure with wind-dependent dispersion and SORA-consistent operational volumes and ground-risk buffers. Such a platform would publish auditable dashboards (noise exceedances, CNS availability, complaint rates) and support staged deployment from offline replay to shadow mode to controlled pilots with public-value missions.

Looking forward, U-space maturation reinforces this trajectory. CORUS-XUAM's roadmap anticipates a transition from foundational implementations to integrated systems, with more automation and richer services (dynamic conflict resolution, real-time weather) and a gradual shift from piloted to increasingly unmanned operations as safety cases harden and costs fall. Achieving that potential, however, requires closing the gaps we have documented: standardizing a minimum common dataset across cities; replacing equal weights with stakeholder-elicited schemes; upgrading acoustics from stand-off proxies to propulsion- and trajectory-specific models; validating CNS proxies with measurements; encoding regulatory constraints as executable rules; and benchmarking routing to ensure consistency across tool chains.

In sum, this thesis offers a replicable approach for understanding where UAM infrastructure is reasonable under current rules and data - and, equally, where it should not be placed. The maps and tests show that promising spatial structures do exist (for example, inland trunk lines with feeders and peri-urban interchanges). However, real feasibility in dense European settings depends on clear limits for noise, risk, and privacy; on reliable CNS and weather-aware operations; and on governance that keeps the public interest at the center. The way forward is not a straight line between two points but a sequence of auditable choices. Planners must make explicit decisions about routes, heights, time windows, and who benefits from the service. When those choices are documented - and when the tools used to make them are open for others to reuse and inspect - the sector can move from static maps to managed operations that are safer, fairer, and easier to accept.

The evolution of U-Space services further supports this approach, as outlined in the (CORUS-XUAM, 2022) study, which provides a roadmap for transitioning from foundational implementations to fully integrated systems. This progression involves the incremental deployment of UAM infrastructure tailored to operational demands, the integration of advanced services such as dynamic conflict resolution and real-time weather updates, and a shift towards unmanned operations surpassing manned ones. These advancements are underpinned by technological improvements that reduce costs and enhance autonomy, making UAM operations more accessible and sustainable.

In addition to technical and operational considerations, societal acceptance remains a critical factor in the successful deployment of UAM. Studies have underscored the influence of noise pollution, visual disturbances, and privacy concerns on public support for drone operations. To address these challenges, strategies such as noise-optimized routing, community engagement, and adherence to stringent regulatory frameworks are being developed. The use of geofencing, both static and dynamic, is particularly promising for managing operational constraints and mitigating risks while responding to environmental and social concerns.

Looking to the future, achieving the full potential of UAM will require further research in several key areas. These include dynamic airspace management tailored to varying traffic densities, integration of ground infrastructure such as vertiports with existing urban planning frameworks, and addressing the interplay between technological limitations, such as GPS inaccuracies in urban canyons, and operational demands. By addressing these interconnected challenges, a comprehensive framework for managing large-scale drone traffic can be established, paving the way for a safer, more efficient, and socially acceptable UAM ecosystem.

APPENDICES

A. European and world aviation institutions and stakeholders

In the field of airspace and drone regulation, several key institutions play a leading role globally. At the international level, the *International Civil Aviation Organization* (ICAO) sets standards and recommended practices (SARPs) aimed at ensuring safe, secure, and orderly growth of international civil aviation, increasingly addressing the integration of unmanned aircraft systems (American National Standards Institute, 2020). In Europe, regulatory and operational oversight is primarily managed by the European Union Aviation Safety Agency (EASA), responsible for developing common aviation safety rules, including those for drone design, production, and operation. EUROCONTROL, an intergovernmental organization with broader European membership, focuses on supporting pan-European air traffic management (ATM), contributing technical expertise and coordinating efforts towards achieving the SES, including aspects related to drone integration (McInally, 2010).

Beyond Europe, other countries actively involved in drone regulation have their own aviation authorities. In the United States, the FAA oversees drone regulations, and this is driving modernization efforts withing the National Airspace System (NAS) through initiative like the NextGen program, aiming to enhance drone integration (Federal Aviation Administration, 2023). SESAR, the European equivalent, is modeled after NextGen, sharing its goal of integrating drones safely within controlled airspace (Bolić et al., 2021).

China's Civil Aviation Administration of China (CAAC) is also expanding its regulatory framework to address the rapid growth in drone usage. The United Arab Emirates relies on the General Civil Aviation Authority (GCAA) for regulatory guidance in drone operations, especially given the high demand in urban areas (Zhang, 2024). Similarly, Japan's Civil Aviation Bureau (JCAB) and South Korea's Ministry of Land, Infrastructure and Transport (MOLIT) are working on policies to support safe drone operations in densely populated areas (Nakamura, Harada, and Oura, 2018; Ministry of Land, 2020). South Korea is advancing its UAM framework through initiative like K-UAM Grand Challenge program.

In many cases, these international and national organizations collaborate to address regulatory challenges, ensuring that airspace integration and safety standards keep pace with technological advancements in unmanned aerial vehicles (UAVs).

The drone market encompasses a diverse range of stakeholders, each playing a **critical role in shaping the regulatory, operational, and technological landscape**. These stakeholders contribute to the safe integration of drones into airspace, the development of innovative solutions, and the establishment of a sustainable market. The primary stakeholders can be grouped as follows (CORUS-XUAM, 2022):

- **Regulatory and Advisory Bodies**: crucial for creating and implementing policies, standards, and frameworks that govern drone operations. These include:
    - Advisory Council for Aviation Research and Innovation in Europe (ACARE): Provides strategic advice and fosters innovation to support aviation research, including the integration of drones.

    - Standardisation Bodies: Actively participate in harmonizing standards for drone operations through groups such as:
        - EUROCAE Council
        - European ATM Standards Coordination Group
        - European UAS Standards Coordination Group
- **Air Navigation and Service Providers** (ANSPs): play a pivotal role in managing air traffic and ensuring safe integration of drones into existing airspace. They collaborate with regulatory bodies and technology developers to implement solutions that address operational challenges.
- **Professional Staff Organizations**: contribute valuable operational and technical expertise, ensuring that new drone technologies and frameworks align with real-world operational requirements. Their input is vital for training programs and workforce adaptation to evolving industry demands. Research institutions and academia also play a significant role here through research and development.
- **Airspace Users**: both civil and military, are directly impacted by the introduction of drones into shared airspace. Their collaboration is essential for developing deconfliction strategies, improving situational awareness, and ensuring safety for all parties.
- **Airports**: European airports are key stakeholders in the drone market due to their role in facilitating operations such as:
    - Cargo delivery
    - Passenger transport using drones (urban air mobility)
    - Surveillance and infrastructure inspection
    - Airports also contribute to the development of vertiports and other drone-related infrastructure, ensuring seamless integration with traditional aviation.
- **Industry and Market Actors**: Straubinger et al.Straubinger et al. identifies the main market actors including platform providers, service providers, vehicle owners, vehicle manufacturers, maintenance providers, insurance companies, ground infrastructure providers, communication infrastructure providers, and UTM providers.

B. Technology Readiness Levels (TRL)

To measure the progress of SES towards achieving DES, specific metrics are used to evaluate the technological readiness level attained. The Technology Readiness Levels (TRL) framework provides a standardized classification system to assess the maturity of a technology throughout its development (Gkoumas et al., 2021). The TRL scale ranges from 1 to 9, with each level corresponding to a specific stage of technological advancement, from basic research to full operational capability. Below is a summary of these stages:

- **TRL 1 - Basic principles observed**: Identification of fundamental scientific principles.
- **TRL 2 - Technology concept formulated**: Development of ideas or potential applications.
- **TRL 3 - Experimental proof of concept**: Initial laboratory testing to confirm feasibility.

- **TRL 4 - Technology validated in the lab**: Testing of components or prototypes in a controlled environment.
- **TRL 5 - Technology validated in a relevant environment**: Testing under simulated operational conditions.
- **TRL 6 - Technology demonstrated in a relevant environment**: Functional prototype tested in simulated or real-world scenarios.
- **TRL 7 - System prototype demonstration in an operational environment**: Prototype evaluated in real operational conditions.
- **TRL 8 - System complete and qualified**: Integration of the technology into operations.
- **TRL 9 - Actual system proven in operational environment**: Fully operational and implemented technology.

To address the gaps identified in the stages and SESAR classifications of technologies, the following activities are prioritized:

- **Exploratory Research** (TRL 0-2): Focused on fundamental scientific concepts and innovative ideas, funded under Horizon Europe.
- **Industrial Research and Validation** (TRL 3-6): Aimed at demonstrating the feasibility of technologies in relevant operational environments, also funded under Horizon Europe.
- **Fast-Track Innovation and Uptake** (TRL 2-7): Activities designed to accelerate the adoption of technologies through pilot projects and demonstrators, supported by funding.
- **Digital Sky Demonstrators** (TRL 7-8): Large-scale testing of integrated technologies under real-world conditions, funded by the Connecting Europe Facility (CEF) in collaboration with CINEA (European Climate, Infrastructure and Environment Executive Agency).

C. Single European Sky (SES)

The SES is a European Union initiative designed to unify and optimize air navigation across its member states, addressing inefficiencies and the fragmentation of European airspace management. Launched officially between 2001 and 2004 (McInally, 2010), the SES was inspired by the United States' NextGen system to create interoperability between the two regions while reforming Europe's Air Traffic Management (ATM) architecture. Initially, EUROCONTROL was tasked with establishing the framework for the SES, but the responsibility shifted to a more EU-centered approach to tackle the complexities of fragmented air navigation systems. The initiative aims to transform European airspace into a seamless, efficient, and globally interoperable system capable of accommodating the increasing demands of modern aviation.

The SES is based on a comprehensive regulatory framework established in 2004, which includes Regulation (EC) No 549/2004 (European Parlament, 2004c) to set the overall framework, Regulation (EC) No 550/2004 (European Parlament, 2004a) for the provision of air navigation services, and Regulation (EC) No 551/2004 (European Parlament, 2004b) concerning the organization and use of airspace. These regulations have been regularly updated to address emerging challenges, enhance efficiency, and produce innovation in air traffic management.

A cornerstone of the SES initiative is the SESAR program, which serves as its technological pillar. SESAR focuses on defining, developing, and deploying innovative solutions to modernize air traffic management, including concepts such as Virtual Centers. These centers integrate multiple Air Navigation Service Providers (ANSPs) into centralized or distributed operations, promoting resource sharing, reducing costs, and improving network resilience. SESAR's phased implementation includes the Definition Phase (2005 - 2008), which delivered the European ATM Master Plan, the Development Phase (2008 - 2013), which validated the required solutions, and the Deployment Phase (starting 2014 and ongoing), which oversees their large-scale implementation under the coordination initially of the SESAR Deployment Manager and now continuing within the framework of the SESAR 3 Joint Undertaking (Bolić et al., 2021).

The EASA plays a critical role in the SES, acting as the regulatory authority for safety in civil aviation. It **ensures the standardization of safety procedures** and has expanded its responsibilities to include the certification and declaration of ATM/ANS equipment, and the approval of organizations involved in their design and production. By working closely with stakeholders, EASA facilitates the harmonization of norms and procedures, enabling the integration of new technologies and improving the overall efficiency of European airspace management (EASA, 2024).

The SES initiative is designed to address key challenges such as increasing air traffic density, enhancing environmental sustainability, and maintaining high safety standards. It also ensures that airports are equipped to manage current and future traffic demands while remaining adaptable to technological advancements (SESAR, 2020b). Comprehensive staff training is emphasized to prepare personnel for operating in an increasingly automated and interconnected ATM environment. Furthermore, SES prioritizes the seamless integration of manned and unmanned aircraft into a unified airspace, ensuring equitable and safe access for all users.

By combining a robust regulatory framework, innovative technologies through SESAR, and active collaboration among stakeholders, the SES aims to create a safer, more efficient, and sustainable airspace system. This transformation supports Europe's broader aviation and transport policy goals, ensuring the region remains competitive and capable of addressing future demands in air traffic management.

D. Digital European Sky (DES)

The DES can be seen as an evolutionary stage of the SES, with its origins dating back to 2017 (SESAR, 2020a). While introducing new procedures and technologies into air traffic control is complex, it is even more so in a fragmented context like the EU, where each state has its own characteristics.

The DES is the level of automation without compromising security that the EU aspires to for the SES in the Phase D depicted in Figure 38 (Balakrishnan et al., 2018). This will be achieved through total ATM integration, combining air-ground systems. The integrated device will be capable of solving problems in real-time using AI, enabled by shared navigation data. It will make possible the virtualization of routes to simplify human-machine interaction.

The DES initiative aims to create a safer, more efficient, and sustainable airspace system, addressing challenges such as increasing air traffic, cybersecurity threats, and environmental impact. The primary objectives include (SESAR, 2020a):

- **Automation Advanced Systems**: Implementing a high level of automation in air traffic management, minimizing human intervention while ensuring operational efficiency.
- **Mixed System Integration**: Ensuring the coexistence of manned and unmanned aircraft in European airspace, addressing operational and safety challenges.
- **Secure Data Sharing**: Leveraging digital platforms to facilitate real-time data sharing among stakeholders, enhancing situational awareness and decision-making.
- **Advanced Connectivity**: Utilizing technologies like 5G and satellite systems to enable reliable, high-speed communication between ground and airborne systems.
- **System Resilience**: Developing robust infrastructure capable of withstanding critical events such as communication disruptions and cyberattacks.
- **Environmental Sustainability**: Optimizing flight routes and operations to align with the European Green Deal, reducing emissions and promoting greener aviation.

The main solutions of the SESAR 2020 R&D program until the end of Phase C will be aimed primarily at the ATM world. Attaining these levels will pave the way for reaching the next Phase D. However, developing complementary solutions outside the traditional ATM world will be necessary (SESAR, 2020a):

- **Future Operations**: Fully scalable and multi-node environments, highly resilient to problems and efficient in airport operations, giving user centrality.
- **Air/ground Integration and Autonomy**: Machine learning and AI implementation to automatically verify situations that would otherwise require human intervention.
- **Virtualization Serving Scalability and Resilience**: Augmented and virtual reality systems will also allow the delivery of geographically decoupled services.
- **Hyper-connectivity and Machine-to-Machine Applications**: Increasing connectivity capacity, speed, and reliability, e.g., through 5G.
- **Data Sharing and Data Services**: Creating collaborative platforms to optimize processes and services further while analyzing and improving routes based on encountered issues and user needs.
- **New Standards for Safety and Security**: Addressing cybersecurity threats by transferring knowledge from other research areas to aviation.

