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Operational Challenges and Prioritization of Potential Solutions for Integrating Vertiports into Airports

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Abstract

The integration of vertiports into airports for eVTOL/UAV flights poses operational challenges. The aim of the study was to propose and prioritize solutions to overcome these challenges. A comprehensive literature review identified remote vertiport networks, geofencing technology, dedicated airspace corridors, advanced collision avoidance systems and dynamic airspace management as potential solutions. These solutions were prioritized using the Analytic Hierarchy Process (AHP) based on criteria such as safety, cost, efficiency, feasibility, and sustainability. Dynamic airspace management (=0.396) was the highest priority, followed by remote vertiport networks (=0.385), dedicated airspace corridors (=0.273), geofencing technology (=0.205), and advanced collision avoidance systems (=0.137). The study highlights the importance of dynamic data sharing and real-time planning through integrated ATM/UTM systems, enhanced by AI technologies, to ensure safety and efficiency. In addition, the development of remote vertiport networks and dedicated airspace corridors is essential to manage growing air traffic and ensure the safe coexistence of eVTOL/UAVs and traditional aircraft. Geofencing technology and advanced collision avoidance systems are also essential to maintain safety and operational integrity. It is recommended that future studies focus on the integration of ATM/UTM and the application of artificial intelligence. Continued collaboration between UAM stakeholders is essential to develop effective integration strategies.

Keywords: Airport, electric vertical take-off and landing, unmanned aerial vehicle, unmanned traffic management, urban air mobility, vertiport.

Havalimanlarına Vertiportların Entegrasyonundaki Operasyonel Zorluklar ve Potansiyel Çözümlerin Önceliklendirilmesi

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Özet

Vertiportların eVTOL/UAV uçuşları için havalimanlarına entegrasyonu fırsatlarla beraber operasyonel zorlukları da beraberinde getirmektedir. Bu çalışmanın amacı, bu zorlukların üstesinden gelmek için çözümler önermek ve bu çözümleri önceliklendirmektir. Kapsamlı bir literatür taraması sonucunda havalimanı civarında vertiport ağları, coğrafi sınır belirleme teknolojisi, ayrılmış hava sahası koridorları, ileri çarpışma önleme sistemleri ve dinamik hava sahası yönetimi gibi potansiyel çözümler belirlenmiştir. Bu çözümler emniyet, maliyet, verimlilik, uygulanabilirlik ve sürdürülebilirlik kriterlerine dayalı olarak Analitik Hiyerarşi Süreci (AHP) kullanılarak önceliklendirilmiştir. Dinamik hava sahası yönetimi (=0.396) en yüksek önceliğe sahipken, bunu sırasıyla havalimanı civarına konumlandırılan vertiport ağları (=0.385), ayrılmış hava sahası koridorları (=0.273), coğrafi sınır belirleme teknolojisi (=0.205) ve ileri çarpışma önleme sistemleri (=0.137) takip etmiştir. Çalışma uçuş emniyeti ve verimliliği sağlamak için entegre ATM/UTM sistemleri aracılığıyla dinamik veri paylaşımı ve gerçek zamanlı planlamanın, yapay zeka teknolojileriyle desteklenmesinin önemini vurgulamaktadır. Ayrıca artan hava trafiğini yönetmek ve eVTOL/UAV'ların geleneksel hava araçlarıyla emniyetli bir şekilde bir arada bulunmasını sağlamak için havalimanı civarına konumlandırılan vertiport ağlarının ve ayrılmış hava sahası koridorlarının geliştirilmesi gereklidir. Coğrafi sınır belirleme teknolojisi ve ileri çarpışma önleme sistemleri de operasyonel bütünlüğü sürdürmek için önemlidir. Gelecek çalışmaların ATM/UTM entegrasyonuna ve bu entegrasyonda yapay zekanın uygulanmasına odaklanması önerilmektedir. UAM paydaşları arasındaki sürekli iş birliği, etkili entegrasyon stratejileri geliştirme sürecine fayda sağlayacaktır.

Anahtar Kelimeler: Havalimanı, elektrikli dikey kalkış ve iniş hava aracı, insansız hava aracı, insansız hava araçları trafik yönetimi, kentsel hava hareketliliği, vertiport.

1. Introduction

Urbanization leads to an increase in the volume of traffic in cities, resulting in traffic congestion. Congestion causes delays, inconvenience, economic loss and air pollution (Afrin & Yodo, 2020; Jain et al., 2018). These negative effects are particularly pronounced for transport between airports and city centers, which are often located far from city centers and are often chosen for their short travel times. The provision of efficient and modern transport services between cities and airports is therefore of paramount importance (Caulfield et al., 2013).

