An interdisciplinary research perspective for tackling Vertiport design and developmental challenges

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Abstract

Urban Air Mobility (UAM) embraces a broad range of subjects that include stakeholders from local, regional, national, and international levels. Due to such multi-tiered nature, the efforts to make UAM a reality transcend the realm of engineering. Thus, at Politecnico di Milano (PoliMi), researchers from the Department of Aerospace Science and Technology (DAER) and Department of Architecture and Urban Studies (DASTU) collaborate at the junction of two disciplines. This interdisciplinary approach is aimed to reflect and combine the ongoing PhD research in both the departments to tackle the challenges pertaining to Vertiport design and development. In this paper, first a literature review is performed to outline Vertiport requirements from an engineering and architecture perspective. Later, a requirements overlap and contradiction analysis is executed to identify points of conflicts and intersections. The results from this analysis confirms and further emphasizes the need for a fastened interdisciplinary research approach to resolve the issues concerning the development of Vertiport.

1 Introduction

Urban Air Mobility (UAM) is a new proposed mobility solution that intends to utilize electric Vertical Take-off and Landing vehicles (eVTOLs) to improve and enable faster connectivity within the cities. Such mobility concept requires new infrastructures in the urban areas for the UAM vehicles or eVTOLs to takeoff and land. Hence, UAM infrastructures or Vertiports are integral and critical for the realization of any UAM ConOps (Concept of operations). This fact is also emphasized in [1], where UAM infrastructure are identified to represent one of the main challenges in the realization of UAM. However, despite the Vertiports crucial role, only a small percentage of studies published is focused on UAM infrastructure [2, 3]. And, many of these studies, currently, focus only on the definition of main geographical areas for UAM operation feasibility and not on the identification of the actual location and shape of the Vertiport [2]. Moreover, finding a suitable location for Vertiport emplacement is difficult due to the dense urban landscape, the undefined size and design of the Vertiport [1].

The design and localization of the Vertiport comprises of issues which affect the domains such as the engineering, operation, architecture, urban design, etc. Therefore, the focus on the integration and design of the Vertiport should be considered jointly. In fact, there are several research groups such as the Center for Urban and Regional Air Mobility (CURAM) in Georgia [2] and Berkeley Transportation Sustainability Research Center (TSRC) [4], etc., which integrate expertise from economics, policy, business, urban studies and engineering to tackle the UAM challenges. Similarly, the work conducted at PoliMi is aimed at combining aeronautical engineering, urban design and architectural perspectives on the Vertiport design and development.

This paper aims to identify the overlaps and contradictions of the localization and design of the Vertiport through a comparison of a series of requirements in the following categories: Aircraft, Wind, Infrastructure and Urban Form, Architectural Design. Therefore, the first part of the paper provides an introduction, the second part of the paper is structured into four subsections to describe and draw out the corresponding requirements from each of the aforementioned category, the third part analyzes all the identified requirements per each category to determine

potential overlaps and contradictions, and the fourth part discusses the key findings from the analysis performed in the third part. Lastly, the conclusion is furnished in section five.
Scope of this paper is to only perform a qualitative analysis. This paper will only consider passenger eVTOL of weight less than 3175kg as per [5] and not account for emergency services or automated drone based logistics. Moreover, the presented collection of requirements should be considered non-exhaustive, as this study focuses only on aircraft, wind, urban and architectural perspectives, and discards other significant categories, such as acoustics, operations, policy making, etc. In the context of the paper, in case of overlapping of similar requirements, EASA standards [6] are considered over FAA [7].

2 Architectural and Engineering standpoint on Vertiports

2.1 Aircraft

The minimum requirements for Vertiport design were established by EASA in the Prototype Technical Specifications for the Design of VFR Vertiports (PTS-VPT-DSN) [6], referred to as PTS in this paper. The PTS provides guidance on the physical characteristics of a Vertiport and the required obstacle environment, which will be the focus of this study. Visual aids, lights and markings, and taxi-routes/taxiways and facilities layout dictated by ground operations (maintenance, storage, charging etc.) or simultaneous operations are not considered.
The PTS provides information regarding optimal position and minimum size of Touchdown and Liftoff Areas (TLOF), Final Approach and Take-off Areas (FATO) and Safety Areas (SA), see Figure. 1. FATO refers to the zone where the eVTOL executes its final approach to touchdown or initiates departure flight (Req. A1). TLOF is a smaller area, which is bearing the most demanding eVTOL dynamic loads associated with landing (Req. A4). TLOF can be situated within a FATO, a portion of a taxiway or a stand. FATO and TLOF dimensions are dependent on the length of the Rejected Take-off Distance for the required take-off procedure that is prescribed in the Aircraft Flight Manual (AFM) of the eVTOL for which the FATO/TLOF is intended, or a prescribed fraction of the Dimension D, whichever is greater. ‘D’ is defined in MOC VTOL.2115 [8] as the diameter of the smallest circle enclosing the VTOL aircraft projection on a horizontal plane, while the aircraft is in the take-off or landing configuration. The load-bearing capacity of the TLOF is determined by factors such as eVTOL weight, landing/take-off procedures, and downwash. SA is always associated with FATO and its aim is to provide a margin area for maneuvering errors in challenging wind conditions. Its size depends on the Dimension ”D” (Req. A2) and might be enlarged to account for the downwash requirements described later in this Chapter.

