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Drone Infrastructures Planning on Large-Scale for Passenger Transport

Stefano Cunietti [1], Chiara Sammarco [2], Ilaria Ferrando [1], Juan Vicente Balbastre Tejedor [3] and Domenico Sguerso [1]

[1] University of Genova, Geomatics Laboratory, 1 Via Montallegro, 16145 Genova, Italy
[2] Geodatalab srl, 912 Via Tiburtina, 00156, Roma, Italy
[3] Technical University of Valencia, Research group Sistemas de Navegación Aérea, Camí de Vera, s/n, Algirós, 46022, Valencia, Spain
Tel.: +39 010 33 52664
E-mail: stefano.cunietti@edu.unige.it

Summary: This paper presents a case study on vertiport positioning for taxi drones in Valencia, Spain. The proposed methodology applied as a "preliminary phase" preceding the three established phases of flight planning - Strategic, Pre-Tactical, and Tactical - adopted in European Union Aviation Safety Agency (EASA) regulations. This phase identifies suitable areas for unmanned aerial system (UAS) operations through a multi-criteria analysis (MCA) considering critical aspects like social acceptability, safety, and accessibility. This involves evaluating factors such as Communication, Navigation, and Surveillance (CNS) services which also include positioning, together with noise regulations, and ground risk. The result of overlaying various factors, transformed into a suitability layer, is a map that guides decision-makers and industry in locating infrastructures like vertiports and corridors.

Keywords: U-space, Advanced Air Mobility, Infrastructure Planning, Vertiports, Spatial Analysis, Planning

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1. Introduction

Unmanned Aerial Vehicles (UAVs), commonly referred to as "drones" are widely recognized as versatile tools for advanced data acquisition and analysis [1]. Their applications span various fields, including topographic surveys, precision agriculture, environmental monitoring, and infrastructure inspection, as well as recreational activities. However, technological innovations are expanding their potential uses, such as for transporting goods and people. This evolution provides opportunities to integrate drones into mobility systems, with significant territorial implications at the local level.

Unlike traditional aviation, where the impact is largely confined to airports and predefined flight paths, drone infrastructures such as vertiports - takeoff and landing points for drones - and corridors - the future "sky roads" - will extend across broader territories. This dense spatial distribution will necessitate the involvement of authorities at all levels in the decision-making process to identify the most suitable areas [2].

Despite growing interest in Urban Air Mobility (UAM) and Advanced Air Mobility (AAM), a significant gap remains in the development of standardized methodologies to guide the identification of suitable areas for these infrastructures [3]. UAM focuses on integrating drones into urban and peri-urban transport systems to enhance last-mile delivery, connectivity and reduce congestion. AAM broadens UAM scope to include regional and rural areas, enabling applications such as intercity passenger transport and cargo delivery. Both concepts require careful planning to address technical, regulatory, and social considerations [4]. However, existing approaches often fail to integrate these dimensions effectively, leaving stakeholders without robust tools for comprehensive and data-driven planning.

This approach must account for various factors, which we have grouped into categories such as:

- safety (e.g., risk of falling to the ground),
- social acceptance (e.g., noise, privacy),
- drone performance (e.g., energy consumption),
- urban planning frameworks (e.g., integration with existing urban and transport plans, land-use regulations),
- infrastructure compatibility (e.g., availability of charging stations, antennas for connectivity and positioning, and other systems that can support vertiport and drone operations).
- accessibility (e.g., seamless connectivity with existing infrastructure).

Each factor needs to be evaluated according to current regulations; for instance, regarding noise, it will be necessary to verify that drone sound emissions do not exceed legally permitted limits. By addressing these gaps, this study proposes a methodology that combines multi-criteria analysis (MCA) with geospatial tools. This approach is intended to support stakeholders in identifying optimal locations for vertiports and corridors, facilitating a structured and data-driven decision-making process.

2. Objectives

This work aims to identify the key factors necessary for selecting suitable areas for both vertiports and corridors. The authors propose transforming all elements that may have a positive or negative effect on the implementation of these infrastructures - such as regulations (e.g., noise pollution limits, land uses), environmental factors (e.g., protected natural areas), and insights from existing mobility plans (e.g., most relevant interchange nodes, congested areas) - into representative GIS (Geographic Information System) raster layers. These layers are classified on a scale ranging from "suitable" to "absolutely unsuitable", facilitating a structured and comprehensive analysis. Once each factor is represented, these layers are synthesized into a comprehensive map using a multi-criteria analysis approach [5].