The development of Urban Air Mobility (UAM) technologies may offer a potential solution to the challenge of providing efficient and modern transport services between cities and airports. The current period is one of great excitement for those involved in the development of UAM, as it represents a significant opportunity to fundamentally change the paradigm of urban transport (Cizrelioğulları et al., 2022; Gillis et al., 2021; Tuncal & Uslu, 2021). Defined as intra-city air mobility, UAM encompasses Electric Vertical Take-Off and Landing (eVTOL) vehicles, including Unmanned Aerial Vehicles (UAVs). eVTOLs/UAVs have the potential to radically change urban transport infrastructure in the near future. It is expected that in the near future (Ackerman et al., 2021; Clarke et al., 2019; Lombaerts et al., 2020; McQueen, 2021; Qu et al., 2023). The benefits of eVTOLs/UAVs include reduced noise and emissions, increased safety, and vertical take-off and landing capabilities. eVTOLs/UAVs represent a promising solution to the urban transport challenge, providing a faster, more efficient and environmentally friendly way to travel point-to-point, offering an alternative to traditional ground transport (Eissfeldt, 2020; Guida et al., 2023; Kleinbekman et al., 2018; Mudumba et al., 2021; Raigoza et al., 2022; Rothfeld et al., 2021; Yang et al., 2020).

Traffic congestion between airports and cities is becoming increasingly problematic, making it difficult for travelers to reach their destinations. In response to this challenge, the concept of UAM is emerging as a promising solution. The proposal is to build dedicated landing infrastructure, called "vertiports", directly at airports. This initiative aims to integrate eVTOLs/UAVs into the broader framework of urban transport. Vertiports are designed to facilitate the functionality of eVTOLs/UAVs, serving both passenger and cargo operations within urban and sub-urban landscapes (Thu et al., 2022; Zelinski, 2020). The planned and effective integration of vertiports into airports plays a critical role in maximizing the potential of UAM (Park et al., 2020). However, in order to ensure the successful and sustainable implementation of vertiports at airports, it is essential that factors such as space constraints, operational requirements and safety concerns are considered. The growing demand for air travel is driving the continuous upgrading of airport infrastructure, which is becoming increasingly complex (Abeyratne & Abeyratne, 2014; Zanin & Lillo, 2013). Similarly, increased traffic volume leads to more complex operations (Cheng, 2004; Sridhar et al., 2008; Tomaszewska et al., 2018; Xie et al., 2004; Zhang, 2019). In order to prevent any accidents or incidents, all safety concerns are given the highest priority at airports (Chang et al., 2015; Janic, 2000; Koscak et al., 2019).

The evolution of the UAM concept is leading to the emergence of vertiport implementations at airports. Airport vertiport operations allow eVTOLs/UAVs to operate independently of aircraft traffic and existing airport operations. Such operations can use either existing airport infrastructure or dedicated vertiport facilities. It may be necessary to construct separate vertiport facilities and implement special approach and departure procedures in the event that air traffic volumes affect operations (Michael & Meyers, 2022). The first vertiport passenger terminal in Europe was unveiled at Pontoise-Cormeilles airport in France, providing a complete passenger experience for future eVTOL/UAV operations. A vertiport has also been built at Rome's Fiumicino airport following a successful test flight, paving the way for the introduction of UAM services by 2024 (Volocopter, 2022). In the meantime, São Paulo Airport is developing plans to construct a vertiport hub, with the objective of connecting Guarulhos to other areas where eVTOLs/UAVs are in operation, by 2026 (Future Travel Experience, 2022). Furthermore, a passenger terminal testbed has been unveiled at Pontoise-Cormeilles airfield in France, offering a comprehensive passenger experience for prospective eVTOL/UAV operations (Groupe ADP, n.d.). In addition to these existing projects, the planned vertiport hub development at Al Maktoum Airport in Dubai is anticipated to commence commercial operations by the targeted timeframe of 2025-2026 (Vitale, 2023).

A review of the literature on vertiport studies revealed that the majority of research has focused on the design aspects (Peng et al., 2022; Preis, 2021; Preis, 2023; Taylor et al., 2020; Yedavalli, 2021; Zelinski, 2020), operations (Ellis et al., 2023; Preis & Hornung, 2022; Schweiger & Preis, 2022; Song et al., 2021) and capacity (Brunelli et al., 2023; Preis & Vazquez, 2022; Rimjha & Trani, 2021; Unverricht et al., 2024; Vascik & Hansman, 2019). A recent study has been conducted to develop an analytical model for eVTOL/UAV as air taxi operations and their capacity impact on airports (Ahrenhold et al., 2021). However, there appears to be a noticeable gap in the literature concerning the integration of vertiports into airports. Addressing this critical gap is essential for the successful implementation of UAM.

The aim of the study is to propose solutions to overcome the challenges associated with the integration of vertiports into airports and to prioritizes these solutions using the Analytic Hierarchy Process (AHP). This study is important because it serves as a valuable resource for policy makers, airport operators, air navigation service providers, Unmanned Traffic Management (UTM) service providers and other stakeholders involved in the development of vertiport infrastructure. It also helps to identify key research gaps that need to be filled to ensure the safe and efficient integration of vertiports into airports.

The study acknowledges a number of limitations. These include difficulties in keeping data up to date due to rapid advances in eVTOL/UAV technologies, potential limitations in scope due to regulatory issues and differences in infrastructure, and reliance on existing research without introducing new findings. Despite these limitations, the study remains significant in providing a thorough overview of the challenges and prioritizing solutions associated with integrating vertiports into airports. This research will help shape policies and regulations to ensure the safe and efficient integration of vertiport infrastructure into the aviation system. The study first examined the topology of vertiports and then detailed the challenges and proposed solutions for integrating vertiports into airports based on existing literature.