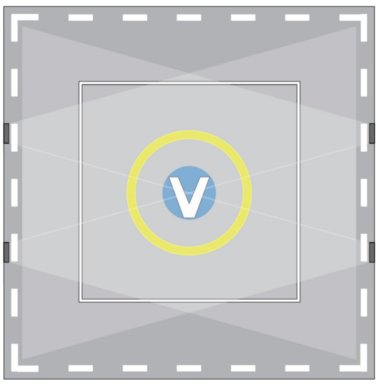

Figure 1: Example of a rectangular FATO and TLOF, from [6]

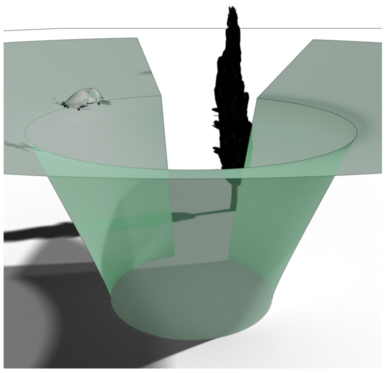

Figure 2: Example of a conical OFV with omnidirectional approach and take-off climb surface and prohibited sector, from [6]

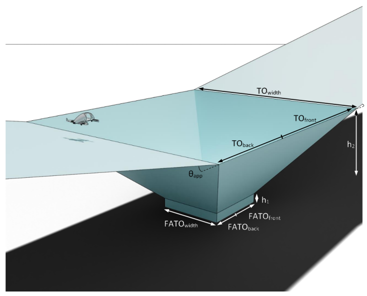

Figure 3: Vertical take-off and landing procedure volume and its defining parameters, from [6]

The obstacle environment described in the PTS is composed of two elements: a newly introduced feature called the Obstacle-Free Volume (OFV) (Req. A6) and Obstacle Limitation Surfaces (OLS) (Req. A5) which is a well-known concept established in heliports specifications. The OFV represents a funnel-shaped airspace situated above the Vertiport which accounts for the capability of the eVTOL aircraft to perform landings and take-offs with considerable vertical component and, if being conically shaped, opens a possibility for designing of omnidirectional trajectories, as depicted in Figure. 2. The PTS provides guidance for the OFV design, through the parameters defining the eVTOL vertical Take-off and Landing procedure (see Figure 3), considering FATO size and shape, and buffer volume dependent on the SA. The OLS may be composed of multiple planes (see Figure 3) or a conical surface (see Figure 2), in case of an omni-directional approach, attached to the top of the OFV and inclined depending on the approach/departure angle which is meeting the eVTOL performance in case of failure. These surfaces are established in such way that no projection of a high obstacle, such as tall buildings, radio masts or mountains, is permitted.

The downwash effect must be considered seriously by the Vertiport designers, not only in terms of size of take-off and landing zones but also in terms of infrastructure placement and operational procedures when eVTOLs are maneuvering close to the ground. The downwash can be observed from two perspectives, depending on the flight phase. An eVTOL passing by or approaching/departing creates a downwash. When the eVTOL approaches the ground and the flow-field generated by the rotors start to interact with the ground, the effect can be referred to as outwash [9]. The PTS [6] provides minimum requirements for assessing the size adequacy of the SA for outwash protection (Req. A3 (a) (b)), based on the measured values on a 2D circle while the aircraft is in 1 m hover in no-wind conditions. The measured values will depend on multiple factors, such as horizontal and vertical configuration of rotors, the duration of the maneuver and wind conditions. The outwash flow-field can also exhibit azimuthal asymmetry since the vortices tend to persist near to the aircraft and interact, resulting in a localized strong ejection of vorticity, known as the "jetting phenomenon" [9]. To account for downwash on arrival and departure paths, the PTS recommends conducting a safety assessment for each individual aircraft (Req A3. (e)). It is important to note that eVTOLS generally are expected to produce higher downwash velocities than helicopters of the same weight, due to higher disc loading, which may have a more significant influence on path planning than the one for conventional helicopters.

The last issue considered in this study form the aircraft perspective, is the land use compatibility with Vertiports which main purpose is to safeguard urban infrastructure and residents from risk of accidents (Req. A7). Given the anticipated central location of Vertiports and their desired high operational frequency, this issue will surely gain importance for the UAM. Ison [10] highlights the scarce information and guidance on Vertiports positioning considering safety and analyzes available helicopter accident data in the USA to evaluate whether the current standards are adequate. The findings reveal that the majority of the accidents occur during landing (32%) and take-off (35%), with 75% of accidents within the range of 170 feet from the reference take-off and landing point. Ison concludes that the current FATO and SA requirements of the FAA do not cover the elevated risk zone identified in his study and recommends the need to develop guidelines aligned with available accident data. However, the operational and functional characteristics of eVTOLs might result in a different accident pattern. Among the accidents analyzed in [10], 82% involved one-engine and only 18% twin-engine helicopters. Given the distributed electric propulsion of eVTOLs, they may generally be less susceptible to major engine failures. Nonetheless, numerous factors influence the accident potential of eVTOLs, including system complexity leading to unforeseen failures, take-off and landing paths with turns which pose greater demands on pilots, and susceptibility to wind gusts for winged eVTOLs.

2.2 Wind

When inflow wind impinges on the surface of an isolated cubical building, pronounced vortexes of various scales are formed near the ground surface, on the leeward and lateral sides of the building, along with a possibility for flow separation on the roof [11]. These flow characteristics become more convoluted and often difficult to predict when an array of structures and architectural complexity are considered [12]. Furthermore, microscale wind flow is closely associated with other periodic natural phenomenons like seasons, coriolis force, etc., indicating that the likelihood and severity of such wind conditions depend on diverse factors. Such phenomenon would affect the primary purpose of Vertiports to facilitate landing and takeoff of UAM aircraft. Therefore, it is crucial to understand the wind pertinent hindrances to the design and development of Vertiport for strategically reducing the implications of wind on the overall UAM development (Req. W6, W8). This fact is also emphasized in [13] where a systematic review is performed on all the Vertiport publications and regulations thus far.