Indeed, establishing rules for new infrastructures is as important as developing methods capable of quantifying their potential impact. It is worth noting that full compliance with all regulations may not always be achievable; therefore, this map will help to identify areas with the least impact. Once suitable areas are identified, relevant authorities can define measures to mitigate any residual issues whenever possible. In cases where mitigation is not feasible, the area should be excluded from consideration. Furthermore, smaller administrations may lack access to experts specialized in addressing each specific challenge. This highlights the importance of establishing a structured methodology with clear and standardized rules that can be easily applied across different contexts, ensuring consistency and efficiency in decision-making processes.

Additionally, this work seeks to enable a shared planning process among all involved stakeholders, rather than directly assessing the current feasibility of using drones for passenger transport in urban contexts. The distinction is crucial, as passenger transport drones fall under the certified category and require extensive safety measures, currently under discussion, to ensure compliance with stringent regulations. These measures still face technological limitations [6].

While these challenges are being addressed, the issue of identifying suitable locations for supporting infrastructures will persist, highlighting the need for collaboration in developing a structured methodology to address it. Once such methodology is established, its implementation could ensure that clear and standardized rules can be applied to effectively identify the most appropriate sites.

The task of this research can be summarized in three main objectives:

1. **Criteria Identification and Layer Development**: defining and representing relevant factors in geospatial layers that can be normalized and integrated into the MCA process.
2. **Application to Distinct Contexts**: implementing the methodology in two case studies: urban (Valencia, Spain) and extra-urban environments (Emilia-Romagna, Italy) [5], to demonstrate its adaptability and relevance across different settings. The first case study focuses more on human well-being, while the second emphasizes environmental preservation, although the latter is not overlooked in the former.
3. **Validation**: refining criteria weights and validating results through stakeholder involvement to ensure alignment with real-world planning needs and existing transport frameworks.

3. Literature review

The development of a market involving broader and more diversified drone use will demand a complex regulatory framework [7]. Currently, regulations are primarily developed for recreational and technical use, with rules that impose restrictions on weight, size, speed, and minimum technological features of the aircraft [6]. Regarding the available bibliography connected to the objectives of our work, despite progress, the primary focus remains on implementing and structuring U-space - the airspace reserved for drones - while leaving the practical development of a drone market for passenger and cargo transport in an emerging phase.

Worldwide, various organizations are working on defining norms, flight management phases, and drone technical specifications. In Europe, the main players are EASA (European Union Aviation Safety Agency), EUROCONTROL, and the European Commission. Together, they contribute to developing the DES (Digital European Sky) [8] through the SESAR (Single European Sky ATM Research) program [9]. The final goal is to automate all flights under the Single European Sky (SES) initiative, unifying EU airspaces. SESAR funds projects aimed at developing and testing solutions for integration into the aviation system, laying the groundwork for achieving the DES [10].

Beyond Europe, other countries are developing their drone airspace concepts. The United States is making significant advancements in drone integration. The Federal Aviation Administration (FAA), in collaboration with National Aeronautics and Space Administration (NASA), has developed its own UAM Concept of Operations (ConOps), which outlines a phased approach for integrating UAM into the National Airspace System (NAS) [11].

While regulatory frameworks are being developed, some research and institutional efforts, even though progressing at a slower pace, have emphasized the importance of identifying suitable areas for drone infrastructures, particularly vertiports and flight corridors, using GIS methodologies and comprehensive planning approaches. Examples can be found in [12] and [13] where the focus is on a GIS-based MCA to generate suitability maps, and on the development of not MCA-based risk maps to highlight areas with varying levels of suitability for operations, respectively.

Institutional projects at European level further support these efforts. For instance, the CITYAM project, funded through Interreg, is trying to develop a geospatial decision-support tool to aid municipalities in planning and implementing vertiports and corridors [14]. Similarly, the [4] briefing by UIC2 (Urban-Air-Mobility Initiative Cities Community) under the EU's Smart Cities Marketplace underscores the challenge of integrating UAM within existing mobility.

In Italy, ENAC (Ente Nazionale per l'Aviazione Civile - Italian Civil Aviation Authority) has taken a proactive role through its [2], which outlines key considerations for integrating AAM into the national context. The document mention points as:

- integration of vertiport operations with urban structures to mitigate risks;
- design of airspace based on dynamic corridor allocation and advanced traffic management;
- identification of critical issues for implementing AAM within urban environments while aligning with municipal plans.