2. Vertiport Topology

A vertiport is comprised of a series of essential and optional components, each of which contributes to the overall functionality and safety of the facility. The fundamental building blocks, illustrated in Figure 1, include one or more Final Approach and Take-off (FATO) areas, which serve as designated zones for the critical phases of flight operations. Additionally, vertiports comprise one or more Touchdown and Lift-off (TLOF) areas, which provide the specific locations for eVTOLs/UAVs to land and take-off. Protection areas are of great importance in ensuring the safety and security of both aircraft and personnel. They serve to mitigate potential hazards. Furthermore, taxiways and/or taxi-routes are established to facilitate the movement of aircraft within the vertiport, ensuring efficient ground operations. Finally, stands are designated spots where aircraft can be parked, serviced, or boarded, enhancing the operational capacity of the vertiport (Australia CASA, 2023).

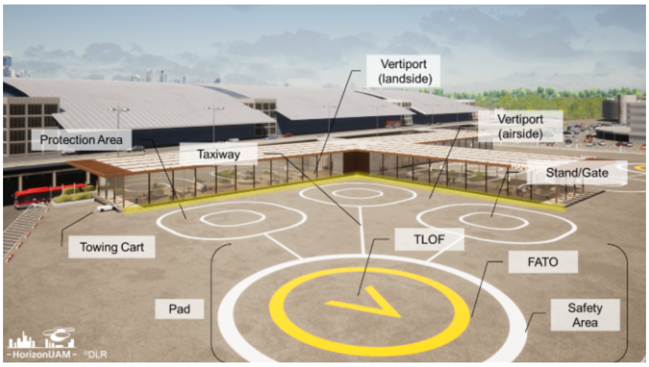

Figure 1. Vertiport topology terms used in the context of UAM (Schweiger & Preis, 2022).

2.1. Final Approach and Take-off (FATO)

The FATO area represents a fundamental component of vertiports designed for UAM. It serves to facilitate aircraft operations, and each vertiport must be equipped with at least one FATO (Ahn & Hwang, 2022). This area is a designated flat zone that has been specifically designed to facilitate safe and precise maneuvers for eVTOLs/UAVs. It plays a crucial role in ensuring the safety and efficiency of autonomous on-demand flight operations (Yang & Wei, 2021). The FATO may be located at ground level, on elevated structures, or at roof-top level. The TLOF, depicted in Figure 2, is situated at the center of the FATO. It is surrounded by the safety area. It is recommended that the FATO and the safety area share the same shape as the TLOF, which may be circular, square or rectangular (Michael & Meyers, 2022).

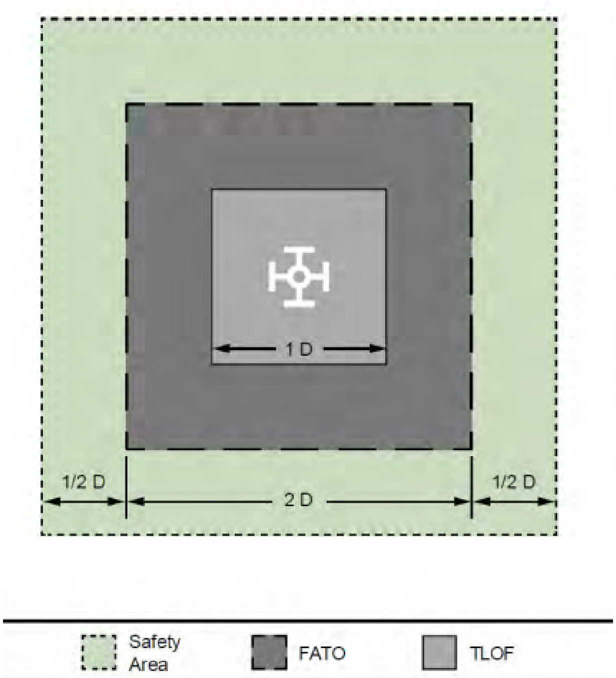

Figure 2. FATO, TLOF, and safety area (Michael & Meyers, 2022).

2.2. Touchdown and Lift-off Area (TLOF)

A vertiport necessitates the presence of a TLOF in all instances where an aircraft is anticipated to touch down or take-off within the confines of a FATO or stand. The location, dimensions and construction of TLOFs are of great importance for the safety of operations. It should be capable of accommodating the largest eVTOL/UAV intended for service, ensuring sufficient friction, an obstacle-free surface, resistance to downwash and outwash effects, and effective drainage. Whether situated within the FATO or co-located with eVTOL/UAV stands, the TLOF must be able to bear the appropriate load, be centered accordingly, and maintain slopes not exceeding 2 percent to prevent water accumulation and ensure safe aircraft maneuvering (Australia CASA, 2023).

2.3. Gates/ Stands

Gates are an essential component of vertiports, providing a safe and efficient way for eVTOLs/UAV to load and unload passengers and cargo. Gates are typically located at the edge of the vertiport's TLOF or FATO, and they provide a designated area for passengers and cargo to board and disembark from aircraft (Ahn & Hwang, 2022).