From an engineering standpoint, aircraft operations are limited to certain wind thresholds and flight envelopes to preserve safety. Hence, emplacing a Vertiport in an area where the surrounding wind velocity field is often prone to shear wind and gusts would risk both ground and air safety during near ground flight phases such as landing, takeoff, and FATO (Req. W2). This, in return, would diminish the Vertiport operational availability and ultimately, lead to disruptions in UAM operations[14, 15]. Thus, it is essential to account the wind constraints for Vertiport locations. Along similar lines, a consideration that is usually made for determining the takeoff and landing approach angles are the wind levels around the Vertiport –i.e, takeoff angle is aligned with the wind flow direction to avoid trajectory deviation, heavy pilot load, collision risks, loss of battery power, reduced aircraft performance, operational schedule changes (delays or early arrivals) [16], easy access to fire extinguisher in case of accident, etc (Req. W5). Hence, the take-off and landing pads or points must be designed in such a way that it is not oriented against the headwind by determining the frequency and amplitude of the microscale wind conditions (Req. W2).

As mentioned earlier, buildings distort wind flow, thus it is essential to also investigate the airflow across the Vertiport structures to obtain a thorough understanding of the wind flow field changes for different parameters such as wind incidence angle, speed, time of day, etc., (Req. W7) and to avoid incorporation of structures on Vertiports that contribute to increase in turbulence or wind shear [17] (Req. W1, W8). Similarly, it is also important to install wind sensors at critical locations on and around Vertiports for real-time awareness of wind conditions and relevant decision-making (Req. W3, W4).

2.3 Infrastructure and Urban form

The introduction of a new mobility system inside an urban environment will inevitably affect the city and its urban form. The first problem when introducing and importing the Vertiport inside an urban area is where to localize the new infrastructure. The problem of localization regards mainly the *size* of the Vertiport itself and the *position* in the city.

The size of the Vertiport, in terms of its extension, affects its placement inside the urban form. Although the Vertiport is a typology under experimentation, it is possible to group it in different categories. Vertihubs are the biggest one with more than 10 landing pads, Vertiports, Skyports, Vertistations are the most common ones with 5-10 landing pads, Vertipads are the smallest one with 1 up to 3 landing pads [3]. According to the flows generated by the Vertiport due to its position, the dimensions of the Vertiport can change (Req. U1). However, the relationship with the context will inevitably influence its volume, due to the available space and its modification of the urban design. It has to be highlighted that this new kind of mobility system won't generate a huge footprint on ground comparing to the other types of mobility services like highways, railways or metropolitan tracks. Consequently, its anchoring to the ground is even more relevant because its footprint won't generate barriers or walls [18], but can be the outcome of a mindful urban design process, integrating the structure in the context as an already existing element that enhance, define and become expression of the selected landscape [19]. An infrastructural project, in fact, deals with a scale that exceeds the boundary of the single building and connects in one project geography, urban design and landscape [19].

Vertiports require to be highly accessible to the public to be effectively used. Accessibility can be guaranteed through inter-modality (Req. U2) inside the city. They should be strongly connected with the ground-transportation system to ease the shift of the different mobility services [3]. Inter-modality arises problems on the nature of the connections of the new mobility layer on existing infrastructural nodes. The addition of UAM service in these intersection points can be adapted in the city, scaling the possible dimensional ranges of the Vertiport (from Vertipad to Vertihub) [1], according to the availability of space and function required. As a result, UAM can be spread more capillary, grasping even remote areas.

This new mobility system, in fact, allows to face even hard connections that metropolitan or urban area may challenge due to their particular topographical condition (i.e. the presence of a lake or a valley, a mountainside or seaside city) (Req. U3). The results of the simulation conducted by [20] in the Zurich metropolitan region highlight how the most demanded trips, even with an increase in the trip cost, are still the ones connecting not only outer cities, but also places separated by a harsh topography. Therefore, it is evident how Urban Air Mobility can fill in lack of adequate ground transportation system and can be a resource to be used for improving the connections towards inner areas or places with a difficult topographical situation. An adequate analysis of the urban form and urban pattern can address such topic and carefully manage and implement the urban design of the selected location.

Vertiports' position shapes the trip trajectories of the urban air mobility system, whose design is still under examination. [21] proposed an aerial network scenario derived from the localization of the Vertiport inside the city of Bologna (Italy), where the leading factors orienting the localization of Vertiports relies on the composition of the city in terms of population density, job density, median income, ground transportation, points of interest and possible constraints (e.g., proximity to schools, unavailability of space, etc). Eventually, their orientation of the Vertiports inside the city fell into central locations such as railway stations and median/high-income neighborhood. However, relying only on mono-disciplinary modelling can exclude of some portions of the city. This exclusion can eventually lead to exacerbate gentrification inside cities or exasperating the urban sprawl, due to faster connections only from city center to the high-income suburbs [22], impacting the urban form and design of the city. These aspects raises questions on the nature of the addition in relation to the whole quality of connections provided in the city. The relationship between the track and the stopover generates the experience of the infrastructure that should valorise the urban landscape where it is embedded [23], therefore its localization can grasp from both socio-demographic factors and the urban form and design of the city (Req. U4).

Infrastructural system constitutes the skeleton and the shape of current cities and urban environments. Roads and railways can provide guidelines and tracks for the development of future mobility (Req. U5). [24], in fact, set the UAM network from the organization of the current highway system. This process can guarantee distribution of the service and adaptability to every morphological situation.