E. SESAR program

The term SESAR refers to **two distinct entities**: the SESAR Joint Undertaking (SJU) and the SESAR Deployment Manager (SDM), which serve distinct yet complementary roles within the SESAR program. The **SJU is responsible for managing the research** and development phase, focusing on the creation, validation, and refinement of innovative air traffic management (ATM) solutions. It coordinates activities among public and private stakeholders to ensure the alignment of technological advancements with the strategic goals of the European ATM Master Plan. In contrast, the **SDM oversees the deployment phase**, ensuring that the validated solutions developed by the SJU are effectively implemented. Its role is to manage the large-scale integration of these technologies into operational use, coordinating with air navigation service providers, airports, and airlines to align local implementations with the broader SESAR objectives. Together, **the SJU and SDM bridge the gap between innovation and practical application**, driving the modernization of Europe's ATM systems. When referring to SESAR program in the next text, the reference will be for SJU.

a. Evolution, structure, and objectives of the SESAR program

The management of efforts to establish the SES, initially entrusted to EUROCONTROL, was deemed inconclusive by European policymakers. They identified significant inefficiencies in European ATM and recognized the need for a more unified and strategic approach. While EUROCONTROL played a central role during the initial stages, the European Union assumed a more proactive role in tackling these challenges by establishing the EASA in 2002 to centralize aviation safety regulations, followed by the launch of the SESAR project in 2004 to modernize and harmonize air traffic management systems across Europe (Bolić et al., 2021). SESAR was launched as the technological and operational pillar of the SES initiative, with the overarching goal of modernizing and harmonizing ATM systems across Europe to improve efficiency, safety, and environmental performance.

SESAR's development followed a phased approach:

- **Definition Phase** (2005 - 2008): Led by the SESAR Consortium, this phase resulted in the first European ATM Master Plan, providing a roadmap for research, development, and deployment activities necessary to achieve SES objectives.
- **Development Phase** (2008 - 2016): This phase, managed by the SESAR Joint Undertaking (SJU), focused on the creation, validation, and refinement of ATM solutions, addressing operational and technological challenges.
- **Deployment Phase** (2014 - Present): Overseen by the SESAR Deployment Manager (SDM), this phase ensures the coordinated implementation of validated solutions to modernize Europe's ATM systems.

The primary objective of SESAR (specifically the SJU) is to analyze and evaluate the implementation and development phases of the program to optimize the management of European air traffic. This is achieved through a systematic study of historical data, current trends, and future projections related to air traffic, with a particular focus on technological innovations and operational improvements. The tasks necessary to achieve this objective, as outlined in the SESAR 3 Joint Undertaking regulation (e.g. Article 143), (SESAR 3 Joint Undertaking, 2022), include:

- Coordinating SESAR operations by implementing and pursuing the objectives of the European ATM Master Plan.
- Organizing, coordinating, and monitoring the projects and works financed during the SESAR development phase.
- Deliver solutions to support development and research efforts involving ANSPs, airspace users, professionals, industry stakeholders, and research institutions.
- Ensuring the involvement of both civil and military aviation stakeholders.

- Coordinating large-scale demonstration activities to validate and implement solutions.

To achieve its objectives and carry out the tasks, five strategic areas of operation have been identified:

1) Provide strategic steering to the DES program (keep connection between development and deployment)
2) Deliver exploratory research (categorized into the element/projects that deal with relevant fundamental scientific subjects)
3) Deliver industrial research and validation
4) Facilitate an accelerated market uptake of SESAR Solutions
5) Deliver SESAR outreach (Cooperation, synergies and cross cutting themes and activities).

The SESAR program relies on structured funding mechanisms to support its research and innovation (R&I) activities, ensuring the development and deployment of advanced ATM solutions. These funding mechanisms are tailored to address the different phases of the R&I lifecycle, from fundamental research to large-scale demonstrations. To this end, **three types of calls for proposals have been established**, covering distinct R&I phases:

- **Exploratory Research**: Funded through the Horizon Europe program, these calls focus on fundamental scientific research and innovation. They target early-stage projects that explore new concepts, technologies, and methodologies critical to shaping the future of air traffic management.
- **Industrial Research and Validation**: Also supported by Horizon Europe, these calls address more advanced research and development projects. They include fast-track innovation initiatives to accelerate the maturation and adoption of validated solutions, ensuring their readiness for operational deployment.
- **Digital Sky Demonstrators**: These calls are funded through the CEF program and managed by the European Climate, Infrastructure and Environment Executive Agency (CINEA) in close cooperation with SESAR 3 JU. They focus on large-scale demonstration activities to test and validate solutions in real-world environments, bridging the gap between research and deployment.

b. Introduction to the SESAR programmatic plans

The SESAR program operates within a structured framework consisting of **three main plans**, each corresponding to a specific temporal interval to guide its research, development, and deployment activities. These plans ensure that SESAR’s objectives remain aligned with the overarching goals of the SES initiative while adapting to evolving technological advancements, operational needs, and environmental challenges.

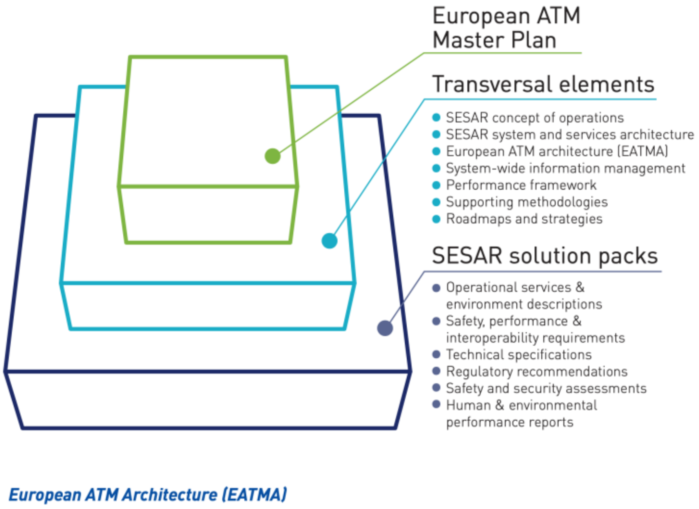


Figure 37. Source European ATM Master plan (SESAR, 2020b)

The priorities of SESAR are indicated in three main plans:

- **European ATM Master Plan** is the cornerstone of SESAR's strategic framework, outlining the priorities for development and deployment required to achieve the objectives of the SES (Figure 37). It provides a roadmap that bridges the gap between regulatory directives and the research activities undertaken by SESAR. By transferring these priorities to the SESAR Joint Undertaking (SESAR JU), the plan ensures that research and development activities focus on delivering practical, innovative solutions. These priorities are often defined in consultation with stakeholders from the European Civil Aviation Conference (ECAC), reflecting a collaborative approach to shaping Europe's air traffic management (ATM) landscape (SESAR, 2020b).
- **Multiannual Work Programme** (MAWP) is designed to operationalize the high-level objectives of the Master Plan over a longer timeframe. The current version, covering 2022-2031, identifies both general and specific objectives, ensuring a strategic approach to achieving SESAR's goals. The MAWP is particularly focused on aligning SESAR's research and innovation activities with Europe's broader priorities, including sustainability, digital transformation, and resilience in ATM systems. It serves as a guiding document for SESAR JU's initiatives, helping to structure and prioritize the research projects and development efforts required over the decade (SESAR 3 Joint Undertaking, 2022).
- **Bi-Annual Work Programme**: provides a more granular and time-specific outline of SESAR's research and innovation (R&I) activities. Designed to complement the higher-level Master Plan and MAWP, this plan focuses on short-term objectives and actions, ensuring that SESAR's activities remain agile and responsive to emerging needs and reflect evolving priorities based on research outcomes. For example, the 2022-2023 version, highlighted the strategic R&I objectives linked to the "Nine Flagships" defined in the MAWP. These flagships aim to accelerate the delivery of an inclusive, resilient, and sustainable DES through focused research and innovation efforts. The Bi-Annual Work Programme emphasizes key themes such as accelerated development, inclusivity, resilience, and sustainability,

reflecting SESAR's commitment to meeting Europe's evolving aviation needs. It should always be alongside the upper-level plans, to ensure alignment with the long-term vision and priorities (SESAR Joint Undertaking, 2022a).

c. *European ATM Master Plan*

Given that the goal of the DES is to achieve high levels of automation, it is unsurprising that the European ATM Master Plan outlines a progressive increase in automation for flights. This ambition naturally includes drones, as they represent a growing component of the airspace ecosystem (SESAR, 2020b). In reviewing these documents, specific elements were identified as particularly relevant to the objectives of this research. These key points include:

- The **U-Space** creation (Point 4) and **virtualization** of services (Point 5): Both elements are essential for establishing a scalable and efficient drone integration framework.
- **Dynamism** and **optimization** (Point 7): These elements are fundamental for supporting the development of U-Space and ensuring that the entire flight environment is integrated and communicative. This integration is particularly critical at junctions where different levels of airspace interact (e.g., upper and lower airspace).
- **Trajectory-based** operations (TBOs - Point 8): Originally applied to manned aircraft, this concept can be extended to U-Space, enabling the calculation of the shortest and most efficient path between two nodes.

However, implementing pure TBOs faces challenges: it may often be possible to move between two nodes using the geodetically shortest path due to various areas with flight restrictions. Predefined corridors are expected to serve as the means to comply with these limitations. This highlights how identifying suitable locations for such corridors, anticipating no-fly zones, and determining efficient routes become crucial research objectives.

To achieve effective trajectory management as outlined in the Master Plan under Point 8, along with 4D planning and virtualization, other factors come into play, such as the sharing of data between various decision-making entities both national and international, military and civilian. This collaborative approach is essential to plan the optimal trajectory and ensure effective control.

TBOs imply predictability and accuracy of trajectory. **This will be enabled by a "data-driven" approach**, **sharing data** through a platform known in traditional aviation as System Wide Information Management (SWIM). Through SWIM, ground-based entities like, Flight Operations Centers (FOCs), Network Manager, Airports and ANSPs will share trajectory information. Regarding the operational environment, service providers would be able to work together as if they were a single organization, optimizing both airspace and services provision according to traffic patterns.

Optimization revolves around the concept of the shortest feasible route from departure to destination. Achieving this high level of connectivity and automation between the various ATM components. An obstacle remains the fragmentation caused by national borders, hindering seamless operations and uniform activities across different national aviation agencies (both civil and military).

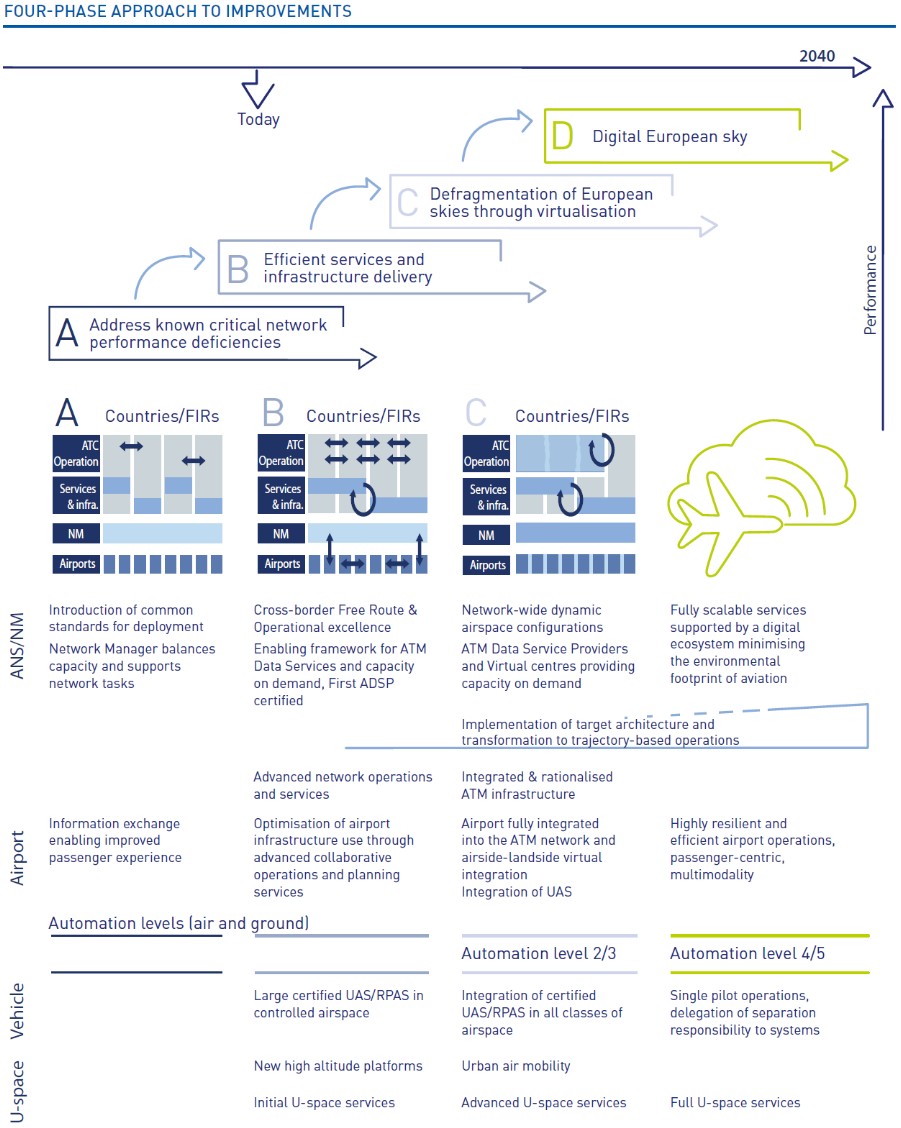


Figure 38. Four-phase approach (SESAR, 2020b)

The goal is the creation of an ATM network that "...**will become more modular and agile, allowing air traffic and data service providers, regardless of national borders, to connect their operations where necessary, supported by a wider range of services**" (SESAR, 2020b). Modernization must also address new technological developments. To adapt to new needs, the integration of very low-level Airspace (VLL) operations is expected, facilitating routes especially for highly automated flights.