Gates are designed to accommodate the specific needs of the eVTOLs/UAVs that operate at the vertiport. The size of the gate must be large enough to accommodate the aircraft's wingspan and tail rotor, and the gate must be able to support the weight of the aircraft. Furthermore, gates must be equipped with charging facilities. These positions represent critical resources that influence the capacity of vertiports and their ability to accommodate the fleet of eVTOLs/UAVs (Jin et al., 2024).

2.4. Taxiways

Taxiways constitute another essential component of vertiports, providing a safe and efficient means for eVTOLs/UAVs to navigate within the vertiport. They typically consist of paved surfaces linking gates, FATOs, and other areas. Taxiways are tailored to meet the specific operational requirements of eVTOLs/UAVs at the vertiport. The width of the taxiway should be sufficient to accommodate the wingspan of the aircraft, while also supporting its weight (Scott, 2022; Zhang et al., 2022).

2.5. Vertiports Surfaces

The final approach and take-off for eVTOL/UAV is of critical importance, as accurate location information and vertical height guidance are essential for the creation of a secure operational environment (Pradeep & Wei, 2018; Ye et al., 2020). The approach/departure surface is centered on each approach/departure path for aircraft and begins at the edge of the FATO area. The slope of the runway is 8:1 (horizontal to vertical) and extends horizontally for 4.000 feet (1.220 meters) from the starting point. At the conclusion of this distance, the surface attains a width of 500 feet (152 meters) and an elevation of 500 feet (152 meters) above the vertiport. Transitional surfaces are situated in an outward and upward direction from the lateral boundaries of the primary surface and approach surfaces. These surfaces have a slope ratio of 2:1 (horizontal to vertical) and extend horizontally for 250 feet (76 meters) from the centerline of the primary and approach surfaces (Michael & Meyers, 2022).

In order to ensure the safety of aircraft operations, it is imperative that the area under the approach/departure surface is free of penetrations and obstructions. In the case of TLOFs that are designed to accommodate multi-directional operations, a minimum separation of 135 degrees is required between two surfaces. A separation distance of 60 meters between two FATOs is proposed as a reference for simultaneous helicopter operations where the maximum take-off weight does not exceed 3175 kg (European Union Safety Agency, 2022).

Figure 3(a) depicts the approach/departure surface with an 8:1 slope extending 1220 meters from the FATO, with a width of 152 meters at a height of 152 meters. Figure 3(b) illustrates the transitional surface extending outward and upward with a 2:1 slope from the lateral boundaries of the approach surface. Figure 4 depicts the dimensions of an omnidirectional obstacle-free volume, including angles and heights associated with the approach/departure and transitional surfaces.

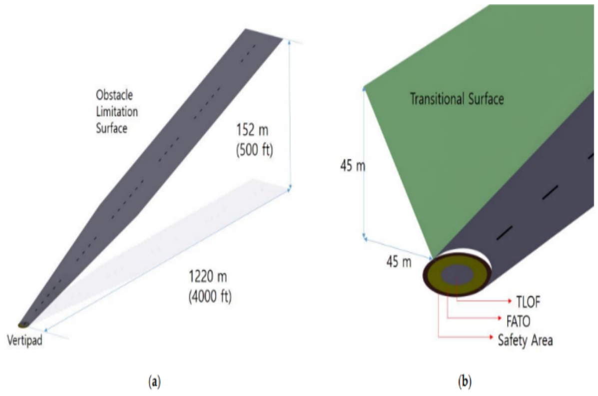

Figure 3. Approach/departure surface and transitional surface with a 1:8 slope: (a) approach/ departure surface; (b) transitional surface (Ahn & Hwang, 2022).

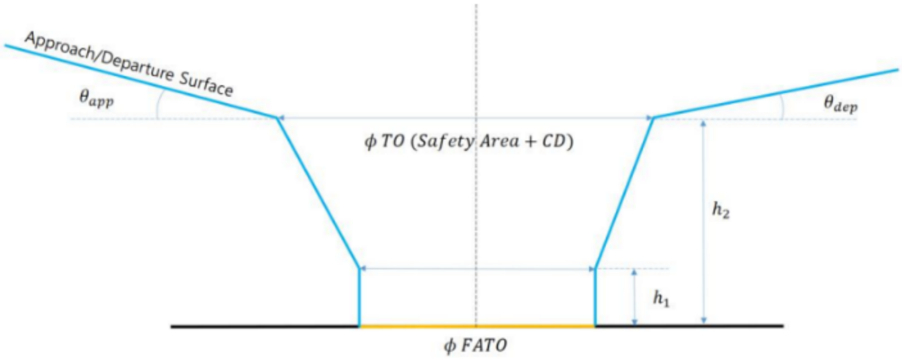

Figure 4. Dimensions of an omnidirectional obstacle-free volume (Ahn & Hwang, 2022).

2.6. Marking and Lighting

The alignment markings and lighting of flight paths are regarded as optional elements in vertiports, providing visual guidance for pilots when necessary. The vertiport identification marking serves to indicate the location of the vertiport and to highlight the TLOF, as depicted in Figure 5. Lighting is a vital component for night-time operations, assisting pilots in locating the vertiport and outlining its operational area. Wind cones play a pivotal role in indicating wind direction and magnitude. For night-time operations at vertiports, an identification beacon is a mandatory requirement; however, this requirement does not apply to vertiports located at airports (Michael & Meyers, 2022).