Existing approaches often remain project-specific, highlighting the need for replicable and adaptable frameworks that integrate technical, social, and regulatory dimensions.

4. Methodology

The integration of drones for passenger transport adds complexity to urban transport systems. However, it also offers opportunities to develop more sustainable solutions, such as addressing congestion in heavily trafficked areas with electrical vehicles. In rural areas, drones have the potential to mitigate isolation and enhance connectivity [15]. A critical step in this process involves identifying key factors to construct a suitability map that minimizes the negative impacts of drones. The CITYAM framework categorizes these factors into "pull-to" and "push-away", respectively positive and negative factors, serving as a foundation for our methodology.

The next phase applies the Analytic Hierarchy Process (AHP) to assess the relative importance of these factors. AHP structures decision-making into a hierarchy of objectives, criteria, and alternatives, enabling pairwise comparisons to calculate weights for each criterion. These weights, validated through stakeholder input, prioritize factors within the MCA framework while ensuring consistency across evaluations [12]. Once a reasonable consensus among the parties is reached, the map will be generated, and new observations will be incorporated, adjusting the MCA framework accordingly.

In our research, several layers have been developed, including factors such as noise, socioeconomic status, protected areas and flight-restricted zones according to regulations, fatality risk calculation, and meteorological conditions. However, for the purpose of demonstration, only three are presented as examples. Indeed, a crucial part of this research involves identifying the most relevant factors and developing methods to make them representable within the MCA framework.

Moreover, a differentiation in the analysis type was considered: the extra-urban environment was analyzed in Emilia-Romagna (Italy), while the urban environment focused on Valencia (Spain). The results here presented are based on the latter case-study and focus on a passenger transport drone, VoloCity [16].

Finally, to follow the "pull-to" and "push-away" method, the layers involved in MCA map were normalized on a scale from 0 to 1, where 0 indicates suitability and 1 represents unsuitability. The choice of this scale was motivated by the subsequent calculation of the Least Cost Path (LCP), which requires higher values to indicate areas with greater traversal costs. Once the MCA map was generated by overlaying all layers, it was compared with interchange nodes identified in mobility plans to select the most suitable areas for vertiports. Subsequently, the LCP was used to identify low-risk routes connecting the selected nodes on the MCA (Fig. 4).

4.1 Positioning and Coverage Assessment Using Ground Base Station Antennas

The first layer identifies areas where an additional positioning level, beyond Global Navigation Satellite System (GNSS), can be achieved. This option could prove beneficial in urban environments where GNSS accuracy is compromised due to satellite occlusion and multipath interference. Using 5G base stations from mobile networks, an acceptable margin of error is ensured. To provide Communication, Navigation, and Surveillance (CNS) services for safe automated flights through corridors connecting vertiports, additional infrastructure is needed. This is because the lower part of the sky, known as Very Low Level (VLL), is not covered with conventional CNS systems for flight operations, unlike the higher altitudes used in traditional aviation. Therefore, existing systems, such as mobile networks emerged as a natural way to provide that coverage.

These networks could facilitate continuous communication between the operator and the drone, alongside others. Moreover, they could aid in locating drones using techniques such as multilateration (MLAT) combined with GNSS [17]. In this case, the focus is not solely on identifying which existing technologies could benefit drones but also on evaluating where they can be effectively applied.

Coordinates and stations characteristics were sourced from a Spanish ministerial database [18]. Positioning error for each 50 m resolution raster pixel in the metropolitan area was calculated using the Cramér-Rao Lower Bound (CRLB), simulating a drone flying at 150 meters. After assessing the potential signal reach using Equation (1), a Digital Surface Model (DSM) was used to identify visible antennas from any point in the sky, excluding those obstructed by obstacles.

$$P_r = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4 \cdot \pi \cdot d)^2} \quad (1)$$

Equation 1 represents the Friis transmission equation, used to calculate the received power in a free-space telecommunication system. In this context, P_r is the power received by the receiver, expressed in watts, while P_t is the power transmitted by the transmitter, also in watts. G_t represents the gain of the transmitting antenna, which is dimensionless and often expressed linearly or in decibels, and G_r is the gain of the receiving antenna, also dimensionless. λ denotes the wavelength of the transmitted signal in meters, which can be determined using the speed of light *c* and the frequency *f*, through the relation in Equation 2. It represents the distance between the transmitter and the receiver, measured in meters. Factor 4π accounts for the geometric dispersion of electromagnetic waves in free space.

$$\lambda = \frac{c}{f} \quad (2)$$

An algorithm we developed selected the optimal antenna combinations to minimize localization error, employing the CRLB with Time-Difference-of-Arrival (TDOA) - based MLAT techniques (Fig. 1). The acceptability of errors depends on the drone positioning requirements within the flight environment.