One of the main problems is the **impossibility of seeing flights as a single flow due to national borders**. Moreover, capacity growth will become increasingly complex and costly for both ATM and airport; airport capacity expansion involves long delivery times and complex planning consultation, making it a priority issue. Finally, ATM configurations often **driven by national boundaries rather than traffic flows**, lead to significant variations in Air Traffic Control Officer (ATCO) workload and complex capacity management (Figure 38).

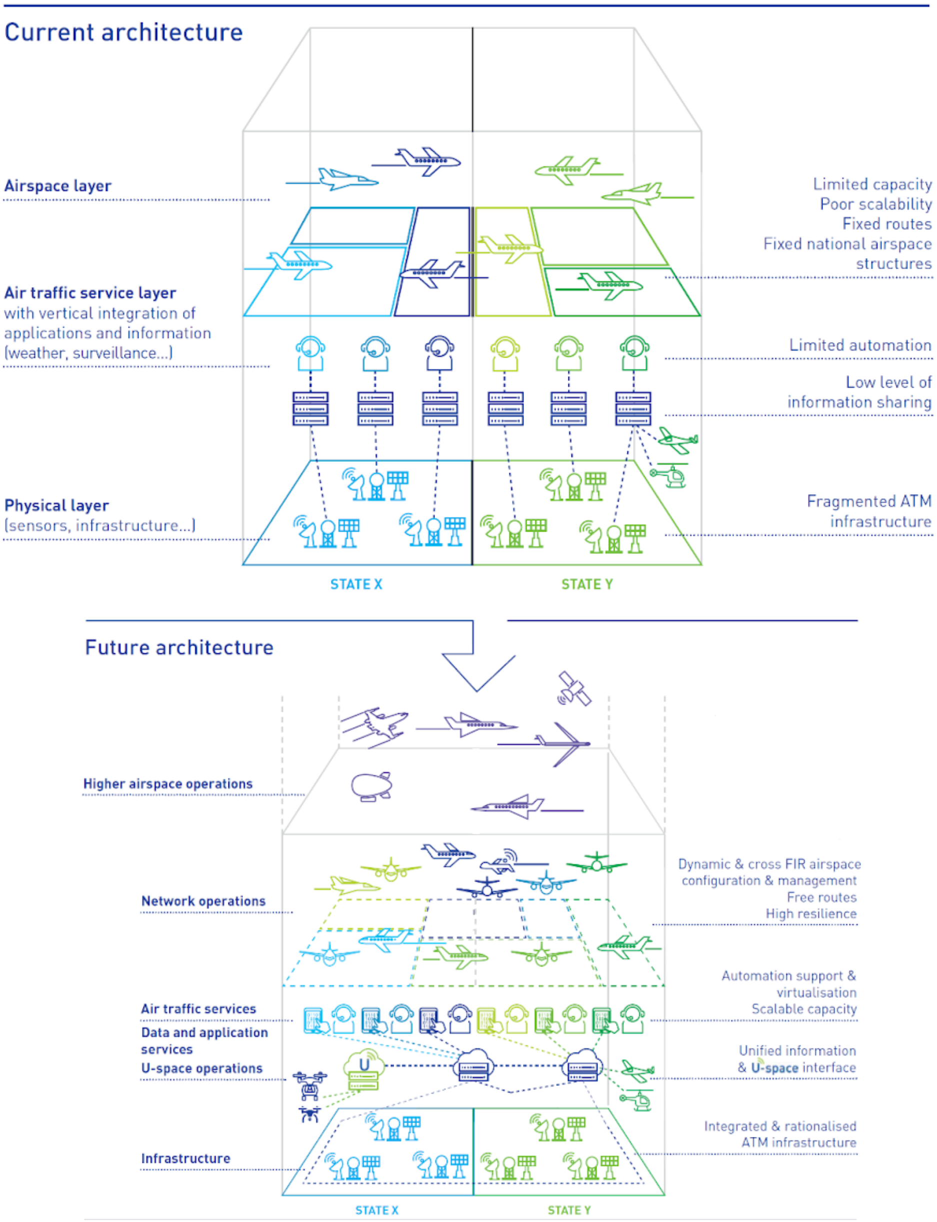


Figure 39. Present and future airspace architecture (SESAR, 2020b)

Another advantage of 4D planning and virtualization is the increased efficiency and, consequently, enhanced flight sustainability. As stated in the Master Plan: "*...it is necessary to accelerate the modernization of the air infrastructure to offer greater capacity and capability, making it more resilient to future traffic demands and more adaptable through more flexible ATM procedures. Additionally, reducing the impact of aircraft noise and improving air quality will remain priorities around airports*".

In addition to 4D planning, the gradual integration of deconfliction measures is proposed. As traffic density increases, relying solely on human action becomes insufficient. Machine intervention becomes essential, leveraging computational capabilities for rapid, parameter-based decisions. However, humans oversight and comprehension remain crucial, necessitating simplified interfaces and structured airspace. The Master Plan provides specific deconfliction scenarios based on SESAR's automation levels (Figure 39).

The purpose of virtualization is to partly simplify human understanding of machine-made and assist controllers in verifying their appropriateness. A key component, particularly for corridors, is the concept of minimum separation. Concept like the “bubble” method, explored in projects, such as BUBBLES, define protected zone around the drone to facilitate deconfliction (Balbastre Tejedor et al., 2022). However, consensus on the best approach to minimum separation is still developing with different projects, proposing varying interpretations of corridors.

Additionally, projects like this one aim to develop a risk model based on several factors, the most significant being the acceptance of a specific number of fatalities depending on whether the operations occur in populated or unpopulated areas. The document explicitly highlights the virtualization process to identify conflicts during flight:

Figure 40. Bubble deconflictualization process (Balbastre Tejedor et al., 2022)

The BUBBLES project also conceptualized a pre-flight strategic deconfliction process illustrated below (Figure 40 and 41), complementing the in-flight tactical phase.

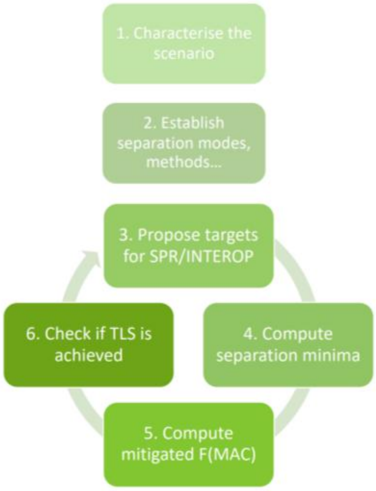


Figure 41. Bubbles pre-deconflictualization process

The Master Plan divides the development phases of the SES from A to D (Figure 38). Each phase entails an increasingly high level of automation, with D corresponding to complete process.

Summarizing the main objectives from the plan relevant to this research:

- *“...accelerate the digital transformation of aviation infrastructure to* ***accommodate aircraft, which are set to become more autonomous, more connected and smarter***”,
- Implementation of the SJU increasing the level of collaboration and automation,
- Efficiently and safely place drones for all classes in the sky, especially in the VLL,
- *“...**improvement of air transport infrastructure and a performance-oriented communication, navigation and surveillance** (CNS) infrastructure*” with a final target of 2030,
- “**The definition of Phase D of the Master Plan**, for the delivery by 2040 of a fully scalable system capable of managing both manned and unmanned aviation”.

These **goals will be achieved thanks to a “data-driven” approach**. Information gathered, especially from demonstration projects, will be crucial to understand the effectiveness of proposed solutions. Performance ambitions, introduced in 2012, are measured using **Key Performance Areas** (KPA) categories:

- capacity,

- safety,
- environment and
- cost efficiency.

The measurement of KPAs is carried out with the “Key Performance Indicators” (KPIs).

d. Multiannual work programme (SESAR 3 Joint Undertaking, 2022)

The Multiannual Work Programme (MAWP) delves more specifically into the space reserved for drones, particularly U-space, in Section D, where it focuses on “supporting safe and secure drone operations in Europe.” The development of U-space is divided into four levels of advancement, ranging from U1 to U4 (Figure 42):

- **U1** services are described as “**ready and available now**”, providing basic functionalities to support drone operations.
- **U2** services are deemed “**technically possible and can be realized today**”. These include features like geofencing and identification, which are already available. However, a lack of standardization has resulted in variations in performance, highlighting the need for further harmonization.
- **U3 are advanced services that support complex operations in dense areas**; include capacity management (Dynamic Capacity Management) and assistance for conflict detection/tactical conflict resolution, enabled by automated DAA (Detect and Avoid) functions and more reliable communications.
- **U4 full high-tech services** and completely integrated with crewed aviation/ATM, delivering the full operational capability of U-space thanks to very high levels of automation, connectivity, and digitalization, both onboard and on the ground.

Despite these advancements, there are still gaps in capability and it is still a long way to go to U4. For instance:

- Challenges remain in sharing information with other stakeholders.
- Managing the operation of multiple drones simultaneously is not yet fully resolved.

Additionally, the delivery of U-space services has been characterized by underperformance in connectivity and interoperability, which poses a significant barrier. This is especially problematic because many business models rely on drones conducting long-distance operations, commonly referred to as BVLOS (Beyond Visual Line of Sight).

SESAR’s R&D program identifies, evaluates and validates technical and operational concepts in simulated and real-world operating environments. R&D will help develop Phase C by defragmenting the sky and virtualizing it by processing data and the solutions for its development must come mainly from R&D. The implementation of “...services requires that all parties are connected to a high bandwidth low latency network infrastructure based on Internet protocol (IP)” through the CNS. Critical points in the performance of services will remain at airports.

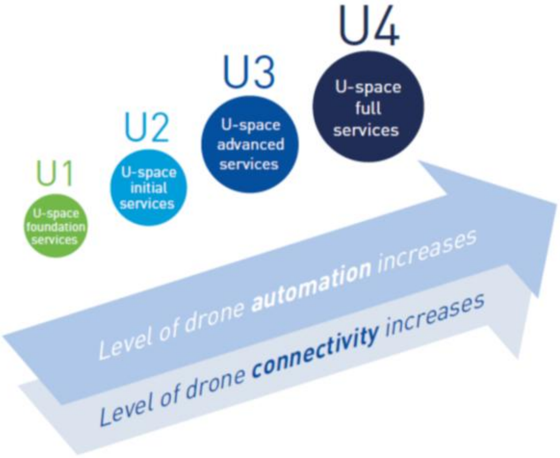


Figure 42. The four levels of U-space development

The solutions can be summarized in 4 key groups (key features):

- High-performing airport operations,
- Advanced ATS (Air Traffic Services),
- Optimised ATM network services,
- Enabling aviation infrastructure

The need to rationalize airspace arises from the expectation that, in the future, an increasing number of aerial vehicles will be in flight. Managing flight density will require the development of safe and efficient air traffic systems that also minimize environmental impact. The focus will extend beyond the safety of individual aircraft to include the security of systems connecting various ATM components, particularly in the realm of cybersecurity.

These systems must be resilient to adverse factors, such as communication failures, ensuring continuity and reliability. The most complex challenge lies in the integration of manned and unmanned devices within the same airspace, requiring seamless interaction and coordination.

The overarching purpose of these plans is to establish a common, pre-negotiated vision of airspace operations. This framework will facilitate easier decision-making without the need for continuous consultation with individual stakeholders for every operational choice.

Nine “Essential Operational Changes” (EOC) - Through a service-based approach, CNS services will be specified through contractual relationships between customers and providers, with a clearly defined, European-wide set of harmonized services and level of quality. The progressive introduction of a service-based approach to CNS will enable the virtualization of ATM (consisting in decoupling the provision of ATM data services from ATS) and will enable ANSPs to make implementation choices about how new services are provided. It will also provide a better environment for the integration of new CNS services, such as space-based automatic dependent surveillance broadcast (ADS-B) and satellite communications.

The Nine R&I SRIA flagships that have to be developed in the interval 2021-2027 are:

1) Connected and automated ATM
2) Air-ground integration and autonomy

3) Capacity-on-demand and dynamic airspace
4) U-space and urban air mobility
5) Virtualization and cybersecure data-sharing
6) Multimodality and passenger experience
7) Aviation Green Deal
8) Artificial intelligence (AI) for aviation
9) Civil/military interoperability and coordination.

I report here some schematic points as within the MAWP related to the research theme of this work:

- **Point D.2.1: Is U-space fully covered?** The U-space services were researched, developed and demonstrated in a variety of environments (urban, rural, suburban) and airspace (controlled, uncontrolled), taking into account numerous types of flights (manual, partly automated, fully automated, mixed) and operations (visual line of sight (VLOS), beyond visual line of sight (BVLOS), VLL, above VLL), the density of drones, the complexity of the traffic (e.g., simultaneous flights) and the complexity of the service provision (e.g., multiple service providers). This led to a high number of possible service combinations, the analysis of which provides a picture of the coverage of the services researched by the projects.
- **Point D.2.2: Foundation services (U1).** An analysis of the individual reports shows that U1 services were fully addressed by the projects. For example, the registration assistance service was demonstrated by the 'D-flight internet of drones environment' (DIODE) project, with use cases involving one single U-space Service Providers (USSPs), which corresponds to a low-complexity environment.
- **Point D.2.3: Initial services (U2).** Due to activities taking place in parallel, the demonstration projects based their work on the CONOPS (first edition - June 2018), while the current analysis considers the latest CONOPS (third edition - September 2019) as the reference. It is therefore not surprising to see that U2 services introduced in this edition (e.g., citizen reporting) are only partially covered by the projects. This is also the case for other services first introduced in the third edition, such as the population density map or electromagnetic interference information services.
- **Point D.2.6: Key milestones**
    - Delivering a concept of operations for U-space,
    - Showing the feasibility of multiple service provision (promotion of an open drone market where service providers can operate both in cooperation and in competition),
    - Supporting strategic deconfliction (initial trials for strategic deconfliction for a limited number of operational drones,
    - Increasing situational awareness through information exchange (standard protocols to exchange data and serves as a flight information management system… open platform and SWIM, the solution collectively and cooperatively manages all drone traffic in the same geographical region.),
    - Focusing on tracking and monitoring (performance of multiple collision avoidance and tracking systems),

