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LANDING PLATFORM FOR URBAN AIR MOBILITY VEHICLES INTEGRATED INTO PARKING LOT INFRASTRUCTURE IN DENSELY BUILT-UP AREAS

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Abstract

Proposing a new solution for the integration of landing sites for urban air mobility vehicles in densely built-up areas, this paper displays the concept of a landing platform which can be integrated into existing parking lot infrastructures. First, legal requirements are derived, and the minimum space requirement is determined. Then, a design concept is presented, including necessary components and possible operation scenarios. Furthermore, the feasibility is evaluated taking a closer look at selected cities within Europe. Finally, current challenges are examined.

Keywords: Urban Air Mobility, vertiport, infrastructure, spatial analysis

1. Introduction

The use of electric vertical take-off and landing (eVTOL) vehicles in the context of urban air mobility (UAM) to relieve road congestion is an integral part of the vision for long-term urban development. While some UAM manufacturers made promising progress in designing vehicles, Deloitte describes the design and implementation of ground infrastructure as the “biggest hurdle” in urban air mobility [1]. Yet ground infrastructure and operations are key elements for a successful implementation of the technology.
This paper addresses this issue and examines the feasibility of integrating landing platforms for UAM vehicles, or, to be more precise, for electric vertical take-off and landing vehicles, into existing parking lot infrastructures. In this paper the term “UAM vehicle” is used to describe an “eVTOL vehicle”. The aim is to use the free space in the third dimension and place a take-off / landing area above ground level, taking up as little parking space as possible. The paper aims to give an idea of how such a platform could be integrated in densely build-up areas, especially in historically grown cities without a lot of open spaces or tall buildings with flat roofs. To understand the type of platform being considered, the requirements and size demand will be analyzed. On top of that, the platform components and the main operating scenarios will be described. Furthermore, an investigation will be carried out to determine the number of possible suitable parking spots in different cities. This will be done on the example of selected European cities.

The idea developed as a result of the lecture "Systems Engineering" at the Hamburg University of Applied Sciences. In the course of the lecture, an innovative system idea was to be designed and analyzed using SysML, as described in [2]. SysML stands for “Systems Modeling Language” and is a “general-purpose architecture modeling language for Systems Engineering applications” which enables the technology for Model-Based Systems Engineering [3]. With this language, the hierarchical, functional, and structural concept as well as the requirements were analyzed and graphically presented in diagrams such as a stakeholder diagram, a parametric diagram, and a use case diagram. The major findings and resulting conclusions of the analysis are described in this paper.

2. Preliminary Considerations

Currently, urban air mobility is still in the development phase. At present, none of the UAM concepts are fully operational and no vehicle has yet received certification. However, some manufacturers have already unveiled full-size prototypes or even conducted test flights. The European Union Aviation Safety Agency (EASA) speaks of "increasing momentum" [4] in the development and expects that commercial urban air mobility could become reality in the next three to five years [5].

As urban air mobility is still evolving, many factors are unknown at this point and will not be regarded in this paper. This includes certification specifications, for examples, as regulations for UAM vehicles or VTOL vehicles have not yet been agreed upon. Due to the lack of specific regulations, the international ICAO minimum requirements for heliports will be used as a reference, as is common practice in the UAM community [6]. Other aspects on which detailed information is not yet available relate to the operation of the UAM vehicles. These include, for example, the charging infrastructure of the vehicles, the battery capacities as well as the booking processes or aspects concerning the communication between vehicles and the landing platform. Roland Berger believes that eVTOL manufacturers will be a key driver when it comes to developing digital infrastructure and conducting flight operations [7]. This is why topics such as integration into the UAM networks or integration into the operators' software infrastructure are not covered in this paper.

To gain a better understanding of how the platform could fit into the urban air mobility market, it is important to take a look at the different use cases for UAM vehicles and current ground infrastructure types. According to Roland Berger [7], three use cases have emerged in the growing UAM market: City Taxi, Airport Shuttle, and Inter City Transport. While Airport Shuttles and Inter City flights are likely going to be scheduled services between predefined landing stations, City Taxi flights are going to be on-demand services offering flights between any available landing station in the UAM network. This means that several landing sites will be needed within a UAM network to create an appeal to the passenger. In addition to the number of landing pads, strategic positioning also influences the success of Inter City Transport in the context of Urban Air Mobility.