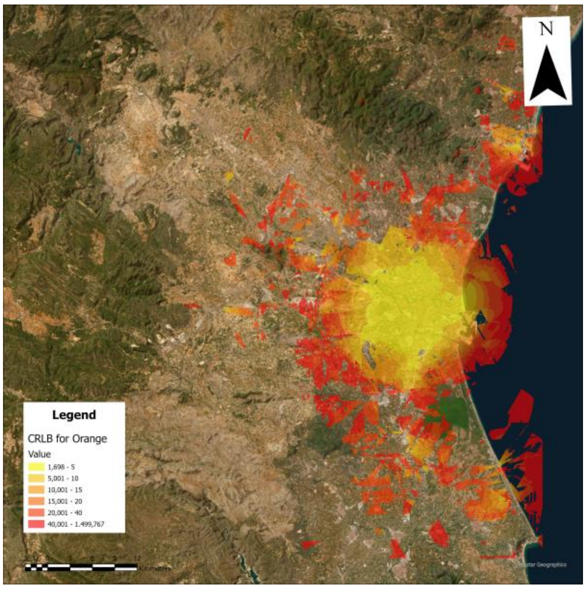

Fig 1. CRLB Calculation for Orange company antennas.

4.2 Noise respect zone

The second layer establishes acoustic compliance zones by calculating the minimum distances drones must maintain to adhere to noise limits. These calculations focus on sensitive urban areas, such as residential neighborhoods, hospitals, and schools, and are based on the land-use map obtained from the geoportal of the Valencia region [19]. Using a regression equation based on drone weight as x in Equation 3 to estimate sound levels, this method integrates urban planning regulations to support acoustic comfort [20].

$$L_{1m} = 7.2 \cdot \ln(x) + 74.5 \quad (3)$$

The presented result (Fig. 2) was calculated for nighttime conditions, while legislation allows for less stringent limits during the day. Different compliance zones were defined for each land use type, as shown in [21]. Here, a vertical distance was also calculated to define the fly altitude for noise compliance.

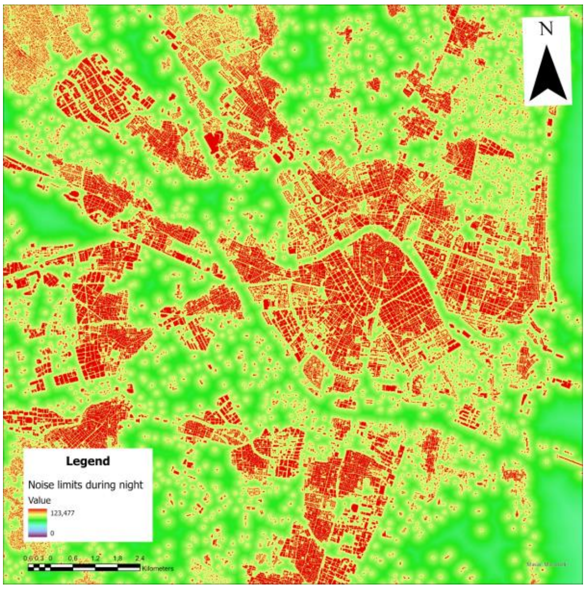

Fig 2. Noise limits during night.

4.3 Possible ground fatalities

The third layer estimates the potential number of people impacted within each pixel, determined based on the pixel dimension (Fig. 3). This analysis is performed by extracting a component of the process defined in the Specific Operations Risk Assessment (SORA) methodology, as outlined in [22]. The layer calculates the fatality rate by correlating key factors such as population density, terminal velocity, and impact energy with specific drone parameters. These parameters include a mass of 900 kg, a speed of 30.56 m/s, and a standard altitude of 150 meters, which are applied in the calculation of AC (Critical Area).
The Equation used was [22]:

$$EC = \lambda_{GI} \cdot D_{pop} \cdot AC \cdot F_{exp} \cdot P(fatality|impact) \quad (4)$$

where:

- EC: expected casualties
- λ_{GI}: aircraft failure rate;
- D_{pop}: population density in the risk area;
- AC: critical area of the aircraft;
- F_{exp}: fraction of exposed population;
- P(fatality|impact): probability of fatality given an impact.