2.4 Architectural design

The conceptualization of Vertiports within urban environments heralds a significant paradigm shift in architectural design, unveiling an urban design problem [25]. This shift is rooted in the dual objectives of Vertiports: to meet the complex technical requirements of eVTOL aircraft and to integrate seamlessly into the densely populated urban fabric. The design of Vertiports is intrinsically linked to the dimensions and specifications of eVTOL aircraft [3] and operations (Req. AD5), where the vehicles' size, weight, and operational needs critically influence the spatial and dimensional considerations of Vertiport infrastructure. This connection necessitates an approach that extends beyond traditional aesthetic and spatial considerations, incorporating advanced technologies and addressing the operational dynamics of urban air mobility.

Typology (Req. AD1) is at the core of Vertiport design. It engages with the form and function of analogous architectures, guiding the transformation operations [26] that allow pass-through the implementation of various functions, such as transportation hubs and commercial complexes. Defining typology represents a framework that systematically classifies and differentiates architectural elements based on their inherent characteristics and functions. The concept of typology emerges as a key element, tackling the dual challenges of ensuring eVTOL functionality and achieving harmonious integration with the urban environment to serve community functions. Typology provides a framework that guides Vertiport's categorization and development.

External events, such as new techniques or societal changes, often drive architects towards creating a new architectural type [27], establishing a dialectical relationship with history. The interplay between typology and innovation is a fundamental force shaping architectural evolution. Within this architectural narrative, the interplay between typology and sustainability becomes crucial, underscoring a holistic approach to Vertiport design that is both innovative and environmentally conscious. The typological adaptability of Vertiport design emerges as a critical element for navigating evolving urban landscapes and addressing environmental challenges. This flexibility ensures Vertiports's long-term sustainability and functionality (Req. AD4), underscoring the integral relationship between typology and the capacity to respond to dynamic contextual shifts. Through their versatile typological framework, Vertiports position themselves as resilient infrastructural elements capable of accommodating the evolving demands of both environmental and urban dynamics. Typology, in its essence, provides a blueprint for understanding how Vertiports can be integrated into the urban fabric, not just as functional infrastructures but as embodiment of sustainable development.

By leveraging typological insights, Vertiport designs prioritize energy efficiency and the integration of renewable energy sources and pioneer new benchmarks in sustainable infrastructure [28]. This approach incorporates green roofs, vertical gardens, and other elements that enhance urban biodiversity and air quality, thereby improving community well-being and the aesthetic appeal of urban landscapes. Sustainable water management practices, including rainwater harvesting, grey-water recycling, and environmentally friendly materials and construction methods. Through these strategies (Req. AD2), Vertiports emerge as exemplars of how architectural design can harmonize operational efficiency with environmental stewardship and social benefits, marking a significant evolution in urban infrastructure planning. The typological approach also highlights the importance of community integration and accessibility, ensuring that Vertiports serve as inclusive public spaces that enhance urban connectivity and social cohesion (Req. AD3). This perspective encourages the design of Vertiports as multi-functional hubs, supporting urban air mobility and serving as vibrant centers for social interaction, commerce, and recreation.

The principle of adaptive and resilient design, informed by typology, enables Vertiports to manage shifts in urban landscapes and environmental challenges. It underscores the need for Vertiports to be flexible and resilient, ensuring their long-term sustainability and functionality in the face of climate change and other urban pressures.

3 Requirements analysis

The different categories describe a series of specific issues that affect the design and the localization of the Vertiport. All these issues represent the identified requirements. The requirements have been listed together in the the tables provided in the Appendix. An ID has been assigned to each requirement, matching the number with a letter related to the category it belongs to. The following mind map, see Figure 4, visualizes the results of the comparative analysis, pointing out in blue the overlapping requirements and in red the conflicting ones. The same

ID of the tables' requirements has been used, grouping on the left side aeronautical features and on the right side architectural and urban characteristics.

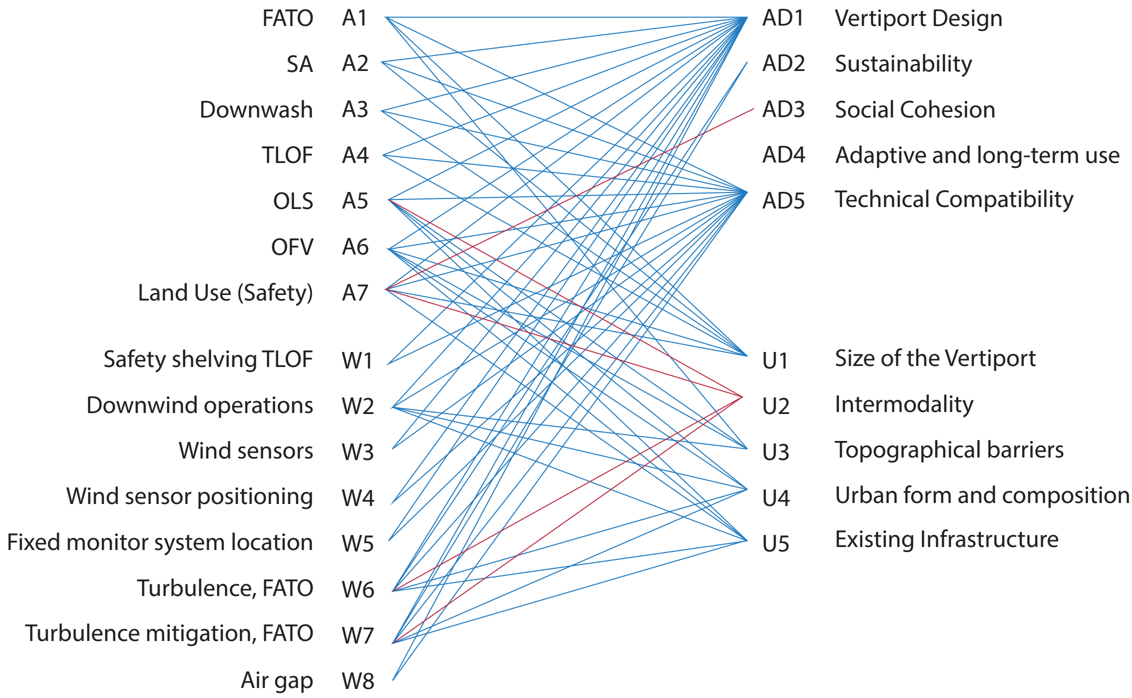

Figure 4: Mind Map (Overlaps in blue and contradictions in red)