  - Addressing the interface with manned aviation (vehicles need to be visible each other's, especially in the VLL),
  - Harnessing results from non-U-space SESAR research project
- **Point D.3: Future research and development needs**
  - Urban air mobility (enables on-demand, highly automated, passenger- or cargo carrying air transport services… where aviation is often highly regulated today),
  - Air traffic management / U-space convergence (collaborative approach between all actors with the objective of ensuring an efficient interface between U-space and ATM. A fully integrated ATM/U-space ecosystem without segregation between U-space and ATM operations also requires the setting up of common fundamental enablers),
  - Advanced U-space services (enable UAM missions in high-density and high-complexity areas),
  - Strategic/tactical conflict resolution,
  - Detect-and-avoid solutions (cooperative and non-cooperative) (capability of ensuring aircraft and obstacle avoidance through the use of appropriate ground-based or on-board equipment, including DAA / collision avoidance logic),
  - Mobile telecommunication infrastructure and its suitability for U-space ("… current commercial mobile networks are typically built and optimized for users on the ground. …This will also require developing new common business models for the cooperation between U-space and mobile telecommunication service providers"),
  - Multiple U-space service providers (exchange of data between multiple USSPs and enable this vision of a federated U-space with multiple USSPs),
  - Geofencing
- **Point D.6: U-space services catalogue**
  - D.6.1 Identification and tracking
    - D.6.1.1 Registration and registration assistance services
    - D.6.1.2 Remote identification and e-identification service
    - D.6.1.3 Tracking, position report submission and surveillance data
  - D.6.2 Airspace management and geofencing
  - D.6.3 Mission management
    - D.6.3.1 Operation plan processing, operational plan preparation and optimization and risk-analysis assistance services
    - D.6.3.2 Dynamic capacity management service
  - D.6.4 Conflict management
    - D.6.4.1 Strategic and tactical conflict resolution services
    - D.6.4.2 Emergency management service
    - D.6.4.3 Accident and incident reporting and citizen reporting services
  - D.6.5 Monitoring
    - D.6.5.1 Monitoring and traffic information services
    - D.6.5.2 Legal recording and digital logbook services

    - D.6.5.3 Navigation and communication infrastructure monitoring services
  - D.6.6 Environment
    - D.6.6.1 Weather information service
    - D.6.6.2 Geospatial information, population density map, electromagnetic interference information, navigation coverage information and communication coverage information services
  - D.6.7 Interface with air traffic control

e. Bi-annual work programme (SESAR Joint Undertaking, 2022a)

Indicates the strategy for the implementation of the SESAR project at the application level. It is promoting the SESAR 3 JU and showcasing 2020 results through events. It provides guidance to members and projects (beneficiaries) and monitors their compliance with obligations and commitments to communicate, disseminate and exploit project outcomes. It is ensuring the effective and efficient financial, administrative, legal and corporate management of the SESAR 3 JU through the implementation of internal control principles and systematic quality assurance. The development of the strategic objectives is divided by the program into 3 financing options:

- **Exploratory research** (Horizon Europe funding)
- **Industrial research and validation** (Horizon Europe funding)
- **Digital Sky Demonstrators** (CEF funding managed by CINEA)

In addition, it must plan the following activities:

- **Supervision of ongoing projects under the exploratory research**
- **Supervision of ongoing projects under industrial research and validation** (IR) and very large-scale demonstration (VLD)
- **Completion of release 11 in line with the plan published** in 2020 and execution of release 12 based on the plan published at the end of 2021
- **Supervision of ongoing projects under the open call for proposals** (VLD Open 2 (H2020-SESAR-2020-1)), management of related grant agreements and closure of these grants.

The two branches of industrial and exploratory research are divided into two:

- **ATM excellent science and outreach**: help to develop emerging technologies and methods to the level of maturity required to feed into the applied research conducted by the JU (automation and autonomy, complexity, data science and information management, environment and meteorology for ATM, performance, economics, legal and regulation, ATM's role in intermodal transport, CNS for ATM),
- **ATM application-oriented research**: Link the results of ATM excellent science and outreach with the higher maturity ATM research performed with the wider research community.

f. Phases for requesting authorization to fly

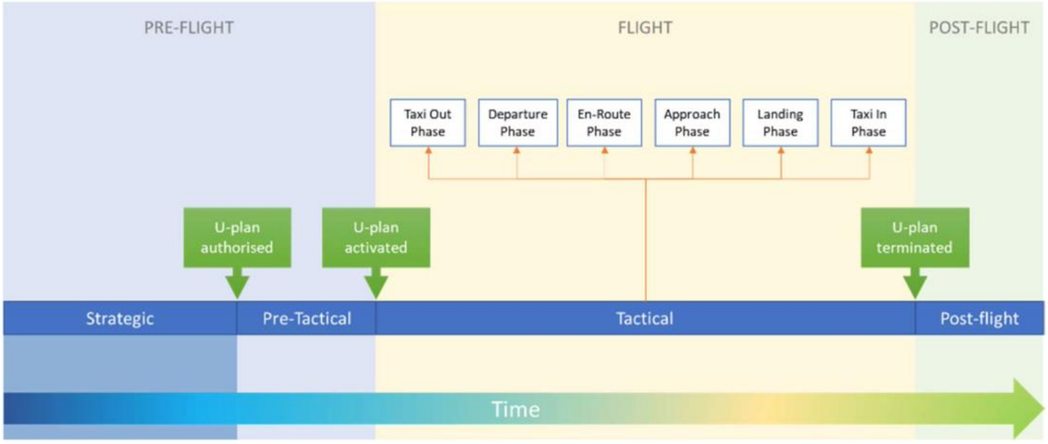


Figure 43. Source: CORUS

The authorization process for drone operations is structured across four progressive phases, each corresponding to a different stage in the planning, execution, and closure of the flight (CORUS-XUAM, 2022). These phases - strategic (long-term), pre-tactical, tactical, and post-flight (Figure 43) - reflect a layered and dynamic approach to airspace management, especially in the context of U-space implementation. This framework allows for the integration of safety, capacity optimization, regulatory compliance, and real-time responsiveness, which are essential in high-density or complex operational environments.

- **Strategic (long-term)**: This initial phase encompasses all preparatory actions that enable future operations, often months or years in advance. It includes airspace design and redesign, registration of UAS operators, and type approval of specific UAS models. Operators must ensure that their aircraft are certified according to applicable technical and safety standards and that they are eligible to access defined airspace blocks. Additionally, this phase involves acquiring operator licenses and participating in long-term capacity planning, both at the fleet and airspace levels. This phase focuses also on mission planning and risk assessment. One of the core activities is the Specific Operational Risk Assessment (SORA), a methodology developed by JARUS to classify the mission within an operational category and to define the associated mitigations. Additional tasks include requesting airspace access or overflight authorizations, selecting and configuring the drone and crew, and establishing contingency protocols. Priority rules may also apply - for example, giving precedence to UAVs conducting critical services. Furthermore, vertiport compatibility must be verified, including aspects like aircraft specifications and the availability of Final Approach and Take-Off area (FATO) areas. Finally, the flight plan (U-plan) must be optimized and submitted for authorization.
- **Pre-tactical phase:** The pre-tactical phase takes place shortly before the flight and focuses on conflict detection and resolution, as well as demand-capacity balancing. During early stages of U-space implementation, the U-plan can be authorized only if it is free from conflicts with other operations. Tools such as “Reasonable Time To Act” (RTTA) are applied to resolve anticipated conflicts dynamically and to manage airspace capacity considering evolving constraints. This phase helps to

address uncertainties that may not have been captured during the strategic phases, ensuring smoother coordination among operators.

- **Tactical phase (real-time)**: This phase begins with the activation request and continues through the entire flight operation. It includes the start of tactical U-space services and real-time monitoring of the flight's conformity with the authorized operational plan. In the event of non-conformance, contingency protocols are triggered. Real-time updates to the operational plan may be required in response to changing conditions (e.g., weather, emergency airspace restrictions), and the system must be capable of adapting dynamically. The tactical phase concludes with the termination of the flight and the formal end of tactical services.
- **Post-flight phase**: After the flight, operators are responsible for logging relevant data, submitting reports if required by regulations, and carrying out performance assessments. This phase also includes the maintenance and possible recalibration of equipment, ensuring that future operations remain safe and compliant. The post-flight analysis contributes to the continuous improvement of operations and feeds into the broader ecosystem of performance monitoring in U-space environments.

g. Relevant Projects for the research project

Several SESAR projects have demonstrated foundational U-Space services, providing key insights relevant to this thesis. For example, some projects address services that were not featured in the first CONOPS, such as geospatial information service. The Finnish-Estonian "Gulf of Finland" (GOF) very large U-space demonstration project (GOF U-space) and the "European UTM test bed for U-space" (EuroDRONE) project demonstrated this service, though by addressing some cases involving only one unique USSP. UTM stands for Unmanned Traffic Management. The scenarios typically involved partially automated flights in controlled airspace and fully automated flights in uncontrolled VLL airspace.

When considering the U2 (Figure 42) block of services (initial services for U-space), demonstration projects like DIODE, "Demonstration of multiple U-space suppliers" (DOMUS) and EuroDRONE provided a significant coverage. However, some services were only partially covered, such as emergency management. Furthermore, many of the investigations were limited to uncontrolled airspace, in VLLs, and with only one USSP at a time.

Specific infrastructure-related services were also investigated. Research was done on the communication and infrastructure service by EuroDRONE, covering and involving scenarios fully automated flights in uncontrolled airspace and one USSP.

Meanwhile, DOMUS and EuroDRONE addressed the navigation infrastructure service, but again, with scenarios covering only uncontrolled airspace. This highlights that the integration and management of services within controlled airspace requires complementary activities and further research.

F. Advanced Air Mobility (AAM) and Urban Air Mobility (UAM)

Figure 44. Urban Air Mobility Venn diagram (CORUS-XUAM, 2022)

The transition toward a digital, interconnected sky is accelerating the emergence of new air mobility models. In this context, the terms Advanced Air Mobility (AAM) and Urban Air Mobility (UAM) are often used complementarily: AAM is the broader umbrella, encompassing passenger and cargo transport - along with various other missions - at urban, regional, and interregional scales; UAM is a subset of AAM focused on air transport systems in and around urban environments. Figure 44 illustrates this conceptual overlap: the UAM area arises at the intersection of urban airspace, crewed aircraft, and uncrewed aircraft. This representation highlights how UAM requires solutions capable of accommodating heterogeneous platforms in the same urban space, balancing operational, safety, and social acceptability requirements.

a. Unmanned Aircraft Systems (UAS) role in transport: challenges and opportunities

Unmanned Aerial Systems (UAS), commonly referred to as drones, present a transformative opportunity for mobility, yet their implementation also poses significant challenges. These opportunities and challenges span both the transport of goods and people (resume in Table 1 and 2). When referring to passenger transport, the focus lies on the potential to accelerate mobility using sustainable means. Conversely, for goods, drones are primarily considered for small-package delivery, with their potential benefits extending to both urban and remote areas.

Drones have the potential to revolutionize transportation by *reducing congestion* in urban environments and providing *faster, more direct routes*. According to (Bauranov et al., 2021) UAM represents a major advancement that demands a shift from traditional air traffic management systems, such as those defined by the ICAO, to new approaches tailored to drone traffic. As we have seen, these new systems must account for dynamic separation requirements and corridor-based operations, which could optimize airspace usage while maintaining safety. Drones also offer opportunities for integrating *geofencing* technologies to dynamically adapt to environmental and urban constraints. This adaptability is particularly relevant in adverse weather conditions or when specific urban zones require restricted access due to safety or heritage preservation, a significant limitation for today's electrically powered drones. One of the main advantages of drones, particularly in urban environments, is their ability to take off and land vertically. The goal is to enable delivery services directly to individuals. However, as highlighted in the article by Poikonen and Campbell, even companies like Amazon have had to revise their short-term plans (Poikonen et al., 2021). Hybrid drones have also been developed; these drones take off vertically, and once they reach altitude and horizontal speed, they transition to flying like a conventional airplane.

From an economic perspective, (Garrow et al., 2021) emphasize the potential *cost benefits* of drone delivery, particularly in suburban or inter-city contexts. While current costs are higher than traditional road transport, technological advancements are expected to reduce drone flight costs by up to 60%, making them competitive with conventional means soon (Ploetner et al., 2020). This *cost reduction*, coupled with time savings, makes drones a viable option for huger segments of the market. Another key aspect emphasized is the necessity of *integrating ground transportation* to access vertiports, particularly for passenger drone services. A critical factor for the success of such systems will be the speed and efficiency of the transfer between ground vehicles and aerial transport. Achieving this requires careful planning of vertiport locations, which must involve dialogue with local authorities (ENAC, 2022). Unlike traditional aviation, which typically has localized impacts (Damiani et al., 2012), drones are expected to have widespread effects on urban and suburban areas. Therefore, it will be essential to engage in consultations with stakeholders, review existing planning tools, and adapt them to accommodate the unique requirements of this emerging transportation mode. It is important not to consider drones as a complete replacement for other modes of transportation, but rather as tools to be employed as a completion, where they provide a clear advantage or where "greater advantage in doing so or where no alternative exists" (Poikonen et al., 2021). In fact, the concept of *combining different modes of transport* has also been explored. For instance, a truck could carry a drone to a point where it is more convenient, after which the drone takes over to complete the journey (Di Stefano et al., 2018).

However, the deployment of drones is not without challenges. *Infrastructure, regulation, technology, and social acceptance* remain significant barriers. As (Lineberger et al., 2019) argue, the absence of adequate *vertiport infrastructure*, unclear *regulatory frameworks*, and concerns about *safety, privacy, and noise* are among the most pressing issues. Addressing these aspects, particularly safety and privacy concerns, is essential for gaining public acceptance, which depends on effective collaboration between governments, industry leaders, and local communities. Studies like those by (McKinsey & Company, 2021), a study funded by the EU to assess the feasibility of drone implementation, and (Yedavalli et al., 2019) highlight public apprehensions about *safety*, particularly regarding the risk to individuals on the ground. One of the key challenges highlighted, particularly by manufacturers, is the implementation of vertiports or VTOL (Vertical Take-Off and Landing) infrastructure. This is primarily due to the lack of clear regulations. While the EASA has published guidelines, these currently focus only on piloted vehicles and do not address unmanned aircraft systems (EASA, 2022). This *regulatory gap*, coupled with previously discussed issues such as societal acceptance, safety concerns, and the absence of a structured airspace framework designed to accommodate drones, significantly complicates the straightforward development of such infrastructure.