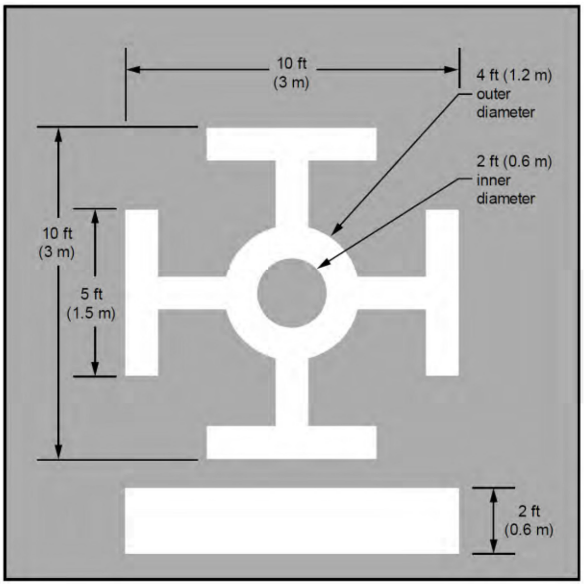

Figure 5. Vertiport identification symbol (Michael & Meyers, 2022).

3. Challenges to The Operational Demands of Integrating Vertiports into Existing Airports

The field of UAM is undergoing rapid development, with the potential to revolutionize urban transportation. The concept of eVTOLs/UAVs has the capacity to transform intra-city transportation. The development of a robust network of vertiports, or specific infrastructure hubs that support eVTOL/UAV operations, is essential for the realization of UAM (Daskilewicz et al., 2018; Peng et al., 2022; Wang et al., 2022; Willey & Salmon, 2021; Wu & Zhang, 2021; Yedavalli & Cohen, 2022; Zelinski, 2020). However, integrating these hubs into existing airport ecosystems poses a complex challenge, requiring a balance between operational demands and spatial constraints (Dulchinos et al., 2022).

The main difficulty is finding space for vertiports in airports. Airports are confronted with significant challenges, including limited space and incompatible land use, which impede the ability to expand in a manner that meets the growing demand for efficient, effective, and safe operations among existing taxiways, runways, and supporting infrastructure (Forsyth, 2007; Gelhausen et al., 2013; Janic, 2016). In order to achieve a balance between optimizing operational efficiency and minimizing the enlargement of the area in question, a sophisticated approach to integration is required. Failure to achieve this situation risks jeopardizing the smooth flow of existing airport operations and compromising safety.

Another significant challenge is ensuring the safety of both traditional aircraft and eVTOL/UAV. The location of vertiports must be carefully considered to reduce the risk of collisions in the constantly changing and frequently congested airspace around airports (Schweiger & Preis, 2022). Achieving a harmonious balance between the unique operational needs of eVTOLs/UAVs and the established air traffic patterns of traditional aircraft is essential for upholding the integrity of the airspace and safety. The high volume of airport operations, coupled with the low-altitude nature of vertiport flights, creates a heightened risk of collision within the airport environment (Pothana et al., 2023). This is especially concerning for vertiports located in close proximity to runways, as the potential for conflict between vertiport and traditional aircraft is significantly increased.

4. Solutions to Challenges in Integrating Vertiports into Existing Airport

The preceding discussion highlighted the intricate difficulties associated with integrating vertiports into the existing airport environments. While operational demands and constraints present significant challenges, the transformative potential of UAM necessitates a proactive approach to addressing them. This section examines potential solutions and strategies for navigating these challenges, paving the way for a seamless and successful integration of vertiports into the airport.

4.1. Remote Vertiport Networks

The establishment of dedicated vertiport hubs outside the immediate airport vicinity presents a promising solution to mitigate congestion and enhance accessibility for both passengers and cargo (Peksa et al., 2023). Strategically positioned near major transportation hubs or densely populated areas, these vertiports could serve as critical nodes within the broader transportation network (Kim et al., 2023). By connecting to airports via high-speed transit links, these remote vertiports would significantly reduce the pressure on central airport infrastructure. This connectivity ensures that travelers have various transportation options to reach these remote vertiports from any point within the transportation network. Particularly in metropolitan areas plagued by congested traffic, these remote vertiports provide a rapid and efficient alternative for reaching airports, bypassing the challenges of urban traffic congestion. This accessibility feature not only enhances the overall efficiency of transportation but also provides travelers with greater flexibility and convenience in reaching their destinations.

4.2. Geofencing Technology

Establishing dynamic buffer zones through the application of geofencing technology presents a promising solution to potential conflicts with existing infrastructure, particularly in the vicinity of airports and vertiports. Geofencing technology involves the creation of virtual boundaries within specific geographical areas to effectively manage and regulate the navigation of autonomous eVTOLs/UAVs (Hosseinzadeh, 2021; Stevens & Atkins, 2020; Yılmaz, & Ulvi, 2022). This approach serves as a secure alternative to detect-and-avoid mechanisms, redirecting autonomous eVTOLs/UAVs upon approaching predefined altitude or lateral boundaries (Stevens et al., 2015). The adaptable perimeters surrounding vertiports and runways can dynamically adjust their size and configuration in response to real-time air traffic conditions. This capability ensures the secure separation of vertiport operations from conventional aircraft movements, thereby minimizing the risk of mid-air collisions.