Aircraft requirements (A1-A6) shall form a basis for the Vertiport design (AD1, AD2, AD5) and the size of the Vertiport related to its scaling into the city (U1). Moreover, wind indicators affect the typological and technical specifications of the Vertiport (W3, W4 with AD1, AD5), as they require space to be inserted where there is little turbulence. The wind requirements W6 and W7 related to the suitable distance of TLOF/FATO from objects that can cause air turbulence (trees, buildings, terrain, etc.) is linked to the urban form of the city (U4) and the network of the existing infrastructural system (U5), constituting a first input of Vertiport localization. In fact, if for example there is the will to insert the Vertiport inside a certain neighborhood, then suitable specific location can be selected by considering both urban form of the area as well as the interference of wind with nearby buildings. A hint can be given by existing infrastructural tracks, where in the immediate nearby, due to the free-space required by buffer zones, there is less occupied volume that can impact wind flow. Finally, the Vertiport design itself (AD1) must be compatible with the location of the TLOF/FATO. Direction of take-off and landing paths (A5, A6) is dependent on the main direction of the wind in the Vertiport direct surroundings (W2) and affects the Vertiport design (AD1) and its location (U3, U4).

It can be seen on the mind map that several conflicts have emerged. Vertiport integrating various services will attract many people (AD3) and create gatherings which will worsen the possible consequences of an accident (A7). Inter-modal nodes (U2) represent as well one of the main issues of contradictions, due to their typical position in congested and crowded areas. This aspect can constitute an increase of danger in case of possible accidents (A7) and can affect the generation of turbulence (W6, W7). Moreover, it might be difficult to provide adequate obstacle environment (A5, A6) around dense urban tissues. If there is a penetration of the OLS by masts, buildings, or areas of high ground, the possible directions of take-off/landing paths are restricted (contradiction between U2, U3, U5 and A5). Inter-modal connections represent a boost for the implementation of the service, however generally inter-modal nodes are located in high-density areas where the level of urbanization is high too, reducing the availability of space both for Vertiport placing and aircraft maneuvering procedures [21].

The following histogram, see Figure 5, shows the number of times the requirements are related to each other, separating the count for overlapping and conflicting connections. From the histogram, it can be noticed how four requirements do not overlap at all. Inter-modality (U2) and Social Cohesion (AD3) present only situation of conflicts, while requirement Adaptive and long-term use (AD4) is mainly related to architectural features of the building that do not intersect other requirements. Requirement AD1 and AD5 present the maximum number of overlapping, in fact technical compatibility is strictly linked to safety issues and the typological layout of the

Vertiport can guarantee an adequate and functional internal and external organization of all the technical specifications. The histogram reveals more coherent situations rather than contradictions. This aspect positively affects the collaboration activities in reality. However, attention should be given to conflicting issues, that can require tight collaboration.

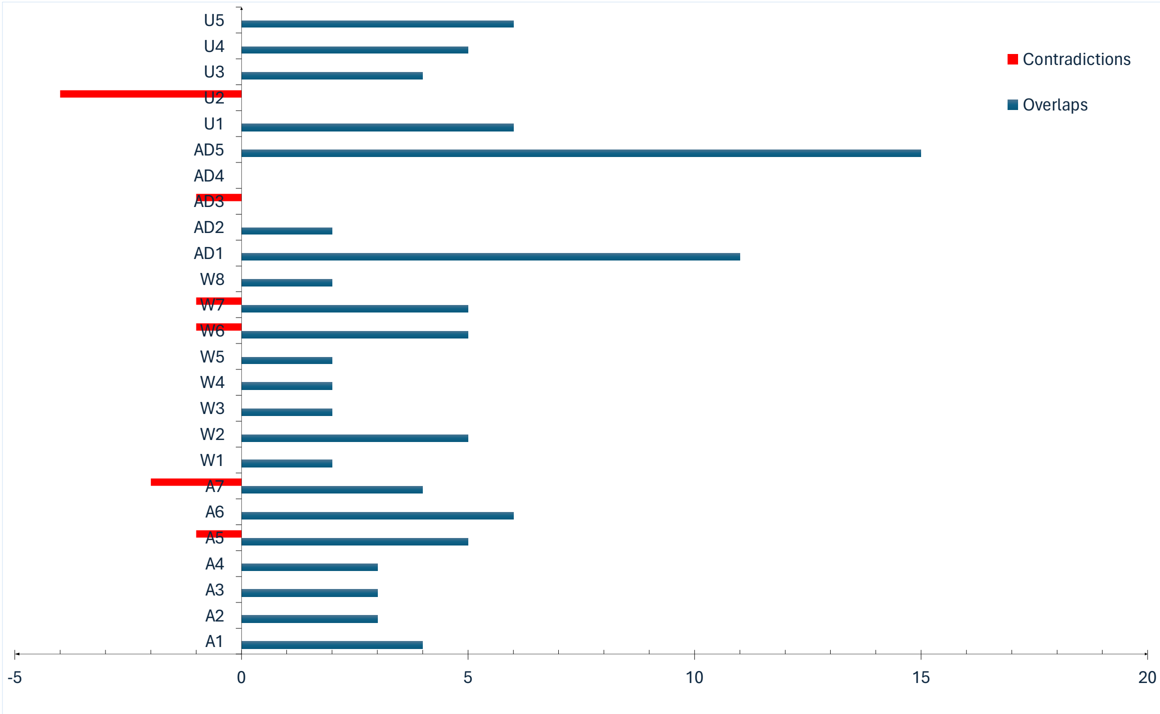

Figure 5: Histogram showing number of overlapping and contradicting requirements

4 Discussion

As indicated by the requirements comparison, the starting point for possible collaboration should be oriented towards the aspects of overlap to provide integrated solutions while also addressing conflicting aspects through collaborative efforts. Inter-modal nodes may represent a tough allocation for Vertiports, due to the need to be reconciled with aircraft obstacle avoidance requirements and the wind behaviour. Therefore, tackling wind effects on the surroundings paired with future urban design development, it is possible to boost suitable areas, even at the outskirts or in broader metropolitan regions, that will hold an inter-modal primary role.