Table 6. Challenges of UAS in Transport

Category	Specific Challenge	Description
Social & Human	**Social Acceptability**	A primary barrier, highly dependent on public perception.
	Public Concerns	Dominated by fears over **safety** (risk to people on ground), **privacy**, and **noise pollution**.
	Geographic & Demographic Divide	Acceptance varies significantly by location (e.g., Southern Europe vs. NZ) and age (generational divide).
	Psychological Barriers	User hesitation towards new models, such as ride-sharing services.
Regulatory & Policy	**Regulatory Gaps**	Lack of clear, comprehensive frameworks (e.g., EASA rules only cover piloted aircraft).
	Airspace Management	Need for new Air Traffic Management (ATM) systems tailored for drone density.
	Localized Approaches	A "one-size-fits-all" policy is insufficient; localized planning is required.
Infrastructural	**Vertiport Infrastructure**	Significant lack of necessary take-off and landing infrastructure.
	Urban Planning	Difficulty in planning and siting vertiports, requiring dialogue with local authorities.
	Ground Transport Integration	Need for efficient, fast transfers between ground vehicles and vertiports.
Technical & Operational	**Noise Pollution**	Reported as one of the most disruptive factors for the public.
	Safety & Reliability	Ensuring safety in dense traffic; managing GPS inaccuracies in urban canyons; need for redundancy.
	Technology Limitations	Current limitations related to adverse weather and battery life.
Economic & Adoption	Initial Costs	UAM operations are currently more expensive than ground-based alternatives.
	Adoption Factors	Adoption is heavily influenced by socio-economic status (income, education) and network density.
	Service Efficiency	User satisfaction is highly sensitive to processing times and vehicle availability at vertiports.

Garrow et al. (2021) provides a comprehensive comparative analysis of UAM, electric vehicles (EVs), and autonomous vehicles (AVs). Their findings emphasize that UAM's adoption will be influenced by factors such as cost, time savings, and public acceptance. The study reveals that UAM operations are currently more expensive than ground-based alternatives but could become competitive as advancements in battery technology reduce costs by up to 60%. Moreover, they stress the importance of high-fidelity demand models and simulations to optimize vertiport topology and evaluate energy demands.

One of the most critical insights from Garrow et al. is the role of *socio-economic and demographic characteristics* in shaping adoption patterns. Factors such as income, geographic location, and travel habits influence individuals' likelihood to embrace UAM. For example, younger, highly educated individuals living in urban areas are identified as the most likely early adopters. (Straubinger et al., 2020) support this observation, emphasizing the importance of user profiling to design targeted services. Ploetner et al. (2020) add that UAM adoption is influenced not only by demographic characteristics but also by the density and accessibility of UAM networks. For instance, high-income households tend to dominate early demand, with urban network density enhancing adoption by increasing convenience and reducing overall travel times. Garrow et al. also address *psychological barriers* to adoption, particularly regarding ride-sharing models. Privacy concerns and perceived safety issues are highlighted as significant deterrents, potentially limiting the acceptance of shared UAM services. These findings align with Straubinger et al., who point to noise and environmental impact as additional public concerns that must be addressed to gain societal trust. Ploetner et al. expand on this by analyzing user sensitivity to processing times and vehicle availability at vertiports, showing that delays significantly impact user satisfaction and willingness to adopt UAM.

Additionally, Garrow et al. explores the role of time savings *eVOTL* as a key driver for UAM adoption. Their analysis suggests that UAM services have a competitive advantage in scenarios where rapid travel is prioritized. Straubinger et al. further elaborates on operational concepts for intra- and inter-city UAM services, highlighting the necessity of integrating these systems seamlessly into existing transport networks to avoid redundancies and inefficiencies. Both Garrow et al. and Straubinger et al. recognize the regulatory challenges facing UAM implementation. While Garrow et al. emphasized the need for a harmonized framework to address airspace management and operational safety, Straubinger et al. delved deeper into the certification processes for eVTOL aircraft and market regulation policies. Ploetner et al. reinforce these concerns by highlighting the importance of long-term planning to adapt to sociodemographic changes and future demand patterns, as demonstrated in their case study for Upper Bavaria.

The integration of UAM services into existing urban ecosystems does not depend solely on technical feasibility or regulatory frameworks - it also hinges significantly on *social acceptability* due to the public's perception of drones. Recent studies suggest that acceptance levels vary considerably by *geographic and demographic context* (McKinsey & Company, 2021). For example, research indicates that in Southern European countries, people tend to be more favorable toward the use of drones for cargo delivery and even for passenger transport via air taxis, although some concerns remain. Notably, younger populations demonstrate greater openness to these emerging technologies, highlighting a *generational divide* in acceptance trends. Similarly, (Yedavalli et al., 2019) have shown that geographic metrics reveal higher levels of openness to drones in cities like Mexico City and Los Angeles compared to more cautious responses in places like Switzerland and New Zealand. These differences carry important implications for urban planning, policymaking, and engineering strategies, suggesting that *localized approaches* are necessary when considering the deployment of UAS infrastructure.

Table 7. Opportunities of UAS in Transport

Category	Specific Opportunity	Description
Mobility & Logistics	Accelerated Mobility	Provides faster, more direct routes for passengers and goods.
	Goods Delivery	Enables small-package delivery, especially in urban and remote areas.
	Urban Decongestion	Potential to reduce congestion in traditional ground transport networks.
Operational	Vertical Take-Off/Landing (VTOL)	Allows for point-to-point delivery and landing in dense urban areas.
	Hybrid Models	Combines vertical take-off with efficient horizontal (fixed-wing) flight.
	Dynamic Adaptation	Use of geofencing to adapt to urban constraints or weather.
Economic	Long-term Cost Reduction	Projections suggest flight costs could decrease by up to 60%.
	Time Savings (eVOTL)	High value of travel time savings makes UAM competitive.
Systemic	Integration with Ground Transport	Can be combined with other modes (e.g., "truck-drone") to complete journeys.

From a safety perspective, the integration of advanced navigation technologies, such as ADS-B systems, is essential to overcome current limitations - particularly GPS inaccuracies that are common in dense urban environments (Bauranov et al., 2021). However, these solutions must be not only robust enough to manage the increasing density of drone traffic but also designed with multi-layered redundancy to ensure reliability in case of failures. This involves evaluating and leveraging existing technologies to determine their practical applicability. For instance, ground-based antennas for mobile communications could offer a viable solution. *Noise pollution* is reported as one of the most disruptive factors for individuals. Public surveys conducted by (McKinsey & Company, 2021) indicate that noise, alongside *privacy concerns*, represents one of the key barriers to societal acceptance. However, it is also essential to consider that social acceptance varies significantly depending on individuals' habits, the environments they typically live in, and their overall health conditions.

b. Definition and development of UAM

UAM in (CORUS-XUAM, 2022), one of the main projects funded by SESAR on regulating drones in the EU, is defined as air operations which are:

- above urban areas, at least for part of the flight,
- in 'U-space airspace'
- performed by a mix of traffic which includes aircraft (incapable of flying IFR or VFR, with very limited range),

- in traffic dense enough that tactical separation is needed to ensure safe operations.

"UAM is one of the most demanding use cases for U-space services: it requires exploring dependencies between services and approaching U-space as a system of services from the operational and performance perspectives.

Drone operators and UAM operations will require access to higher altitudes and areas close to commercial manned aviation (e.g., airports); at the same time, flying manned aircraft in or adjacent to VLL could make use of U-space services. A safe and equitable integration of these operations with manned aviation will require additional U3 and U4 services".

UAM refers to the integration of advanced aeronautical technologies to enable air transportation services within urban and suburban areas. It involves the use of drones and electric VTOL vehicles to provide fast, sustainable mobility solutions for both passengers and goods (Schweiger et al., 2022). UAM aims to reduce road congestion, enhance connectivity in urban areas, and offer alternatives for reaching peripheral or hard-to-access locations (Cunietti, Sammarco, et al., 2024). Key applications include passenger air taxis for quick urban transport, drone delivery services for small parcels, and emergency response operations such as medical equipment transport. The concept relies on advanced traffic management systems, such as U-Space and UTM, to regulate low-altitude air traffic. However, its development faces significant challenges beyond those mentioned previously, including considerable technical uncertainties - especially regarding how to reorganize the currently underutilized VLL airspace. It is widely recognized that replicating the existing ICAO classification used in traditional aviation is not feasible (Bauranov et al., 2021). Instead, the focus is shifting towards navigation management divided into sectors, considering that urban drone traffic is expected to grow substantially and become highly dense over certain areas.

Projects funded by SESAR, including earlier initiatives like (Metropolis II, 2021), have already explored the concept of predefined "roads" for drones, referred to as corridors. These corridors could either be static, where all drones consistently follow the same predefined route, or dynamic, where the optimal route is calculated for each drone in real time, considering factors such as safety hazards, societal acceptance, and environmental considerations. In the case of dynamic corridors, a temporary airspace allocation, referred to as a "geofence", is reserved for a limited time. Each drone would then determine its specific route based on onboard technology, the type of transport being conducted, and prevailing environmental conditions.

Similarly, (Bauranov et al., 2021) highlight the challenges of adapting airspace for UAM. Traditional airspace classifications, such as those defined by the ICAO, are insufficient for the complexities of urban environments. The study suggests transitioning to dynamic airspace management techniques, including geofencing and sector-based navigation, to manage dense drone traffic safely. However, these solutions must also address what we already mentioned societal concerns such as noise, privacy, and equity of access. The authors advocate for a planning perspective that integrates zoning, public transit, and urban development to ensure that UAM does not exacerbate existing inequalities.

c. Urban mobility policy: AAM integration mobility plans, case studies

Drones represent emerging dimensions of transportation, requiring innovative regulatory approaches and comprehensive urban planning policies for their effective integration into urban environments. This integration is not merely technical; as we have already seen many times, it deeply intersects urban planning, regulatory frameworks, public acceptance, and sustainability goals. Cities and associations of municipalities are actively developing dedicated strategies, creating exemplary models for integrating drone operations within Sustainable Urban Mobility Plans (SUMPs). This tool is designed to monitor the main commuter and passenger traffic flows, identify key transport interchanges, and plan new or existing infrastructure (Kiba-Janiak et al., 2019). One notable initiative addressing these intersections is the (UIC2 et al., 2021), developed within the EU's Smart Cities Marketplace. UIC2 (Urban Air Mobility Initiative Cities Community) pushes the implementation of UAM by developing comprehensive guidelines and mobility plans that municipalities can integrate into their existing SUMPs. The UIC2 initiative emphasizes the need of integrating the UAM into broader urban planning frameworks, outlining practical steps for urban planners such as vertiport placement, stakeholder engagement, regulatory compliance, and harmonization with existing mobility infrastructures. UIC2 cities such as Hamburg, Toulouse, and Turin have actively participated in pilot projects, offering insights into different strategic approaches (top-down, bottom-up, and greenfield) to sustainably implement UAM within urban contexts.

➢ Policy frameworks and city-level case studies

Toulouse Metropole exemplifies a top-down approach, where the local government assumes leadership in embedding UAM into broader strategic mobility plans. The city has developed a structured methodology identifying critical areas including technology, regulation, public acceptance, multimodality, energy infrastructure, data management, and physical infrastructure. Inspired by projects like (DACUS, 2022), focused on drone traffic management, and TindAIR, which provides tactical deconfliction services for U-space users through extensive real-world demonstrations.

In contrast, Hamburg employs a bottom-up approach, characterized by strong cooperation among local industries, research institutions, and public authorities within a "quadruple helix" innovation framework. Significant projects initiated in Hamburg include Medifly, aimed at transporting medical goods between hospitals using drones, and Udveo, which investigates regulatory and technical requirements for implementing a practical U-space system in complex urban airspace. Hamburg further complements these initiatives with citizen engagement platforms such as the Digital Participation System (DIPAS), enhancing public acceptance and transparency.

Similarly, Turin follows a bottom-up approach emphasizing real-world experimentation through its Torino City Lab (TCL), notably through DORALab (Drone Operations Research and Application Lab), a dedicated area for drone testing and operations. Projects in Turin focus on territorial monitoring, emergency response, last-mile logistics, and innovative use cases leveraging 5G technology. The SkyGate project specifically aims at revitalizing Turin's airport area to become a central hub for eVTOL and drone operations, facilitating transport of passengers and goods.

➢ Methodological Approaches for Infrastructure Planning

These initiatives led to the consolidation of a methodology based on the use of GIS to identify the most suitable areas for the integration of drone-related infrastructure - an approach that has since been adopted and further developed in other studies and bibliographic sources. Fadhil's thesis offers a GIS-based analytical framework to identify optimal vertiport locations, considering geographic constraints, infrastructural needs, and socio-economic factors. The study highlights that strategic vertiport placement in high-demand areas - such as city centers and intermodal transportation hubs - is crucial for maximizing operational effectiveness and public acceptance of UAM (Fadhil, 2018).

Further methodological support is provided by (Rahman et al., 2023) and (Lee et al., 2025). Both studies propose sophisticated GIS-based spatial optimization approaches, addressing operational efficiency, multimodal connectivity, and equitable accessibility. Rahman et al., specifically, integrate vertiports into existing public transit networks, demonstrating how strategic placement significantly enhances overall urban mobility. Lee et al. present a three-stage geospatial analytical framework that systematically addresses complex locational criteria for vertiports, emphasizing the necessity of comprehensive planning.

Complementing these approaches, Wang et al. (2025) underline the importance of assessing environmental and social impacts, incorporating carbon emissions, noise pollution, and public interest considerations in urban air corridor planning. Such assessments are critical for municipalities aiming to sustainably integrate UAM without compromising quality of life.

KIM et al. (2023) further emphasize user-centric considerations in vertiport planning. Their findings demonstrate how public acceptance and increased UAM usage are influenced significantly by perceived safety and multimodal accessibility, reinforcing the need for user-oriented planning criteria from the early stages.

The integration of UAM into city planning frameworks requires more than just regulatory alignment and technological readiness - it calls for a structured, evidence-based approach grounded in both policy and spatial analysis. As municipalities and regional authorities begin incorporating drones into SUMPs, a convergence is emerging between academic methodologies and practical policy frameworks. This alignment is exemplified by initiatives such as UIC2, which translate urban mobility strategies into actionable guidelines for drone infrastructure deployment. Collectively, there is a baseline where academic contributions and real-world case studies provide a cohesive foundation for planners. With a GIS-based analysis, public engagement strategies, and multimodal integration into policy design, cities are better equipped to ensure that the adoption of UAM is not only efficient and innovative, but also sustainable and socially accepted.

d. U-space architecture, principles and core services

The U-space level has not yet been completely implemented by EU countries. However, as this airspace is generally unused by most aircraft, except during ascent and descent, and lies between ground level and 120 meters (500 ft) above it, it offers an opportunity to establish a common and shared framework. This is further facilitated by the absence of fixed legislation governing this specific airspace. The task, however, remains significantly challenging. U-space is defined as: "*A set of new services relying on a high level of digitalization and automation of functions, and specific procedures designed to support safe, efficient and secure access to airspace for a large number of drones, with an initial look at very low-level operations*" (SESAR Joint Undertaking, 2022a).