The parameter λ_{GI} depends on the Specific Assurance and Integrity Level (SAIL) to be achieved and is calculated using the following equation:

$$\lambda_{GI} = \frac{TLOS}{D_{pop} \cdot AC} \quad (5)$$

where *TLOS* (Target Level of Safety) was 10^{-6} for SAIL VI.

D_{pop} represents the maximum population density (in people per square meter) within the ground risk footprint. Adjustments for specific areas are made using grid-based population modeling, with a resolution of 50 meters per pixel, and applying weighted averages to account for variations within the footprint.

The *AC* represents the ground area potentially affected in the event of a loss of control of the drone. Its calculation depends on the size and operational characteristics of the drone. Further details and specific calculation methodologies are provided in Annex F of the SORA documentation [22].

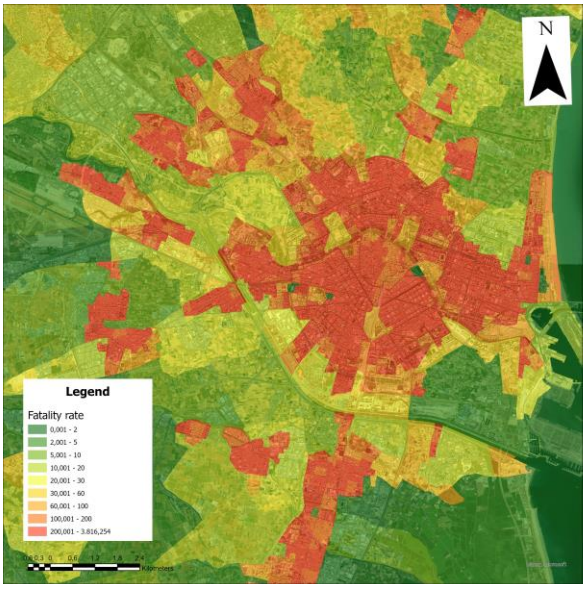

Fig 3. Fatality rate.

F_{exp} is calculated as a complement to the sheltering factor and depends on the specific operational environment and characteristics of the aircraft. The mitigation layer was applied based on land uses, calculated using Sentinel-2 imagery to assign exposure factors, enhancing risk accuracy.

P(fatality/impact) represents the probability of a fatality occurring given that an impact has taken place. In most calculations for conservative safety estimates, the assumption is often made that it is 1.

Although SORA is designed for the specific category of operations rather than the certified category, in this case it was employed to estimate potential fatalities. This is due to its simplicity and its ability to provide an initial assessment of risk proportional to other methodologies.

5. Results and conclusions

This work focuses on the metropolitan area surrounding the city of Valencia, the capital of the "Comunitat Valenciana" in eastern Spain. With its high population density, Valencia presents significant challenges for the real-world implementation of UAM. However, the area benefits from good connectivity, including an international airport (which poses a significant limitation on flying over the city), high-speed rail links, and an extensive highway network, as well as regional rail and road systems, as well as a large harbor with high passenger and freight traffic.

The boundaries of the study area were defined based on the metropolitan transport plan [23], which identifies key commuting flows within the region. From this plan, significant transport nodes were extracted, identified as critical for their interchange capacity and movement of people. These nodes were then assessed to determine their suitability on the MCA map produced as potential vertiport locations, ensuring alignment with strategic mobility needs.

A key aspect highlighted in CITYAM documents employing methodologies like ours is the need to align with existing urban and transport planning tools. To validate our results, we relied on transport plans [23], verifying that the nodes identified as suitable matched major interchange hubs and high-traffic areas as outlined in Fig. 4.

The result of the layer overlap is displayed on the MCA map (Fig. 4), where it is possible to identify appropriate areas for passenger transport drones, comparing to the transport plan of the metropolitan area.

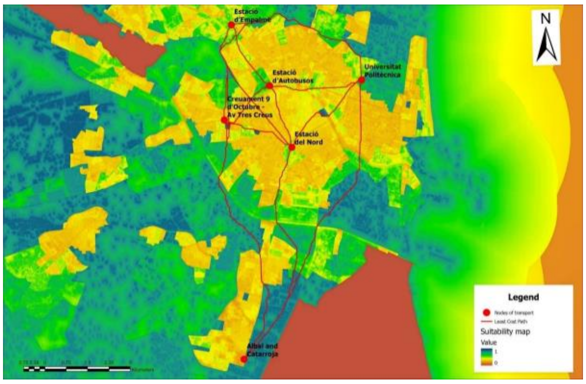

Fig 4. Multi-Criteria Analysis Calculation for a Passenger Transport Drone

Each layer analyzed in the process for identifying suitable area for appropriate vertiport location requires targeted evaluations to address technical, social, and environmental challenges.