The integration of landing pads at these strategic locations presents another challenge. Depending on the size and the position within the network, McKinsey [8] as well as the EASA [4] divide the landing sites, also called "vertiports", into three categories: vertihubs, vertibases and vertipads. While vertihubs and vertibases are medium to large structures, vertipads, are the smallest structures in the UAM network, including only one take-off / landing pad. It is estimated that there could be five to ten vertipads in densely populated cities [8].

This paper describes a concept for vertipads which can be integrated above parking spaces in urban and suburban locations such as retail stores, malls, or sport centers. The majority of the parking spaces can still be used in their intended function, and at the same time the locations are appealing due to the existing shopping or recreational facilities. The intention is to design a platform that can be used by different UAM vehicles in order to reach the largest possible number of customers. The proposed platform offers one landing / take-off pad which also functions as the boarding / deboarding area, not requiring eVTOLs to be able to taxi on their own. The platform aims to function largely autonomously within a shared mobility network. As the platform is supposed to be a member in a network of vertiports, primary charging capabilities will not be offered besides minimal emergency charging capabilities. This aligns with a statement made by Deloitte [1] that there is no compelling need for primary charging infrastructure or parking places for other vehicles at small vertiports.

3. Legal Requirements

A UAM landing platform must be certified by aviation authorities and therefore the platform must be compliant with applicable Certification Specifications (CS). However, within the scope of this paper, it is neither possible nor necessary to address all relevant legal requirements. Hence, only the most considerable certification requirements influencing feasibility and design are presented and assumed mandatory hereafter.

3.1 Certification Basis

An applicable legal basis, further referred to as certification basis, to which compliance can be shown, needs to be chosen appropriately. In an actual approval process, many different legal bases would apply. In this framework only aviation regulations will be considered. Since no specific regulations are published by the European Union Aviation Safety Agency yet, it is common practice throughout the UAM industry [6] and research community [9] to to use the existing regulations for heliports as certification basis. This means that international standards defined by the International Civil Aviation Organization (ICAO) are used. Relevant for this paper are ICAO Annex 14 Vol. 2 (Heliports), Annex 6 Vol. 3 (Operation of Helicopters) as well as Annex 17 (Security).

3.2 Reference eVTOL

When designing a vertiport, a reference eVTOL must be determined beforehand. As stated in Annex 14, the reference aircraft, referred to as “critical design helicopter”, must have “the largest set of dimensions [...] the heliport is intended to serve” [10]. With that being mentioned, aiming for a platform that is constructed to be as versatile as possible and thus can serve many different eVTOLs, the largest eVTOL concept should be referred to. However, the different UAM concepts require different sizes of eVTOLs. Inter City concepts rely on VTOL with larger passenger capacity, whereas Intra City concepts rather ask for smaller passenger capacity eVTOL, often referred to as City Taxis [7]. Moreover, in the context of City Taxi services, a small vertipad is more likely to be operated by smaller sized eVTOLs. Table 1 provides a sufficient list of some promising eVTOL concepts with publicly available design specifications and a maximum passenger capacity of four.

Table 1 – Dimensions of some selected eVTOL concepts

eVTOL	**Length [m]**	**Width [m]**	**D* [m]**	**Passenger capacity**
City Airbus [11]	8.00	8.00	11.3	4
Airbus Vahana [12]	N/A	6.25	6.25	1
Volocity [13]	11.3	11.3	11.3	2
Kitty Hawk Cora [14]	N/A	11.0	11.0	2
E-Hang 216 [15]	5.61	5.61	7.93	2

* The largest dimension between the two most outer tips of the rotors, according to ICAO Annex 14 Vol.2 [10]

For determination of platform size requirements, “the largest overall dimension” (D) [10] of the eVTOL must be calculated. Annex 14 states that D shall be “measured from most forward position of the main rotor tip path plane to the most rearward position of the tail rotor tip path plane” [10]. However, this only applies to single rotor vehicles but will be assumed to be sufficient here.

When determining the largest dimension D, the arrangement of the rotors has an influence. The Volocity eVTOL rotors are arranged circular, which causes D to be the same size as the side length, thus 11.3 meters, whereas the four rotors of the City Airbus eVTOL are arranged in the corners of a square with a side length of 8 meters [11] which also results in a D of approximately 11.3 meters. Since this is the largest overall dimension, this value will be used in the following.

Besides the geometric input variable of a reference eVTOL, a classification into performance classes must be made, as size requirements as well as obstacle limitations will be affected by this. There are three different performance classes for helicopters defined by ICAO Annex 6 [16]. Performance classes subdivision is based on behavior in the event of critical engine failure. Helicopter operating in performance class 2 can continue a safe “flight to an appropriate landing area” [16] in case of critical engine failure occurring in sufficient altitude, which is why this will be assumed for any further evaluation.