➢ Architectural Principles and Core Services

Following this definition, the development of U-space is guided by clearly defined architectural principles that aim to ensure its scalability, efficiency, and safety. These principles outline the fundamental structure needed to support the integration of drones into the airspace while addressing the challenges posed by increasing traffic density and diverse operational requirements. The key U-space architecture principles include (Barrado et al., 2020):

- Service-oriented architecture,
- Modular,
- Safety-focused,
- Open,
- Standard-based,
- Interoperable,
- Technology agnostic,
- Based on evolutionary development,
- Automated,
- Allowing variants,
- Deployment agnostic,
- Securely designed.

Beyond these architectural principles, the U-space framework is operationally defined by a set of **U-space services**. These services are provided by certified U-space Service Providers (USSPs) and are mandated by the European Commission Implementing Regulation (EU) 2021/664. This regulation establishes four mandatory "core services" that form the foundation of the ecosystem, designed to ensure safety and manage traffic:

- **Network Identification:** This service ensures all UAS operating in the airspace are uniquely and securely identified, providing traceability and accountability.
- **Geo-awareness:** This provides UAS operators with up-to-date, location-specific information on airspace limitations, such as restricted zones (e.g., airports, sensitive areas), no-fly zones, and specific operational conditions.
- **UAS Flight Authorisation:** This is the service through which an operator requests permission for a specific flight. It manages the process of submitting flight plans and receiving approval (or denial) before the operation begins, ensuring compliance with airspace rules.
- **Traffic Information:** This service provides operators with real-time information about other drone traffic in their vicinity, enabling situational awareness and supporting detect-and-avoid (DAA) capabilities.

Collectively, these services are designed to manage drone traffic safely and efficiently, particularly in the high-density airspace envisioned by UAM.

➢ Airspace Structure: From ICAO to CORUS

The structure of U-space, and more broadly the VLL airspace, particularly its management, requires a complete foundational redesign compared to traditional aviation (Bauranov et al., 2021). It has become evident that for the VLL new principles of airspace division are required. The current classification system established by the ICAO, which divides airspace into seven classes - A, B, C, D, and E (controlled airspace) and F and G (uncontrolled airspace) - is inadequate for managing the high traffic density expected to grow with the increased use of drones.

Until now, the applications in U-space have been limited to giving support to operators who use drones to figure out where to fly without limitations and if there are, get permissions, where necessary. To do this the U-space airspace has been divided into three categories (CORUS-XUAM, 2022):

- **Controlled** (no flight activated),
- **Not controlled** (no permanent flight)
- **Temporarily structured** (published by the AIP)

It was then tried to find mechanisms to minimize conflicts between flights by more freedom of BVLOS flights. There will be time to test since flights will initially be very few. Initially a separation more advanced than previously indicated will be based on the position of the vehicle, implementing time and/ or distance.

The airspace volumes defined by the **CORUS** project have been incorporated into European legislation and are expected to form the foundation for future flight operations.

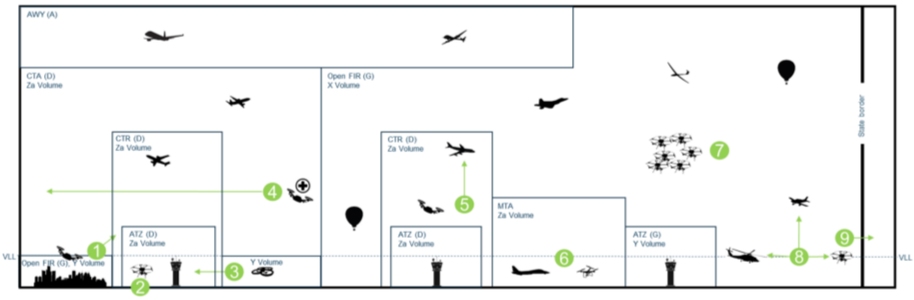


Figure 45. Structuring the sky between drones and civil aviation (AURA, 2021)

These volumes are categorized as follows (Figure 45):

- **X**: No conflict resolution service is offered (no plan and no separation service)
- **Y**: Pre-flight ("strategic") conflict resolution is mandatory (requires an approved plan and plans are deconflicted before flight)
- **Z**: Pre-flight ("strategic") conflict resolution and in-flight ("tactical") conflict resolution are mandatory (there is a tactical conflict resolution service)
    - **Za** in which Air Traffic Control (ATC) manages all the traffic. Such airspaces may exist at an airport. The expectation is that ATC will communicate with UAS through U-space services.
    - **Zu** in which U-space will provide a tactical conflict resolution service
    - **Zz** in which U-space will provide a tactical conflict advisory service

The integration of drones into airspace has not been limited to studies on how to structure the VLL airspace conducted by publicly funded programs or partially public initiatives. Efforts have also been made by individual states and private companies to address this challenge (Lineberger et al., 2019). Building on the classification developed by the International Civil Aviation Organization (ICAO), these entities have proposed their own conceptual frameworks to organize and manage flights, reflecting their specific needs and operational priorities, as exemplified by Germany (Bauranov et al., 2021).

A noteworthy example of early practical implementation is the Prototype Hierarchical UAS Traffic Management System developed in Taiwan (Lin et al., 2019). This project aimed to establish an automated traffic management system for UAVs, ensuring safe operations both below and above 400 feet, in alignment with national civil aviation regulations. The system was designed around a hierarchical architecture, integrating a communication infrastructure like ADS-B, capable of supporting multiple devices to provide wide-area coverage. The proposed UTM system included several core functionalities: it verified pilot qualifications and UAV registration before authorizing flight plans, selected the appropriate communication method, and provided real-time surveillance capabilities. A central feature was the UTM Cloud, a platform facilitating data sharing and access to UAV surveillance information. The system also incorporated a collision avoidance mechanism based on Time to Conflict (TTC) calculations between UAVs. Field tests demonstrated that the system could effectively manage UAV operations, supporting the safe deployment of automated flights within a structured airspace. As such, it offers a valuable real-world example of how automated U-space services might be structured and operated, complementing ongoing efforts in Europe and elsewhere to enable the safe, efficient, and scalable integration of drones into national and international airspace systems.

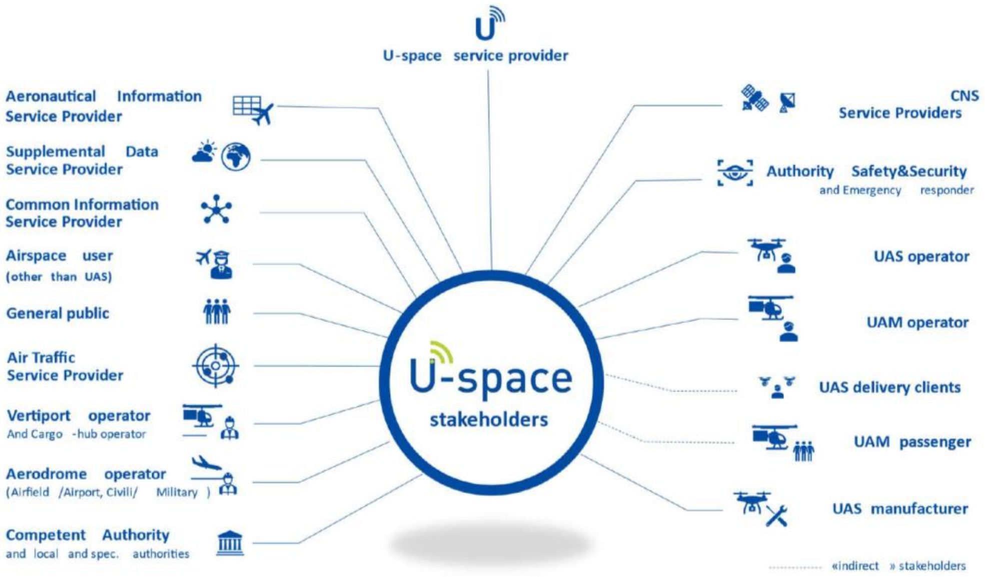


Figure 46. U-space service providers

Although U-space is still in a development phase, several concepts have already progressed to the testing phase, as demonstrated by the Prototype Hierarchical UTM System in Taiwan (Lin et al., 2019). Currently, many documents emphasize the importance of promoting synergy between the industrial and research sectors. The widespread use of drones is likely to develop more rapidly in areas with low population density, particularly in low-conflict sectors such as agriculture. However, the goal is to enable efficient, safe, and socially accepted drone operations in urban environments as well.

This leads to the concept of UAM, which represents the most advanced stage of U-space conceptualization. Due to their high population density, urban areas are expected to present the highest concentration of potential conflicts. Consequently, it is anticipated that machines will need to resolve these conflicts automatically and dynamically to ensure safe and efficient operations.

➢ Stakeholders and data exchange with SWIM

To effectively implement and manage the U-space ecosystem, it is essential to recognize the wide range of stakeholders involved in its development and operation. These stakeholders represent various roles, from regulators and service providers to operators and end-users, each contributing to the safe, efficient, and sustainable integration of drones into shared airspace (Figure 46 and 47).

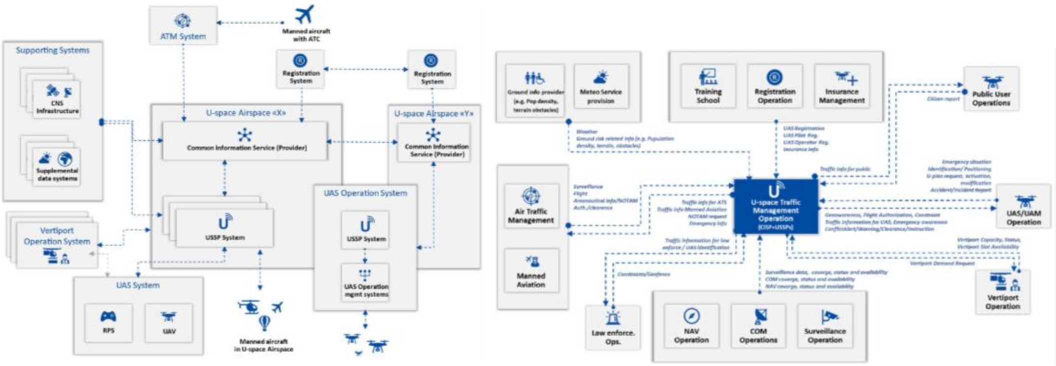


Figure 47. U-space managing structure

Within the broader framework of the DES, the SWIM emerges as a key enabler of seamless data exchange in modern and future air traffic management. As outlined by (Meserole et al., 2007), SWIM provides the technological base for managing the flow of information across diverse aviation stakeholders, both on the ground and in the air. Its objective is to simplify airspace operations and enhance safety and efficiency by offering structured, interoperable, and secure data services.

From a technical standpoint, SWIM is designed to support multiple information domains - ranging from flight data and surveillance to meteorological conditions and aeronautical information - across all phases of flight (surface, terminal, en-route, and oceanic). This interoperability is achieved through the adoption of standardized architectures that ensure both data integrity and cybersecurity compliance. Among its core functionalities, SWIM offers registry services, messaging systems, interfaces for adapting external data, and information assurance mechanisms.

The benefits of SWIM are particularly significant in the context of increasing complexity in airspace usage. It drastically reduces the number of interfaces between systems - by up to 80% compared to traditional architectures - thereby simplifying network management and enhancing scalability. Additionally, it provides end-to-end security in information sharing, a critical requirement in an era of growing cybersecurity threats. Another notable advantage is the structural agility it brings to the aviation system, by enabling loose coupling between data producers and consumers, thus allowing rapid adaptation to evolving technologies and operational needs.

SWIM's role is not limited to traditional manned aviation; it is fundamental for integrating unmanned operations, especially in high-density contexts like UAM and U-space. Its capacity to share data in real time supports TBOs and strategic deconfliction, allowing services such as UAS Traffic Management (UTM) to operate effectively. Through platforms enabled by SWIM, various actors - such as Flight Operation Centers (FOCs), air navigation service providers, and urban mobility stakeholders - can collaborate dynamically, ensuring that decisions are informed, optimized, and coordinated.

e. UAS infrastructures

In the emerging field of UAS, infrastructures play a pivotal role in supporting operations such as BVLOS flights and advanced air traffic management. **Corridors** and **vertiports** are particularly central, providing the spatial and operational foundation for safe and efficient drone activity. However, their implementation depends heavily on the availability of **supportive infrastructures**, including advanced communication networks, reliable navigation systems, and real-time data processing capabilities. As we have already partially seen, the placement of these infrastructures is influenced by several factors, including urban planning, existing technologies, and environmental considerations. For instance, **5G networks**, essential for real-time communication with drones, need to be reoriented to serve aerial operations effectively. Their typical ground-focused configuration must be adapted to provide seamless upward coverage for transmitting and receiving critical flight data. Similarly, **GIS-based terrain analysis** informs the optimal positioning of vertiports by identifying accessible and safe zones for drone landings and takeoffs.

The **EuroDRONE** project highlights the importance of integrated infrastructure systems for enabling U-Space functionalities (Lappas et al., 2020). Its demonstration campaigns validated the use of **cloud-based systems** like DroNav for mission planning, vehicle-to-infrastructure (V2I) communication, and vehicle-to-vehicle (V2V) communication. These systems ensure that drones can communicate effectively, avoid collisions, and adapt dynamically to environmental changes. Demonstrations conducted in Greece showcased how LTE/4G networks support automated BVLOS operations, proving the feasibility of these technologies for real-world applications. The integration of such technologies into the U-Space framework underscores the need for detailed maps and robust sensing equipment. EuroDRONE found that the reliability of sensors like DAA systems and FLARM (Flight Alarm Systems) devices is crucial but still requires extensive validation. These findings emphasize the interplay between physical infrastructure, such as vertiports and corridors, and digital systems, which facilitate navigation and traffic management.