The combination of technical safety requirements and typological architectural analysis, as shown in the mind map before (AD1 with A1-7), can orient the research towards joint solutions to design an effective new infrastructure. In addition to spaces required for aircraft, ground equipment and personnel operation, interlaced areas to accommodate and arrange people flow must be provided. For example, some airports lack areas where to comfortably wait for the flight or do not provide children space and entertainment in case of a possible delay. Moreover, the design of multi-level spaces (accessibility to the underground levels) and the re-allocation of mobility flows in safer areas can be employed to reduce the consequences in case of accidents.

A tool for cooperation can rely on Geographic Information Systems (GIS) [1]. It has been used in the literature for the definition of suitable locations for Vertiports [3], even to test virtual spatio-temporal constraints like no fly zones, wind, etc. [29]. These models can be detailed up to the building design, increasing their level of precision and providing real-life examples that could provide insights to improve engineering and urban regulatory framework. For example, the detailed city/Vertiport models can be used within urban-wind simulating software. The wind data and obstacle environment can be imported into the aircraft flight dynamics simulation model to establish approach/departure trajectories. Finally, the obstacle environment and Vertiport design rendering can be uploaded into flight simulators to verify visual aids provided to the pilot and established landing/take-off procedures.

[1] GIS database generates virtual maps of the territory, geopositions and adds social, economic and demographic data

5 Conclusion

This paper introduces the effort undertook by the Department of Aerospace Science and Technology and Department of Architecture and Urban Studies at Politecnico di Milano to tackle the challenges related to the Vertiport design and development. As an initial step of this interdisciplinary research collaboration, a list of requirements and critical objectives have been identified through a literature survey to qualitatively analyze and determine how and which engineering requirements and architectural objectives overlap or contradict.
The outcome of this paper is currently being utilized to establish research questions and cooperation research topics which form a foundation in the case of future implementation of a real-world Vertiport design. The authors acknowledge that many aspects and issues related to Vertiport design and placement may only become apparent during specific implementation and thus cannot be fully addressed through this high-level analysis alone. However, it is evident that two primary directions of collaboration emerge. The first direction pertains to determining suitable Vertiport locations that ensure inter-modality while also fulfilling technical requirements regarding obstacles, downwash, wind, and turbulence. Additional measures and collaborative efforts are necessary to mitigate the risk of accidents involving eVTOLs and their potentially catastrophic consequences due to operation in areas of high population density. The second direction concerns the design typology of Vertiports, which must adhere to aircraft and wind requirements while also providing commodities to the Vertiport users. The joint focus can be expanded to explore the implications of sustainable designs on UAM ground operations. The tools used by different disciplines, as identified in Chapter 4 (citation), shall be further integrated and used in a specific application. This collaboration could further involve crucial stakeholders such as civil engineers, UAM operators, UAM service providers and acoustic engineers.

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References

[1] European Union Aviation Safety Agency. *Study on the societal acceptance of Urban Air Mobility in Europe*. European Union Aviation Safety Agency, 2021.

[2] L.A. Garrow, B.J. German, and C.E. Leonard. Urban air mobility: a comprehensive review and comparative analysis with autonomous and electric ground transportation for informing future research. *Transport. Res. C Emerg. Technol.*, 132:1–31, 2021.

[3] Matteo Brunelli, Chiara Caterina Ditta, and Maria Nadia Postorino. New infrastructures for urban air mobility systems: A systematic review on vertiport location and capacity. *Journal of Air Transport Management*, 112, 2023.

[4] A. Cohen and S. Shaheen. Advanced air mobility: Opportunities, challenges, and research needsfor the state of california (2023-2030). *UC Office of the President: University of California Institute of Transportation Studies*, 2024.

[5] European Union Aviation Safety Agency (EASA). *Special Condition for small-category VTOL aircraft (SC-VTOL) - Issue 1*, 2019.

[6] European Union Aviation Safety Agency (EASA). *Vertiports: Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category (PTS-VPT-DSN)*, 2022.

[7] Federal Aviation Administration (FAA). *Engineering brief No. 105, Vertiport Design*, 2022.

[8] European Union Aviation Safety Agency (EASA). *Second Publication of Proposed Means of Compliance with the Special Condition VTOL (MOC-SC-VTOL) - Issue 1*, 23 June 2021.

[9] Richard E Brown. Do evtol aircraft create an inherently more problematic downwash than conventional helicopters? In *49th European Rotorcraft Forum, Bückeburg, Germany.*, 2023.

[10] David Ison. Compatible land use for heliports and vertiports: A safety perspective. *International Journal of Aviation Research*, 2024.

[11] J Hunt. Fundamental studies of wind flow near buildings. In *Models and Systems in Architecture and Building - LUBFS Conference Proceedings No. 2*, 1975.

[12] J. Peterka, R. Meroney, and K. Kothari. Wind flow patterns around buildings. *J. Wind. Eng. Ind. Aerodyn*, 21, 1985.