3.3 Space requirements

ICAO Annex 14 [10] distinguishes between four different zones which depend on the parameter $Design\ D$ and determine the minimum size for a landing platform: Touchdown and lift-off zone (TLOF), Stand, Final Take-Off and Landing Area (FATO), Safety Area (see figure 1).

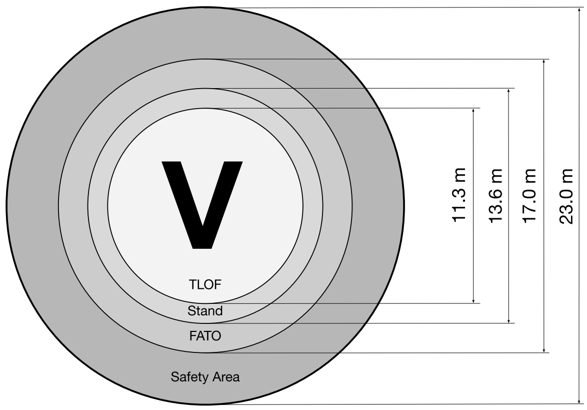


Figure 1 – Calculated dimensions based on the legally required areas for heliports, according to ICAO Annex 14 Vol. 2 [10]

A Touchdown and lift-off zone (TLOF zone) is necessary which shall have a diameter of at least one $Design\ D$ and therefore results in the following:

$$TLOF = Design\ D = 11.3\ \text{m} \tag{1}$$

As the proposed vertipad can only serve one eVTOL at a time, the stand coincides with the TLOF. An eVTOL landed on the platform will be parked and handled at the same spot it arrived, minimizing required space. The stand including the TLOF shall have a minimum diameter of $1.2 \cdot Design\ D$:

$$Stand = 1.2 \cdot Design\ D = 13.6\ \text{m} \tag{2}$$

Dimensions for TLOF and stand are important for platform design, but not decisive to a minimum peripheral size. A minimum size of a platform is driven by the Final Take-Off and Landing Area (FATO) and a surrounding safety area. A FATO provides an area over which an eVTOL can maneuver or hover during the final phase of take-off or landing. A FATO must have a minimum size of $1.5 \cdot Design\ D$:

$$FATO = 1.5 \cdot Design\ D = 17.0\ \text{m} \tag{3}$$

The adjoining safety area shall provide an additional free space to prevent collision in case of unforeseen maneuvering during take-off and landing. The safety area is a function of the FATO size and "shall extend outwards from the periphery of the FATO for a distance of at least 3 m" [10]. Both, safety area and FATO must be free of obstacles.
Adding the margin of 3 meters to both sides of the FATO edges results in a minimum vertiport size of:

$$Safety\ Area = FATO + 2 \cdot 3\ \text{m} = 23\ \text{m} \tag{4}$$

This minimal dimension must extend in all directions, so that a circle with a diameter of 23 meters is the minimum area. Figure 1 shows the areas mentioned with the resulting minimum boundary circle. However, different shapes can be implemented, as long as a circle with a diameter of 23 meters fits into this shape [10]. Assuming a square platform with 23 meters side length, as this is probably the most sufficient shape to be integrated into existing parking lots, the minimum area for the platform is:

$$A_{min,square} = (23\ \text{m})^2 = 529\ \text{m}^2 \tag{5}$$

3.4 Obstacle limitations

For the vertical spatial analysis in Chapter 5.1, attention should also be paid to the closer vertiport environment in terms of urban obstacles preventing airside accessibility for eVTOL. For this purpose, ICAO Annex 14 [10] provides an obstacle limitation surface, which is not to be penetrated by any kind of obstacle. This surface extends from the edge of the vertiport's safety area raising with a specific angle up to a fixed height of 152 meter (500 ft) above the elevation of the FATO. While the clearance height is fixed and therefore independent of aircraft type, the angle is dependent on eVTOL