4.3. Dedicated Airspace Corridors

Integrating eVTOLs/UAVs into existing airspace requires creating dedicated airspace corridors, which is essential for their safe and efficient operation (Al-Rubaye et al., 2023). Aviation stakeholders, including airport authorities, air traffic control, and regulatory bodies, need to work together to define specific routes for eVTOLs/UAVs. This approach reduces conflicts with traditional aircraft and other eVTOLs/UAVs by keeping their traffic separate, which improves safety and efficiency (Pradeep, 2019). Dedicated corridors help manage eVTOL/UAV traffic better and support the integration of advanced Air Traffic Management (ATM) systems, strengthening the UAM framework.

4.4. Advanced Collision Avoidance Systems

Airborne collision avoidance systems are crucial onboard safety tools designed to prevent aircraft from colliding, especially when air traffic control systems fail. These systems work best at lower altitudes (Smith et al., 2020). Specifically, an algorithm for low-altitude collision avoidance helps keep small aircraft safe when flying close to the ground (Lin & Wu, 2011). With the rise in air traffic and the added pressure from eVTOLs/UAVs at airports, these systems are more important than ever. As air traffic becomes more complex with the addition of eVTOL/UAV, new collision avoidance systems need to be developed. These advanced systems must be designed to handle the unique flying patterns of eVTOL/UAV, which often operate in crowded urban areas and near airports. By using these next-generation collision avoidance technologies, we can greatly enhance safety and reduce the risk of mid-air collisions in busy airspace (Sanches et al., 2020). Implementing advanced collision avoidance systems for eVTOL/UAV is essential (Alturbeh & Whidborne, 2020; Panchal et al., 2023). These systems will help manage the increased traffic and ensure safe and efficient airspace operations.

4.5. Dynamic Airspace Management

Dynamic airspace management is essential for optimizing the increasingly complex dynamics of eVTOL/UAV operations in airports. One notable strategy, Collaborative Decision-Making (CDM), has been demonstrated to generate substantial benefits for all stakeholders involved in airport operations (Auerbach & Koch, 2007). This methodology enhances the efficiency of air traffic flow management, resulting in more effective sequencing of take-offs and landings (Almeida et al., 2016). Furthermore, CDM plays a pivotal role in increasing both airfield and airspace capacity, optimizing the use of resources, and refining overall ATM strategies (Nikulin, 2018).

The integration of eVTOL/UAV into airport operations necessitates a robust framework of collaborative decision-making among airport authorities, UAM operators, and air traffic control bodies. This collaborative framework is crucial for developing and implementing effective and efficient ATM strategies (Shmelova et al., 2021). Enhancing this process involves leveraging advanced information and communication technologies to eliminate communication barriers, effectively elicit and represent knowledge, and automate decision-making processes (Karacapilidis, 2000). Moreover, the adoption of these technologies facilitates real-time data sharing and dynamic adaptation to changing conditions, further improving coordination and decision-making.

Incorporating real-time data, a dynamic air management model addresses challenges at congested airports, reconciling flight demand with limited airspace while optimizing capacity and minimizing delays (Cheng et al., 2010; Lanshou & Fuqing, 2010), including those potentially associated with vertiport operations. At the core of this concept lies the ability to reconfigure airspace boundaries and dedicated corridors based on live traffic conditions. Flexible, data-driven systems can be employed to dynamically adjust airspace sectors, accommodating fluctuations in traffic density and optimizing flight paths for airport aircraft (Gerdes et al., 2018).

5. Methodology

Analytic Hierarchy Process (AHP), a multi-criteria decision making technique was used in the study. AHP can be used for decision problems with large numbers of alternatives and several criteria (Abastante et al., 2019). The problem of the study focused on determining solution priorities for the integration of vertiports with airports. This problem also serves as a goal in a hierarchical structure.

The objective represents the first level of the three-level hierarchical structure used in the study. The second level consists of criteria that contribute to the achievement of the objective. Criteria are factors that are believed to contribute to the achievement of the goal. Safety, cost, efficiency, sustainability, and feasibility are identified as evaluation criteria in this study following expert opinions. These criteria ensure a comprehensive approach that addresses essential aspects of aviation operations and infrastructure development. Safety is paramount in aviation and involves the effective management of risks associated with aviation activities (Wipf, 2020). In addition, cost is a critical evaluation criterion as it assesses the economic viability of aviation projects (Gibson et al., 2004). Efficiency is also essential, ensuring consistent performance, optimal use of resources and maximum productivity (Dmitruk & Koshevoy, 1991). Furthermore, feasibility in aviation refers to the ability to solve complex problems and implement practical solutions (Cafieri & D'Ambrosio, 2017). Finally, sustainability is crucial due to the challenges posed by climate change and global warming, which require environmentally friendly practices in the industry (Markatos & Pantelakis, 2022).