[13] Karolin Schweiger and Lukas Preis. Urban air mobility: Systematic review of scientific publications and regulations for vertiport design and operations. *Drones*, 2022.

[14] James C. Jones, Timothy Bonin, and Erin Mitchell. Evaluating wind hazards for advanced air mobility operations. In *AIAA Aviation Forum*, 2023.

[15] Karolin Schweiger, Reinhard Schmitz, and Franz Knabe. Impact of wind on evtol operations and implications for vertiport airside traffic flows: A case study of hamburg and munich. *Drones*, 2023.

[16] Northeast UAS airspace integration and research alliance (NUAIR). High-density automated vertiport concept of operations. Technical report, Nuair, 2021.

[17] Abdulghani Mohamed, Matthew Marino, Simon Watkins, Justin Jaworski, and Anya Jones. Gusts encountered by flying vehicles in proximity to buildings. *Drones*, 2023.

[18] Elena Mussinelli. Hub intermodali e infrastrutture urbane per la qualità ambientale e fruitiva della città. In Elena Mussinelli and Andrea Tartaglia, editors, *Nodi infrastrutturali e rigenerazione urbana. Stazioni, spazio pubblico, qualità ambientale*, chapter 13-22. Maggioli Editore, 2020.

[19] Vittorio Gregotti. Il territorio delle infrastrutture. In Alberto Ferlenga, Marco Biraghi, and Brenno Albrecht, editors, *L'architettura del mondo. Infrastrutture, mobilità, nuovi paesaggi*, chapter 150-157. Editrice Compositori, 2012.

[20] Balac M., R. L. Rothfeld, and S. Hörl. The prospects of on-demand urban air mobility in zurich,switzerland. *IEEE Intelligent Transportation System Conference (ITSC)*, 2019.

[21] Matteo Brunelli, Chiara Caterina Ditta, and Maria Nadia Postorino. A framework to develop urban aerial networks by using a digital twin approach. *Drones*, 2022.

[22] A. Straubinger and R. Rothfeld. Identification of relevant aspects for personal air transport system integration in urban mobility modelling. *Proceedings of 7th Transport Research Arena TRA*, 2018.

[23] Giacomo Polin. L'autostrada come opera d'arte. In Alberto Ferlenga, Marco Biraghi, and Brenno Albrecht, editors, *L'architettura del mondo. Infrastrutture, mobilità, nuovi paesaggi*, chapter 112-119. Editrice Compositori, 2012.

[24] Antcliff K. R., Kolhman L.W., and Patterson M. D. A proposed approach to studying urban air mobility missions including an initial exploration of mission requirements. *Annual Forum and Technology Display, NTRS - NASA Technical Reports Server*, 2018.

[25] Marc Mitchell Cohen. The vertiport as an urban design problem. *SAE Technical Papers*, 1996.

[26] Carlos Matís Arís. *Variations of Identity Type in Architecture*. Editíon Cosa Mentale, 2021.

[27] Rafael Moneo. On typology. *Oppositions*, 1978.

[28] Antônio Márcio Tavares Thome, Paula Santos Ceryno, Annibal Scavarda, and Arne Remmen. Sustainable infrastructure: A review and a research agenda. *Journal of Environmental Management*, 2016.

[29] A. Bauranov and J. Rakas. Designing airspace for urban air mobility: a review of concepts and approaches. *Prog. Aero. Sci.*, 125:1–27, 2021.

Appendix

Existing aircraft and wind relevant requirements from EASA and FAA standards, and key architectural objectives for designing Vertiports.

ID	Name	Requirements/ Objectives
		Engineering - Aircraft relevant requirements from EASA [6]
A1	PTS VPT-DSN.C.210 Final-approach and take-off areas (FATOs)	"(c) The minimum dimensions of a FATO should be: (1) the length of the RTODV for the required take-off procedure that is prescribed in the aircraft flight manual (AFM) of the VTOL-capable aircraft for which the FATO is intended, or 1.5 Design D, whichever is greater; and (2) the width for the required procedure that is prescribed in the AFM of the VTOL-capable aircraft for which the FATO is intended, or 1.5 Design D, whichever is greater. Note: Local conditions, such as elevation, temperature, and permitted manoeuvring may have to be considered when determining the size of an FATO in accordance with SC VTOL.2105. (f) The FATO should be located so as to minimise the influence of the surrounding environment, including turbulence, which could adversely affect VTOL-capable aircraft operations."
A2	PTS VPT-DSN.C.220 Safety areas	"(c) The SA surrounding an FATO should extend outwards from the periphery of the FATO for a distance of at least 3 m or 0.25 Design D, whichever is greater."
A3	PTS VPT-DSN.C.230 Down-wash protection	"(a) The AFM for VTOL-capable aircraft provides the value of the downwash that is measured on a 2 D circle while the aircraft is in a 1-m hover in no-wind conditions. (b) This value can be used to evaluate the adequacy of the SA to protect from downwash. An initial evaluation can be carried out using the values of Table C-1. However, the evaluation should be complemented by a study taking into account the specific local conditions and relevant wind comfort criteria of the affected population (e.g. bicycle path, vegetation, light structures, local regulations, etc.)." (e) "A downwash will also be generated on the arrival or departure paths and may affect other areas of the Vertiport and nearby environment. A safety assessment and an operational evaluation of individual aircraft type to be approved for a given Vertiport is thus also recommended."
A4	PTS VPT-DSN.C.260 Touch-down and lift-of area (TLOF)	"(c) A TLOF should: (1) provide: (i) an area free of obstacles and of sufficient size and shape to ensure containment of the undercarriage of the most demanding VTOL-capable aircraft the TLOF is intended to serve in accordance with the intended orientation; (2) be associated with a FATO, a portion of a taxiway or a stand. (d) The minimum dimensions of a TLOF should be 0.83 D or the dimensions for the required procedure prescribed in the AFM of the VTOL-capable aircraft for which the TLOF is intended, whichever is greater."
A5	PTS VPT-DSN.D.405 General (Obstacle Limitation Surfaces)	"(a) In order to safeguard a VTOL-capable aircraft during its approach to the FATO and in its climb after take-off, an approach surface and a take-off climb surface through which no obstacle is permitted to project is established for each approach and take-off climb path designated as serving the FATO.