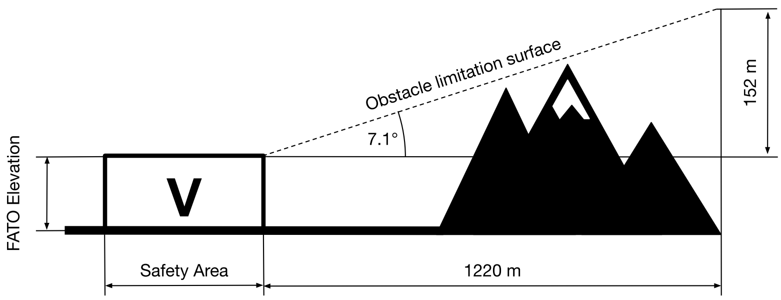


Figure 2 – Obstacle limitation surface for performance class 2 helicopters using information from [10]

performance class. The previously assumed performance class 2 results in a slope of 12.5%, which corresponds to 7.1°, as displayed in figure 2. In conclusion, the obstacle limitation surface expands over 1220 meters starting from the safety area edge.
However, these limitations are associated with so-called take-off climb and approach surfaces [10]. These stipulate that only corridors of a certain width must fulfill the requirements of the maximum obstacle heights stated before. This means, for example, that tall buildings can be located near the platform, provided that at least two opposite obstacle-free corridors are available.

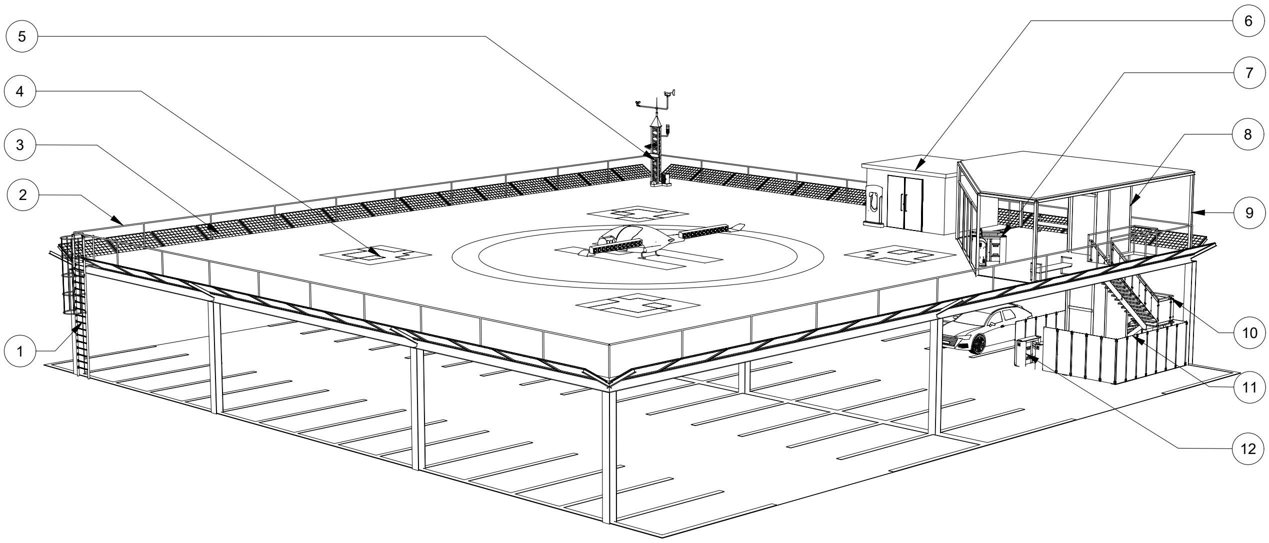
3.5 Security

Since human interactions are a central factor, appropriate security measures must also be taken for unintentional threats, which can also lead to the simple disruption of operations in less severe cases, especially in regard to possible autonomous operation. Measures for ensuring this in the context of civil aviation operations are provided in ICAO Annex 17 [17] and are summarized below.
First, unauthorized people must be denied access. This shall be implemented with the help of a security restricted area. Additionally, identification systems shall be established, which allows to verify people. Because of this, an autonomous vertiport must be equipped with appropriate automatic access restricting mechanics combined with human authorization technology. This basic requirement can also be derived from the need to check valid tickets.
Besides access control in the context of authorization, measures for detecting prohibited objects carried by passengers or being stored in cabin luggage must be established prior to boarding. Nevertheless, there are concerns regarding this requirement. In a study about long-term UAM application potential [9] this security issue has been addressed. A statement by Fraport is quoted, postulating passenger security checks are not mandatory in the context of UAM. This is justified by the fact that once again the underlying certification basis regarding UAM infrastructure has not yet been clarified. The study also brought up a comparison to existing public urban transportation, where security checks are not executed either. This can be substantiated by the fact that especially Intra City UAM concepts take place within city boundaries, thus are not international, which can be interpreted making security checks not mandatory. In this paper, the need of security checks prior to boarding is assumed unnecessary. However, security could be a limiting factor for autonomous vertiports and must therefore be considered with regard to new regulations in the future.