Finally, at the third level of the hierarchy are the alternatives. Following a literature review and expert evaluation, the study identified the following solution options: remote vertiport networks, geofencing technology, dedicated airspace corridors, advanced collision avoidance systems and dynamic airspace management. AHP flowchart is shown in Figure 6.

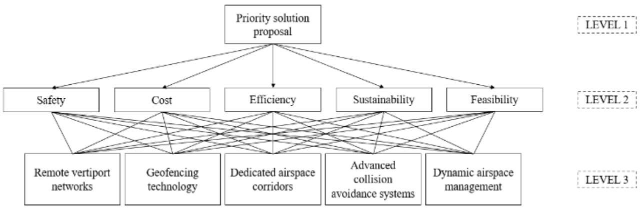

Figure 6. AHP flowchart of priority solution proposal for integrating vertiports into airport.

AHP is used to quantify pairwise comparisons on a scale of 1-9 as shown in Table 1 (Saaty & Vargas, 2006). The study used the opinions of 12 experts in the aviation sector.

Table 1. Saaty's 1-9 scale for AHP preference.

Level of Importance and Definitions	Explanations
1: Equal importance.	Importance of elements are equal.
3: Weak importance.	First element is moderately more important than second one
5: Strong importance.	First element is strongly more important than second one.
7: Importance over the other.	First element is very strongly more important than second one.
9: Absolute importance.	First element is extremely more important than second one.
2, 4, 6, 8: Intermediate values.	Intermediate values between above mentioned values.

6. AHP Application

The relationship between criteria was explored using pairwise comparison matrix through AHP. The study proceeded with the normalization process observed in the implementation phases of AHP, weights were determined and the consistency ratio of the study was assessed following the calculation process. The data obtained from the expert opinions were used for pairwise comparisons, using a scale of 1-9 as a reference. Table 2 shows the comparison matrix of the decision criteria.

The next step was to construct the normalized comparison of decision criteria shown in Table 3. In the normalized comparison matrix, column sums equal to 1 indicate a correctly performed process.

The following stage of AHP is to determine priorities. By finding the priority vector, the criteria are weighted. For this process, the normalized comparison matrix is used and it is done by taking the arithmetic mean of the rows of the normalized comparison matrix. Table 4 shows the eigenvector of the decision criteria.

Table 2. Comparison matrix of decision criteria.

Decision Criteria	Safety	Cost	Efficiency	Feasibility	Sustainability
Safety	1.00	7.35	5.24	2.74	2.98
Cost	0.14	1.00	1.44	1.76	2.01
Efficiency	0.19	0.69	1.00	1.23	1.15
Feasibility	0.37	0.57	0.81	1.00	1.19
Sustainability	0.34	0.50	0.87	0.84	1.00
Total	**2.03**	**10.11**	**9.37**	**7.56**	**8.34**

Table 3. Normalized comparison matrix of decision criteria.

Decision Criteria	Safety	Cost	Efficiency	Feasibility	Sustainability
Safety	0.49	0.73	0.56	0.36	0.36
Cost	0.07	0.10	0.15	0.23	0.24
Efficiency	0.09	0.07	0.11	0.16	0.14
Feasibility	0.18	0.06	0.09	0.13	0.14
Sustainability	0.17	0.05	0.09	0.11	0.12
Total	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**

Table 4. Eigenvector of decision criteria.

Decision Criteria	**Eigenvector**
Safety	0.500
Cost	0.159
Efficiency	0.114
Feasibility	0.120
Sustainability	0.108

The final step was to calculate consistency. Consistency is a crucial factor for the reliability of the study. The eigenvalue for each criterion, as shown in Table 5, was calculated by multiplying the row of the pairwise comparison matrix by the priority vector. For consistency, Consistency Ratio (CR) = Consistency Index (CI) /Random Index (RI) is compared to 0.10. The Consistency Index (CI) value was calculated using formula (1) and the λ_{max} value within the Consistency Index (CI) was calculated using formula (2). As the dimension n=5, the Random Index (RI) value used was 1.12. The calculated Consistency Ratio (CR) value was 0.064, indicating that the consistency ratio is less than 0.10, confirming that the results are consistent.

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n-1} \tag{1}$$

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{\sum_{j=1}^{n} a_{ij} w_j}{w_i} \tag{2}$$

Table 5. Eigenvalue of decision criteria.

Decision Criteria	**Eigenvalue**
Safety	2.913
Cost	0.818
Efficiency	0.590
Feasibility	0.614
Sustainability	0.554

In the continuation of the AHP application, comparison matrices per criterion for alternatives, normalized comparison matrices, and eigenvectors were calculated. Using the importance weight values derived from these calculations, the selection score for each alternative was obtained. The ranking of results is presented in Table 6.

Table 6. Selection score and ranking of alternatives.