The map can serve as a baseline to identify locations with fewer constraints for implementing those infrastructures. However, further verification is necessary to ensure compliance with legal requirements and determine the feasibility of mitigation measures. For instance, Fig. 2 highlights the significant challenges of accommodating a drone such as the VoloCity in urban areas, while Fig. 3 shows that risk exceeds acceptable limits under current regulatory conditions. Conversely, Fig. 1 demonstrates that in urban settings it is possible to leverage existing infrastructures to support these new vehicles. While offering the potential for better economic outcomes because of high mobility demand, densely populated areas often remain challenging for passenger drone operations due to stricter regulatory requirements to mitigate risks and social constraints.

At present, there is no unified framework for implementing UAM infrastructure. Most processes are tailored to individual projects, often aligned with SESAR initiatives to refine and expand regulatory frameworks. European projects such as CITYAM and UIC2 showcase strategies aimed at supporting municipalities in addressing UAM planning challenges. These initiatives emphasize the critical role of local governance and provide analytical tools to facilitate decision-making [15]. This study contributes to this broader effort by providing a methodology that intuitively evaluates potential impacts on territories and aligns proposed infrastructures with transport plans and high-traffic interchange nodes [24].

Efforts should be directed toward developing a common methodology that can be applied across different contexts. However, as demonstrated by the comparison between the case study presented here and that of Emilia-Romagna [5], it is challenging to find comparable datasets, structured in the same way. Type and data availability are key challenges in MCA development. Static data, such as population density, was predominantly used in this study, particularly for estimating fatality rates. However, dynamic factors - such as temporal variations in human activity - must also be considered. For example, areas with high pedestrian traffic during certain times of the day (e.g., near schools) or seasonal peaks (e.g., tourist hotspots) require additional analysis to ensure higher accuracy.

In our case, we relied on static data, whereas it would be essential to incorporate data that reflects the dynamic nature of urban mobility. For instance, while we considered only population density, certain areas experience varying flows of people throughout the day and year. For example, the northeastern node, where the Polytechnic University is located, might initially appear suitable. However, the high flux of students for most of the year necessitates additional information on high-density commuting flows. Similarly, in a highly touristic city like Valencia, the beach area presents seasonal peaks of occupancy that are not considered on the map.

Validation remains a critical step in ensuring the reliability of the process. As emphasized in related works referenced earlier [4], [14], continuous discussions with stakeholders are pivotal for refining weights and criteria, ensuring the methodology aligns with real-world conditions. In force regulations laying down requirements on noise and safety play a decisive role in enhancing the credibility of the results.

Once suitable areas are identified, further steps must be undertaken to ensure feasibility. These include: (1) verifying the availability of connections to the electrical network with adequate specifications, (2) comparing the results to urban planning tools to confirm land use compatibility, and (3) ensuring compliance with Touchdown and Lift-Off Area (TLOF) requirements. For instance, it is crucial to verify that the identified areas are free from obstacles. Additionally, access to high-resolution 3D data can significantly enhance this process by providing precise insights into potential obstructions.

Tools as those presented in [25] can support the selection of locations identified through MCA by refining them further based on the specific datasets used in this work.

Limitations also arise in the case study focusing on passenger transport drones, specifically the VoloCity model (Fig. 4). This type of drone falls under the certified category, requiring extensive safety considerations. However, the primary aim of this work is to develop a methodology for identifying suitable locations for the infrastructure necessary to support these operations.

In conclusion, MCA proves to be a robust tool for identifying suitable areas for UAM infrastructures, but its outputs must be continuously reassessed and validated. Certain constraints may be mitigated, others require additional measures, and some areas may need to be excluded or further developed. This iterative and adaptable process ensures that planning remains aligned with technological progress, regulatory requirements, and the evolving needs of local stakeholders. Indeed, ensuring coherence will require aligning the identified areas with existing territorial planning frameworks, particularly in relation to transport planning. This includes selecting vertiport locations that can alleviate congestion or enhance overall mobility, while also adhering to land-use regulations. By integrating these considerations, the proposed infrastructure can contribute to a more efficient and sustainable urban transport system without conflicting with established planning policies.

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