Projects like **AMULED** (Fransoy et al., 2021) and USEPE (Bhuyan et al., 2022) have further explored the concept of temporary corridors and dynamic airspace management. Temporary corridors, activated only during specific missions, connect the upper and lower levels of U-space, offering flexibility in urban environments. Dynamic adjustments based on traffic density, weather conditions, and mission urgency ensure that these routes remain efficient and safe. For example, USEPE has simulated 3D trajectory planning using Python libraries like BlueSky, integrating wind data to optimize drone operations. Temporary corridors, as discussed in AMULED, allow operators to establish routes dynamically, avoiding unnecessary conflict with other aerial vehicles while ensuring the continuity of operations. These dynamic corridors are particularly beneficial for connecting vertiports in high-density urban zones where flexibility is essential for managing complex airspace.

Despite the advancements, **challenges** remain in establishing robust drone infrastructures. One major hurdle is ensuring **interoperability** between systems, such as integrating drone traffic management with existing air traffic control protocols. Additionally, **public concerns** about noise pollution, privacy, and safety require careful consideration during planning and deployment. Projects like DACUS and Metropolis are refining algorithms for **conflict resolution** and capacity management, focusing on optimizing the allocation of airspace for drone operations while minimizing risks. These efforts highlight the critical role of infrastructure in addressing the technical, social, and operational challenges associated with scaling drone usage.

Infrastructures such as corridors and vertiports not only support the immediate operational needs of drones but also influence broader system development. Their **location often depends on existing infrastructures**, such as telecommunications networks or logistics hubs, which can shape their design and functionality. Conversely, their implementation drives the need for additional supportive systems, creating a dynamic **interplay between physical and digital infrastructure**. For example, while corridors provide a structured pathway for drones, their efficiency relies heavily on continuous communication and navigation capabilities. Similarly, vertiports must be equipped to handle a range of services, from **maintenance and charging** to real-time data exchange, ensuring seamless integration into the broader U-Space ecosystem.

The EuroDRONE (Lappas et al., 2020) findings emphasize that these infrastructures are not standalone solutions, but components of an **interconnected network** designed to support **sustainable and scalable drone operations**. By combining advanced technologies with strategic planning, the U-Space framework can evolve into a fully functional ecosystem capable of managing the increasing complexity of drone traffic in urban and suburban environments.

f. Vertiport concept, siting and operations

The integration of drones and UAM into existing transportation systems has necessitated the development of specialized infrastructure known as vertiports. According to the AMULED project, they are the place where departure and arrival operations, parking, charging, security checks, waiting and reception areas for passengers take place where they are used for this purpose, they can also act as information exchange stations between USSPs (Fransoy et al., 2021). These structures are designed to facilitate the takeoff, landing, storage, and maintenance of drones, and to accommodate both passenger and cargo operations. Currently, vertiports are being developed based on the design principles of heliports (EASA, 2022). Vertiports will operate electronically to manage operations efficiently, including passenger handling and goods delivery. They are expected to be "*...located in any area, but realistically predominantly in urban areas and close to airports, permitting air taxi operations within cities and between cities and airports*"

(Garrow et al., 2021). This dual functionality positions vertiports as principal infrastructure for connecting urban centers with suburban or rural areas, as well as for enhancing logistics chains.

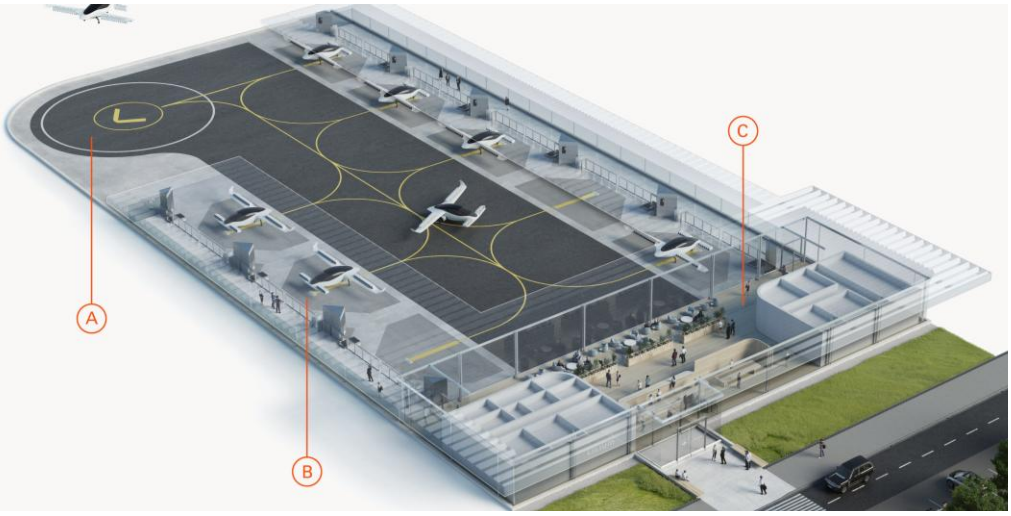


Figure 48. General Vertiport structure

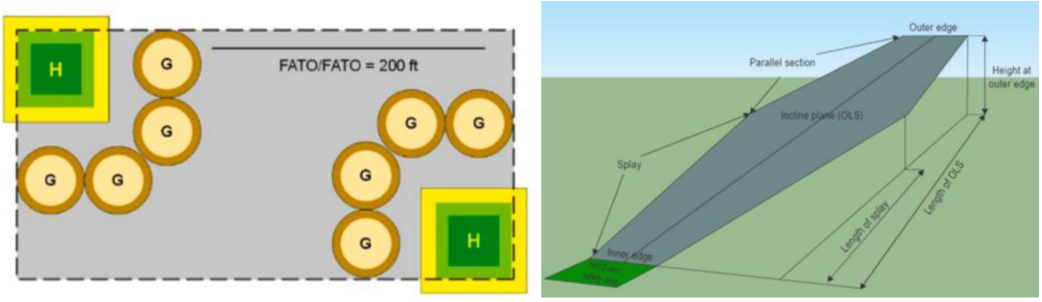


Figure 49. FATO structure (left - (Preis et al., 2025) and OLS structure (right - (EASA, 2022)

The vertiport will serve functions very similar to those of a traditional airport, including a landing area, vehicle parking stands, and a terminal for passenger handling, as illustrated in Figure 48, where:

A. Take-off Area
B. Parking Stand
C. Terminal

The **FATO** is, in simple terms, the area where operations around the vehicle take place, and it can be configured in different ways. In Figure 49 (left), G indicates the parking stands, while H marks the landing and take-off location. Above the FATO lies a zone known as the **Obstacle Limitation Surface** (OLS), which, as the name suggests, defines the airspace in which the drone can safely begin its landing or take-off (Figure 49 - right). This area must remain free of obstacles to ensure safe operations.

Regardless of whether vertiports are deemed beneficial or necessary in urban settings, they must either compete with or complement existing transportation modes. These dynamic highlights the need for integrating into the broader mobility ecosystem. Various studies have analyzed the **optimal location of vertiports** within cities, exploring diverse settings such as rooftops of buildings and parking lots (Wang et al., 2025; Lee et al., 2025;

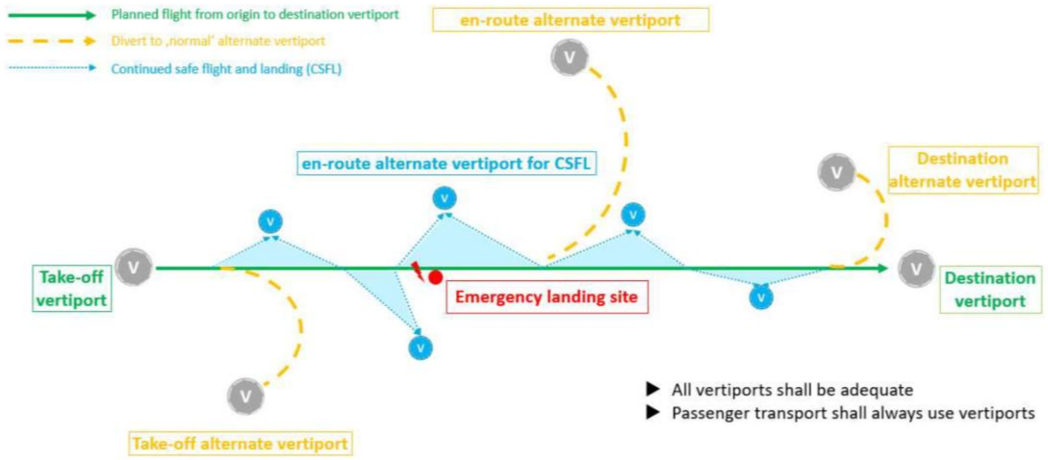
Rahman et al., 2023; Fadhil, 2018; KIM et al., 2023). These studies emphasize that the placement of vertiports depends heavily on factors such as the level of demand, the density of the population served, and social acceptability, including concerns related to noise and privacy. Operational efficiency is another critical consideration, with parking lots being favored in some scenarios for their accessibility and ease of boarding and alighting operations. These elements are essential in ensuring that vertiports are both accessible and effective in meeting urban mobility demands. At the same time, a gap in the literature has been noted concerning the optimization of commercial cargo transport, particularly the movement of goods from distribution hubs to their final destinations, often referred to as the "last mile", Addressing this gap is crucial for fully realizing the potential of vertiports in logistics operations.

The successful deployment of vertiports requires synchronized advancements in traffic management systems to ensure the safety and efficiency of drone operations. Traffic control infrastructure must evolve alongside technological developments, offering solutions that integrate seamlessly with the broader UAM ecosystem. (Niklaß et al., 2020) underscore the importance of developing integrated models for UAM systems, highlighting aspects such as demand forecasting, vertiport design, flight planning, and cost-revenue analysis. Their work emphasizes the need to consider the existing transportation framework, as UAM systems will interface with these infrastructures. By utilizing a low-fidelity analytical approach through RCE software, the authors demonstrated how simulations can inform the design and spatial distribution of vertiports. They propose a two-tier modeling system: Level 0 assesses vertiport capacity without considering physical dimensions, while Level 1 incorporates vehicle size and spatial integration. This multidisciplinary method offers a pathway to optimize operational concepts while evaluating economic impacts.

The proposed concept serves to integrate the use of "**feeder systems**". In this model, passengers from rural regions are transported to city areas serviced by public transport, offering significant advantages in geographically unique regions such as islands, mountainous areas, or those separated by lakes or rivers. This model also suggests that vertiports could provide services along routes where public transportation is either unavailable or inconvenient, creating a valuable complement to existing networks (Cunietti, Sammarco, et al., 2024). Levels of integration could range from physical connectivity between modes to shared ticketing systems, enabling seamless multimodal journeys.

Energy consumption is another critical factor in vertiport operations, especially for drones used in commercial applications. **Battery autonomy** directly impacts the range of drone missions can undertake, particularly for large-scale operations. To support such missions, additional infrastructure such as charging and maintenance stations will become essential components of vertiport design. These stations will not only facilitate drone operations but also ensure their reliability and sustainability in meeting diverse operational needs. The issue of autonomy primarily affects rotorcraft drones, as their energy consumption significantly limits their range. In contrast, fixed-wing drones can cover much greater distances due to their aerodynamic efficiency. An emerging innovation in drone technology involves the development of hybrid drones, which combine vertical takeoff with the aerodynamic efficiency of fixed-wing flight. These drones are capable of transitioning from vertical ascent to horizontal flight, offering greater energy efficiency and extended range.

Due to limitations in flight autonomy and the potential risk of in-flight failures, it is essential to consider the need for **emergency landings**. For this reason, areas suitable for landing must be identified not only at the departure and destination points, but also along the route to ensure safe alternative options in case of unexpected events (Figure 50).



- All vertiports shall be adequate
- Passenger transport shall always use vertiports

Figure 50. Vertiport Classification from Operations Perspective

Vertiports are more than just infrastructure for drone operations; they represent a transformative element in the evolution of urban mobility. By integrating seamlessly with existing ground-based logistics and transportation systems, they have the potential to enhance the efficiency of delivery networks. Vertiports could function as centralized hubs, where large drones transport goods over long distances to centralized hubs, where smaller drones would handle last-mile deliveries, ensuring precise and timely distribution. In urban settings, vertiports are envisioned to serve a dual purpose: enabling passenger air taxi services and supporting logistics operations. However, their successful integration into cities requires meticulous planning to address both technical challenges and public acceptance. Factors such as noise mitigation, energy efficiency, and social concerns must be carefully managed to ensure that vertiports contribute to sustainable and widely accepted urban mobility solutions.

g. Regulatory Framework and Planning Domains

The integration of drones and UAM has led to significant advancements in infrastructure design, with vertiports emerging as critical nodes for operations. Current documentation, such as the **Prototype Technical Specifications for the Design of VFR Vertiports** by (EASA, 2022), and national regulations like the Italian "Regolamento Criteri Nazionali per VCA" (VCA correspond to VTOL - Vertical Take-Off and Landing aircraft), provide foundational guidance for designing infrastructure tailored to VTOL -capable aircraft. However, these regulations **predominantly focus on manned VTOL operations**, reflecting the early stage of regulatory evolution.

Both documents prioritize operations with manned VTOL aircraft, detailing requirements for physical infrastructure, obstacle management, and safety measures tailored to aircraft with pilots on board. For instance, the (EASA, 2022) outlines technical specifications for vertiports designed for manned VTOLs certified under the enhanced category. Similarly, the Italian national regulation addresses operational criteria and airspace requirements primarily for piloted vehicles, including eVTOLs, under the umbrella of Innovative Air Mobility (IAM). This focus underscores the foundational role of manned operations in shaping the initial regulatory and infrastructural landscape.

Despite these advancements, **UAVs are largely excluded from the current regulatory scope**. For example, the applicability matrix in the (EASA, 2022) explicitly notes that unmanned operations fall outside their current framework. This gap highlights the need for aligning infrastructure and operational requirements with the rapidly growing field of drone technology. While manned VTOL operations provide valuable insights into infrastructure needs, the unique characteristics of unmanned systems - such as their smaller size, autonomous navigation, and diverse use cases - demand distinct regulatory and design considerations.