ID	Name	Requirements/ Objectives
	Engineering - Aircraft relevant requirements from EASA [6]	
A6	PTS VPT-DSN.D.445 Generic volume (Obstacle-Free Volume)	"(b) The minimum dimensions required for such surfaces will vary considerably and depend on the: (1) VTOL-capable aircraft size, its climb gradient, particularly for critical failure for performance (CFP), its approach speed and rate of descent on the final approach, and its controllability at such speeds; and (2) conditions under which the approaches/departures are made." "The obstacle-free volume is derived from the vertical take-off and landing procedure volume, provided in the AFM, expressed in terms of the parameters [...]": $$h_1, h_2, TO_{width}, TO_{front}, TO_{back}$$ $$FATO_{width}, FATO_{front}, FATO_{back}, \theta_{app}, \theta_{dep}$$ which are generic vertical take-off and landing procedure parameters.
A7	Compatible land use for Vertiports from the standpoint of safety	Considerations of an accident due to mix of human factors and A/C failures and minimization of its consequences for city infrastructure and residents.
	Engineering - Wind relevant requirements from EASA & FAA [6, 7]	
W1	PTS VPT-DSN.C.260 Touch-down and lift-of-area (TLOF)	"Where the safety shelving is provided, rather than netting, the construction and layout of the shelving should not promote any adverse wind flow issues over the FATO, while providing equivalent personnel safety benefits."
W2	PTS VPT-DSN.D.405 General (Obstacle limitation surfaces)	"Vertiport design and location should be such that downwind operations are avoided, crosswind operations are kept to a minimum, and balked landings can be carried out with the minimum change of direction."
W3	PTS VPT-DSN.E.510 Wind direction indicator	"A Vertiport should be equipped with at least one wind direction indicator."
W4	"	"For FATOs located in environments where the airflow may be disturbed by nearby objects, such as in urban Vertiports and congested areas, where more than one wind direction indicator may be needed, or when the wind direction indicators may be difficult to place near the FATO that is elevated, information on the wind direction, speed, gusts or turbulence may be obtained from meteorological stations near the FATO and be broadcasted/ radio transmitted to the pilots."
W5	PTS VPT-DSN.G.1010 Hazard area	"Where a fixed monitor system (FMS) is installed, trained monitor operators, where provided, should be positioned on at-least the upwind location to ensure the primary extinguishing agent is directed efficiently to the seat of the fire."
W6	FAA 6.4 Turbulence	"When possible, locate the TLOF away from buildings, trees, and terrain to minimize air turbulence near the FATO and the approach/ departure paths."
W7	"	"Assess the turbulence and airflow characteristics near and across the surface of the FATO to determine if a turbulence mitigating design measures are necessary (e.g., air gap between the roof, roof parapet, or supporting structure)."
W8	"	"A minimum 6ft (1.8m) unobstructed air gap on all sides above the level of the top of a structure (e.g., roof) and the elevated Vertiport will reduce the turbulent effect of air flowing over it."

ID	Name	Requirements/ Objectives
		Infrastructure & Urban form objectives
U1	Size of the Vertiport	The size of the Vertiport in terms of extension and capacity (Vertihub, Vertiport, Vertipad) affects its placement and pervasiveness inside the urban environment.
U2	Inter-modality	Inter-modality and ground transportation connections are essential in providing an effective system and easing the shift with different mobility services.
U3	Topographical barriers	The Vertiport localization can ease the connections towards metropolitan or urban areas where the current topography can slow or challenge direct connections.
U4	Urban form and composition	In the modelling and design of the UAM system and Vertiport location choice, socio-demographic, economical factors and the urban form of the city should be taken into account as a spatial input, balancing the distribution of the derived benefit and valorising landscape.
U5	Existing infrastructural system	Existing infrastructural system can provide guidelines and tracks in the localization of the Vertiport and design of its flow.
		Architectural design objectives
AD1	Vertiport Design	Using a typological framework in Vertiport design is a strategic and fundamental approach, guiding the categorization and development of these structures. This design approach involves systematic classification based on inherent characteristics, contributing to creating a framework. This framework ensures adaptability and versatility in Vertiports by accommodating diverse functions, fostering a harmonious coexistence of components, and facilitating flexibility to meet evolving needs in urban air mobility.
AD2	Sustainable Integration	The design should prioritize environmental stewardship, energy efficiency, biodiversity enhancement, water conservation, and new and sustainable construction methods.
AD3	Social Cohesion	They should serve as inclusive public spaces, fostering social interaction, commerce, and recreation. This perspective ensures that Vertiports contribute positively to urban connectivity and social cohesion.
AD4	Adaptive and long-term use	The design is flexible and capable of managing shifts in urban landscapes and environmental challenges. This approach guarantees Vertiports' long-term sustainability and functionality in the face of climate change and other urban pressures.
AD5	Technical Compatibility	Vertiport design must consider meeting the technical requirements of eVTOL aircraft. This includes considerations for the vehicles' dimensions, weight, and operational needs, as these factors critically influence the spatial and dimensional aspects of Vertiport infrastructure. The design should ensure seamless integration with eVTOL technology, supporting safe takeoff, landing, and efficient operations.