4. Design Concepts

4.1 Platform Components

The information about the required platform size has been used to design a first concept of the platform to visualize how the idea could be implemented on a reference parking lot. This design concept is shown in figure 3 including the main components which are needed to achieve a safe environment for the passengers and a smooth autonomous operation for the UAM vehicles.
The minimum size requirement for the selected reference eVTOL, as calculated in Chapter 3.3 based on legal restrictions, results in a diameter of 23 m. However, this size is not sufficient to implement a platform containing all necessary components and features. One of the main goals of the concept is to minimize the negative effect on the usability of the parking lot. Therefore, all components, that do not need to be on parking lot level, should be placed on top of the platform outside of the safety



Pos. Nr.	Component	Pos. Nr.	Component
1	Escape Ladder	7	Passenger Seperation and Authentication Unit
2	Safety Railing	8	Elevator
3	Wind Shielding (Solar Panels)	9	Passenger waiting room
4	ArUco Markers	10	Stairs
5	Weather Condition Sensors	11	enclosed entrance area
6	Blocked space for charging infrastructure	12	Ticket Authentication Unit

Figure 3 – Visualization of platform concept

area. All in all, the estimated space requirements of all necessary components lead to overall concept dimensions of 30 m × 30 m. Furthermore, the level of the landing area has been set to a height of 4.5 m allowing enough clearance for standard sized trucks.

For the reference parking lot, an average size of 2 m × 5 m per parking space has been assumed within a grid of four columns of each 15 parking spaces. To minimize the impact on the usability, the pillars of the platform are located only in between parking spaces. The main impact on the parking lot is the required space for the entrance area of the platform (Pos. 11), which is kept to a minimum of two parking spaces within this concept, while providing the needed space for stairs (Pos. 10) and an elevator (Pos. 8) to increase the accessibility of the platform.

A major aspect of the passenger safety is keeping passengers at a safe distance to approaching or starting vehicles. To achieve this requirement, an enclosed waiting area (Pos. 8) is provided in the corner of the landing platform. To access the landing area from the waiting area, passengers must pass through a turnstile-like authentication unit (Pos. 7), which allows the system to monitor the flow of passengers accessing and leaving the landing area. This information can be used to signal to the vehicle that no unauthorized person is on the landing area, and it is safe to start the landing or take-off procedure. To make sure only authorized passengers are able to access the waiting area and to prevent misuse or vandalism within the waiting area, a second turnstile-like authentication unit (Pos. 12) is used on the parking lot level. This is used to authenticate the ticket of a passenger and could, depending on the local air travel regulations, also be used for ID authentication by means of biometric scanners, as seen in some airports nowadays. Furthermore, all the edges of the platform are surrounded by a safety railing (Pos. 2) to prevent passengers or objects from accidentally falling off the platform. Additionally, wind-shielding plates (Pos. 3) are installed on all platform edges to decrease the effect of downwash on the surrounding ground level area. These wind-shielding plates could incorporate solar cells to provide a part of the power needs of the platform. In addition, an escape ladder (Pos. 1) provides an alternative escape path in the case of emergency.

Further components include operation related components like sensors, visualized within this concept as part of a weather station (Pos. 5). These sensors will provide valuable information for the autonomous operation of eVTOL vehicles such as local temperature, static pressure, wind velocity magnitude and direction, as well as non-weather-related parameters, like local GNSS (Global Navigation Satellite System) coverage, platform status (e.g. free or occupied), and surface condition (dry, wet, iced, etc.). To further aid the autonomous operation and enable optical based autonomous landing procedures, the platform incorporates so called “ArUco” markers (Pos. 4). These can be used by a vehicle to approximate its positioning in relation to the markers [18]. Further technologies to aid autonomous landing procedures, like the “DeckFinder” system by Airbus Helicopters could also be implemented. This would allow vehicles fitted with the needed components to perform autonomous landings even in GNSS shaded areas or in reduced visibility scenarios [19]. The ArUco marker technology has been chosen as a reference, as no standard technology or publicly accessible information from UAM manufacturers for autonomous landing is available. Similarly, charging infrastructures are also not standardized. On one hand, it could be assumed that the situation in the future will be similar to current EV charging infrastructure with a standardized plug system like the “CCS-Plug” currently used within the EU. On the other hand, completely different technologies, like swappable batteries or the usage of gaseous or liquid hydrogen could become the mainstream technology as well. Therefore, the design concept blocks a specific space (Pos. 6) for the needed emergency charging capabilities, without constraining the concept to a specific charging technology. Regardless, the uncertainty about the charging and autonomous landing guidance technology does not impact the feasibility study of this concept, which will be presented in the following Chapter 5. Other aspects to consider for a fully autonomous operation of the platform are a heating system to de-ice the landing area, as well as a self-cleaning system to remove hazards and dirt from the landing area.