The (EASA, 2022) provides essential provisions, including specifications for touchdown and lift-off areas (TLOFs), safety zones, and taxiways to accommodate the operational needs of manned VTOLs. It also introduces innovative concepts like funnel-shaped obstacle-free zones above vertiports to enhance safety in urban environments, alongside recommendations for integrating vertiports into multimodal transport systems and urban settings. Specifically it outlines essential provisions:

- Physical Characteristics: Detailed specifications for touchdown and lift-off areas (TLOFs), safety zones, and taxiways to accommodate the operational needs of manned VTOLs.
- Obstacle-Free Volumes: Innovative concepts such as funnel-shaped obstacle-free zones above vertiports are proposed to enhance safety in urban environments.
- Operational Guidance: Recommendations for integrating vertiports into multimodal transport systems and urban settings.

The Italian Regulation on VCA, meanwhile, emphasizes:

- Flight Corridors: Establishing regulated airspace zones for VTOL operations to minimize conflicts with traditional aviation and ground-based activities.
- Infrastructure Requirements: Ensuring vertiports meet technical and safety standards for manned aircraft while addressing local urban and environmental considerations

The current focus on manned systems provides a necessary foundation, yet the transition to unmanned operations will require significant regulatory and infrastructural evolution. Adapting existing vertiport designs to accommodate UAVs will be crucial, considering their unique operational parameters due to the need of more advanced technologies. As regulations evolve, the integration of unmanned systems into UAM frameworks will unlock new possibilities, enabling seamless logistics and passenger services.

Based on the synthesis proposed by (Maria Krylova, 2022), four main domains have been identified as essential for evaluating vertiport locations: physical capacity and surrounding environment, social context and stakeholder relations, accessibility and multimodal integration, and business model and regulatory compliance. These categories structure the minimum set of considerations required for effective and context-sensitive vertiport planning.

1. **Physical capacity and surrounding environment**: The site must offer sufficient space for infrastructure, including take-off and landing zones and safety areas. Local weather conditions - such as wind, visibility, and precipitation - must support safe operations. Vertical obstacles and complex topography must be minimized to ensure operational feasibility.
2. **Social context and stakeholders**: Noise impact must be limited, especially near sensitive sites such as residential zones and schools. Community acceptance is a critical factor, achievable through transparency and stakeholder engagement. Potential conflicts with critical infrastructure (e.g., hospitals, military areas, protected zones) must be avoided.
3. **Accessibility and multimodal integration**: Locations should be well connected to existing transport systems (rail, metro, road). Easy access is required for passengers, logistics, and emergency services. Supporting infrastructure such as parking or loading areas should be available nearby.
4. **Business model and regulatory framework**: The site must support economic sustainability with acceptable construction and operational costs. Compliance with land-use regulations and integration into urban development plans is essential to ensure legal and spatial coherence.

At the national level, there are some examples of guidelines for the construction of vertiports for unmanned drones, such as the document “National Requirements for Operations, Airspace, and Infrastructure for Vertical Take-Off and Landing Aircraft” (ENAC, 2024)

h. Corridor design for drones traffic management

The **literature on drone phase corridors** is notably limited, as highlighted by researchers as Wang et al. (2025) who have conducted detailed analyses of keywords related to the topic. The primary sources for corridor conceptualization come from projects funded under the SESAR program, with additional insights provided by some academic publications. A common perspective across many documents is that corridors are envisioned primarily in urban environments, where the structure of U-Space will be significantly more complex than in peripheral areas.

The existing literature extensively debates how these corridors should be structured and whether **fixed or dynamic routes** are necessary. The issue of corridors is also closely linked to the need for **minimum separation** between drones to ensure safety standards (CORUS-XUAM, 2022). While the body of research on the dynamic optimization of drone paths is already substantial, the exploration of real-world applications remains in its early stages. This includes addressing territorial restrictions and the development of both physical and digital infrastructure to support corridors. These static, intangible routes are expected to manage the flow of commercial drone traffic, balancing efficiency and safety in increasingly complex urban airspaces.

Regarding in-flight safety separation, it will be essential to develop standards defining the minimum distance between various devices in flight (Balbastre Tejedor et al., 2022). One of the most widely supported approaches is to differentiate these standards based on the technological capabilities of the drones and their payload capacity. The more advanced the technology onboard a drone, the closer it can safely operate to other drones and obstacles.

Three main categories of separation are identified:

- fixed separation,
- dynamic separation and
- no standard separation.

U-Space does not have a clearly defined operational altitude, which can lead to confusion. Initially, it was established to regulate the use of the airspace referred to as VLL, generally uncontrolled and extending from ground level up to 500 feet (150 meters). Its purpose is to provide services to operators, assisting them during flights and granting necessary authorizations (CORUS-XUAM, 2022). This altitude range is also where corridors will be implemented, although their usage will likely differ between cargo and passenger transport. Passenger transport, which falls under the Certified category, will likely require operations above 120-150 meters, depending on national regulations (AURA, 2021). The distinction reflects the higher safety and operational requirements for transporting people compared to goods.

The conceptualization and implementation of drone corridors also involve varying approaches to airspace structuring and navigation. For instance, the **Metropolis 2** project provides a comprehensive overview of how other projects are envisioning and constructing the U-Space (Valera et al., 2021). While corridors are central to most plans, some projects also include the use of **waypoints** to guide drones through specific routes.

Keywords like autonomous flight trajectories and network route drone frequently appear in discussions on **corridor design**. As outlined by (Nguyen et al., 2021), corridors can be conceptualized as *sequences of precise GPS* coordinates that drones must follow. Their study argues that corridors are the most efficient way to manage commercial flights and passenger transport in the future. They further propose a classification of corridors based on priority levels, describing mechanisms for switching between corridors of different priorities, adjusting routes, and ensuring safe lane changes for drones traveling in the same direction. These ideas were validated through experiments to confirm that drones adhered to all proposed rules.

In this context, to identify the future air ways or commonly called corridors, several solutions have been identified, as we will see, within academic research, European-funded projects (primarily through SESAR), and private sector initiatives. One such solution is the concept of "*AirMatrix*" (Yu Wu et al., 2021). In this approach, the original flight path is subdivided into numerous segments represented as matrices of 3D parallelepipeds. Within these matrices, the drone can move between vertices to perform deconfliction operations, effectively functioning as a vector.

The calculation process is described as follows: "The drone's 3D flight path is initially generated without considering time information. Subsequently, during mission planning, time information is added to the path, and conflicts between drones are resolved by adjusting their departure times and flight speeds…".

A key factor in the subdivision process is the priority of the flight, which helps organize operations into subgroups. Energy consumption is also considered when determining movement paths. The article includes detailed formulas used for these calculations and considers the impact of potential interferences from other drones or external devices

The USEPE project has also explored both tangible and intangible infrastructure, aligning with some of the ideas developed in this study (Bueno et al., 2022). It focuses on designing static routes and varied navigation methods for urban, suburban, and last-mile operations. The project employs the BlueSky library, developed by TU Delft, to simulate 3D trajectories within air traffic systems. This library includes basic algorithms for conflict detection and integrates factors like wind data to refine simulations. USEPE's documentation, though extensive and detailed, is often repetitive and challenging to analyze.

In terms of separation methods, the USEPE project outlines two approaches (Figure 51 and 52):

- **Density-Based Airspace Management**: The airspace is divided into 3D cells representing different utilization levels. These cells open or close dynamically based on external conditions and operational needs, primarily within urban areas.
- **Corridors**: Described as "tubes through which drones travel in a single direction", differentiated by speed categories and travel needs. In urban settings, these corridors are envisioned over low-risk areas like rivers (raising concerns about water contamination in case of crashes) and railway lines.

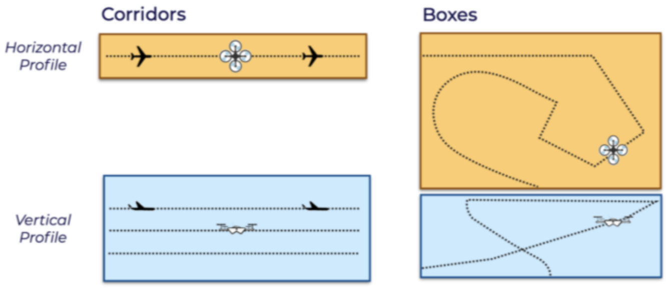


Figure 51. Corridor concept from USEPE 1

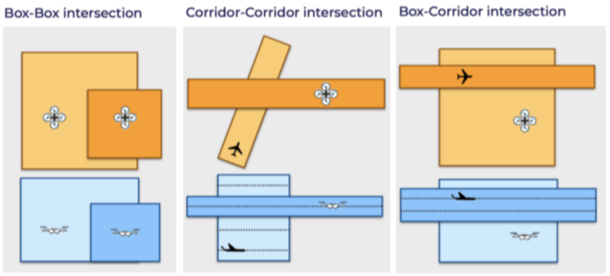


Figure 52. Corridor concept from USEPE 2

To address this complexity, the project is divided into specific subgroups, such as:

- **WP1**: Project management & coordination,
- **WP2**: Concept definition & refinement,
- **WP3**: ConOps definition & classification,
- **WP4**: Separation minima & methods,

- **WP5**: Concept validation,
- **WP6**: Safety, performance, and interoperability,
- **WP7**: Performance monitoring,
- **WP8**: Communication, dissemination, and exploitation.

A significant contribution from USEPE includes algorithms designed to avoid conflicts between drones and external factors like weather, energy consumption, and air traffic management (Güldal et al., 2022). These algorithms form the basis for real-world applications in dynamic traffic environments.

For a broader understanding of how airspace division is being imagined, the article "U-Space Concept of Operations: A Key Enabler for Opening Airspace to Emerging Low-Altitude Operations" (Barrado et al., 2020) provides valuable insights. It discusses the development of corridors for High-Performance Vehicles (HPV) and the ZH volume in the medium term (2025-2030), assigning the management of corridor activation and deactivation to Common Information Service (CIS) providers. **Dynamic corridors**, as described in the document, are activated and deactivated by Vertiport operators or USSPs based on mission requirements. These corridors connect various vertiports and must be avoided by other vehicles, ensuring exclusive use during operations. The AMULED project builds on this concept by proposing that corridor activation be contingent on the type of volume, such as controlled zones like Za, which require ANSP (Air Navigation Service Provider) approval.

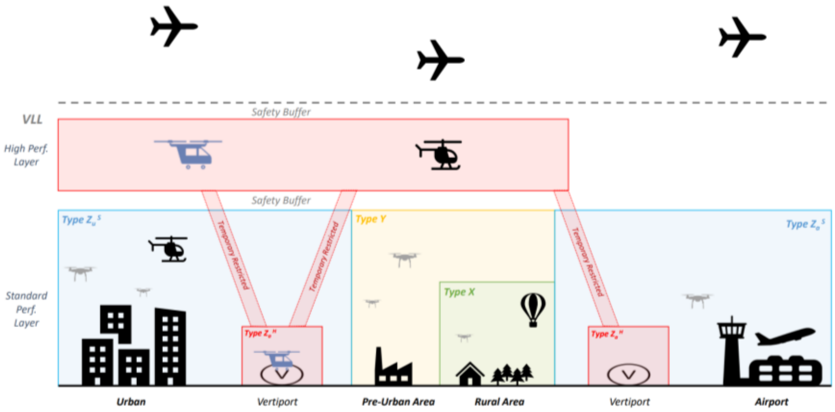


Figure 53. Corridor concept from (Bueddefeld et al., n.d.)

Furthermore, predefined corridors are envisioned for inter-urban connections (100-200 km) and for connecting suburban areas within a metropolis (<50-60 km) where larger vehicles can enable these links. **Static corridors** may also be implemented in areas typically restricted to drone flights, such as airports, to allow safe exits from prohibited zones (Figure 53).

The **Metropolis 2 project** has developed its own algorithms for conflict deconfliction, starting with road graphs to derive flight nodes (Approval, 2021). These algorithms are conceptually divided into two categories: *centralized strategic preflight conflict management* (e.g., replanning, speed adjustments, departure delays) and *decentralized tactical conflict management*. The DACUS project, meanwhile, focuses on traffic management based on airspace capacity and provides detailed parameters for flight planning (Martínez et al., 2022).

One intriguing example is presented in the article (Kim et al., 2022), which depicts corridors as parallelepipeds, with routes positioned along the edges rather than within the volume. Maintaining sufficient distance between edges is crucial to account for positioning errors. The corridor shape will depend heavily on future airspace separation models, as explored by entities like JARUS, DACUS, and CORUS-XUAM.

Once corridors are located, their internal structure must be planned based on essential factors such as minimum separation between drones. This separation, in turn, depends on variables like onboard technology (Bauranov et al., 2021). More advanced technology allows drones to operate closer together. Other considerations include weather conditions, traffic density, and the capacity of designated operators to manage drone activity.

Bauranov et al. also propose various hypotheses for urban corridor planning, including how intersections will be controlled, the relative efficiency of different structures, and the potential for multiple corridor types tailored to drone characteristics, priorities, and tasks. They explore whether overlapping corridors are feasible, the practicality of flying between buildings, and the optimal location of nodes. Their analysis draws on global studies and insights from major companies like Amazon and Google, as well as projects like METROPOLIS, which propose specific airspace divisions for Europe.

The *D3.1 Catalogue of Generic ConOps* offers practical navigation scenarios based on classifications developed in the XUAM project. One example involves rectangular parallelepiped corridors subdivided into sections for traffic and deconfliction, with static entry and exit points located 120 meters apart (Calvo, 2020). Other scenarios explore configurations for different drone types and airspace volumes.

Lastly, the *D4.1 Algorithms for Analyzing the Collision Risk* document provides the groundwork for developing models to calculate conflict levels, including a formula for estimating conflict frequency within a corridor (Vila Carbó et al., 2021). These tools are vital for advancing real-world applications of corridor-based airspace management.

The rapid evolution of UAM presents challenges and opportunities that necessitate a structured approach to airspace management. Recent studies have emphasized the importance of innovative airspace designs to accommodate the exponential growth in drone operations, particularly for delivery purposes. For instance, (Doole et al., 2021) highlighted the value of structuring urban airspaces with **bi-directional and uni-directional configurations** to reduce conflicts and enhance stability in densely populated areas. These designs rely on **vertical segmentation** and horizontal flow constraints to align and separate traffic, ensuring safety and efficiency in constrained urban environments.

Building on this, Garrow et al. Straubinger et al. explored the necessity of reimagining airspace geometry to adapt to diverse drone capabilities and environmental challenges. Their findings suggest the importance of flexible separation standards, ranging from fixed to dynamic approaches, based on the technological sophistication and operational requirements of drones. Such adaptability is essential for balancing safety, capacity, and efficiency, particularly in the face of increasing operational densities and technological advancements.

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