Alternatives	Selection Score	Ranking
Dynamic airspace management	0.396	1
Remote vertiport networks	0.385	2
Dedicated airspace corridors	0.273	3
Geofencing technology	0.205	4
Advanced collision avoidance systems	0.137	5

7. Conclusion and Discussion

The design of airport vertiports for eVTOLs/UAVs presents several challenges. A literature review identified remote vertiport networks, geofencing technology, dedicated airspace corridors, advanced collision avoidance systems, and dynamic airspace management as potential solutions to these challenges. To determine the best alternative among these solutions, prioritization was carried out based on safety, cost, efficiency, feasibility, and sustainability criteria. According to the results of the study, dynamic airspace management was the highest priority solution, followed by remote vertiport networks, dedicated airspace corridors, geofencing technology, and advanced collision avoidance systems.

Dynamic airspace management facilitates the dynamic planning of airport and airspace operations. In the current CDM to minimize delays. Similar real-time data sharing systems between eVTOL/UAV operators, airport authorities, ATM, and UTM service providers would enable dynamic planning of eVTOL/UAV operations. Data shared via datalink can facilitate fully automated flights, thereby minimizing the impact of eVTOL/UAV flights on airport traffic. However, the integration of ATM/UTM is critical in this process. Integrated ATM/UTM systems enable UAM by enabling safe and efficient air taxi operations in urban environments, including airports. Given the increasing use of UAVs for various purposes, including air taxis, the UTM system aims to integrate UAVs into segregated and non-segregated airspace and address the challenges in adopting the current ATM for UTM (Ali, 2019).

Remote vertiport networks emerged as the second priority solution. Considering the complex structures of airports and the different characteristics of traditional aircraft and eVTOLs/UAVs, the positioning of vertiports with metro connections to nearby airports can be proposed as a suitable solution. This approach could also make UAM more accessible, given the high costs associated with airports. Studies have shown that UAM services to and from airports are more expensive than intra-metropolitan travel (Coppola et al., 2024). The use of these vertiports may allow airport operations to continue without interruption. Furthermore, there is no evidence to suggest that any delays will result in safety risks.

The third priority solution is the designation of dedicated airspace corridors. In the initial stages, the majority of UAM operations will be conducted under visual flight rules, whereby aircraft navigate by visual references rather than relying on instruments, predominantly in urban areas (Lascara et al., 2019). At present, routes exist for traffic flying to and from airports under visual flight rules (Tuncal & Uslu, 2021). These routes can be used by eVTOLs/UAVs flying to vertiports at airports. However, an increase in flights could create significant risks and capacity issues for traditional aircraft using visual reference routes. The design of dedicated airspace corridors to minimize interactions between eVTOLs/UAVs and traditional aircraft and reduce the impact on airport traffic is therefore crucial. Dedicated airspace corridors provide 3D airspace for closely spaced, safe flights to avoid collisions (Asslouj et al., 2023; Toratani et al., 2023). Flights in these corridors can be conducted without traditional ATC services (Vascik & Hansman, 2020). Therefore, dedicated airspace corridors are an important solution to overcome the operational challenges of integrating vertiports into airports.

The fourth priority solution for integrating vertiports into airports is geofencing technology. This technology can impose temporal and spatial restrictions on the operation of vertiports at airports (Stevens & Atkins, 2020). The integration of geofencing technology facilitates the adaptation of vertiports to existing airport infrastructure. Particularly at busy airports, this technology can be used to protect take-off and landing routes for conventional aircraft by creating no-fly zones. Furthermore, dynamic planning can regulate flights to vertiports (Zhu & Wei, 2016) and manage flights with virtual boundaries (Hosseinzadeh, 2021), providing a safe alternative to detect-and-avoid systems (Stevens et al., 2015). Therefore, the use of geofencing technology is considered a critical step in the process of integrating vertiports into airports.

The final priority in the solution ranking is advanced collision avoidance systems. This system plays a critical role in ensuring flight safety for both traditional aircraft and eVTOLs/UAVs. One of the main challenges in integrating vertiports into airports is flight safety. The landing phase of airport operations poses significant risks to aircraft (Kong et al., 2022; Wang et al., 2020). Any safety violation during this phase can lead to accidents. Advanced collision avoidance systems can provide situational awareness to pilots by monitoring airport flights.

In conclusion, the integration of vertiports into existing airports for eVTOL/UAV operations, while posing significant challenges, is both feasible and promising with the implementation of prioritized solutions such as dynamic airspace management, remote vertiport networks, dedicated airspace corridors, geofencing technology, and advanced collision avoidance systems. In addition, Artificial Intelligence (AI) technologies play a crucial role in enhancing ATM/UTM, providing advanced capabilities to manage complex airspace and ensure safe and efficient operations around airports. It is recommended that future studies focus on the integration of ATM/UTM and the application of AI. Ongoing collaboration between UAM stakeholders, including airport authorities, air navigation service providers, regulators, and eVTOL/UAV manufacturers, is essential to develop comprehensive and effective integration strategies. By recognizing the challenges, embracing innovative solutions, and prioritizing research and collaboration, the integration of vertiports into airports can revolutionize urban mobility, providing safer, faster, and more sustainable transport options for all.

Author Contributions

The study is single-authored. The author confirms sole responsibility for the conception of the study, the presented results, and the preparation of the manuscript.

Conflicts of Interest

There are no conflicts of interest in any part of the research paper.

Statement of Research and Publication Ethics

For this type of study formal consent is not required.

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