4.2 Possible Operation Scenarios

As stated before, the platform aims to function autonomously with as little interactions from the outside during the two main platform use cases: the use of the platform as a landing site and the use as a take off site. Using a SysML activity analysis, the functional flows for both use cases were analyzed. Furthermore, the platforms interactions with its users were studied. Although the means of communication and the scope of information shared between the platform and the UAM vehicles or the booking systems is yet to be defined, an attempt was made to identify the crucial interactions. However, it is obvious that the platform must communicate with the eVTOLs (or their control software) via some sort of software system. The platform must share its precise position, elevation, and approach corridors, as well as other information needed for autonomous landing, with the vehicles. In addition, a booking system is needed that allows platforms to be selected as possible starting points and destinations. To what extent there will be uniform booking systems for different UAM operators remains to be seen. If each operator develops its own system, the software of the platform must have the ability to handle these different requests so that a smooth integration is ensured.

The operating procedure for the landing use case including interactions could be as follows:
Following a landing request by the eVTOL, the local weather conditions must be checked. If limits (which are yet to be defined) are exceeded, the platform cannot be used for landings and must remain inactive until the conditions are within the limits again. If the weather conditions are in the acceptable range, the usage status of the platform is queried. This will include a check to see if the platform is already reserved for landing by another vehicle or if another eVTOL is already on the platform. Depending on the agreement with the UAM operators in this case, the platform state is either reported back as "occupied" or the parked UAM is requested to departure and move to another parking location. If the platform is free, the platform must be checked for possible pollution, e.g. by snow or leaves. If necessary, the cleaning or de-icing process of the platform must be initiated. In case the platform is free and clean, it will be reserved and the vehicle can approach the platform. Immediately before landing, the weather conditions as well as the platform surface condition (dry, wet, iced) should be checked again to be able to report strong gusts of wind or similar to the vehicle. In the future, the weather information can be used in combination with predictive algorithms to enable more reliable routing [1].
After the autonomous landing, the passengers leave the vehicle. The vehicle must independently ensure that doors and the like can only be operated after a safe landing. Passengers are responsible for removing their luggage from the eVTOL and are instructed to proceed to the exit. Passengers

must "check out" when passing through the "passenger separation and authentication unit", which ensures that all passengers leave the landing area. Passengers can exit the platform via the stairs or the elevator.
The vehicle can remain on the platform until it is booked for a new flight or, depending on the agreement with the operators, is called away to another parking spot. The platform is not intended to provide primary charging capabilities, however, emergency charging capabilities are provided. Should the vehicle require these, it must communicate this information so that further actions can be taken.

The operational procedure for the take-off use case differs depending on the platform occupancy status and could be as follows:
After a booking request, a check of the weather conditions as well as the platform surface condition must be performed first. If there is no eVTOL on the platform, one must be requested through the booking system. In this case, the platform will be reserved until the vehicle arrives. At the same time, passengers can proceed to the platform. At the "ticket authentication unit", passengers are only granted access after scanning a booking confirmation. Via the stairs or elevator, passengers gain access to the enclosed waiting area, where they remain until the eVTOL has landed safely and signaled that it is ready to board. This information must be communicated by the vehicle, so that the platform's software clears access to the take-off area. Before the passengers can enter the area, they must authenticate themselves once again at a "passenger separation and authentication unit". This ensures that only passengers who have booked a flight with the approaching eVTOL can enter the take-off area. It can also be used to verify the number of people in the take-off area and ensures that the vehicle does not pose a threat to the passenger and vice versa. Passengers have to stow their luggage, if necessary, and enter the eVTOL. At this point, it is important that eVTOL manufacturers find a way to ensure that all passengers have boarded. The eVTOL must then signal its readiness for take-off and, after receiving permission to take-off (depending on regulations), can lift off from the platform.
The situation is different if a request is received from the booking system and the platform is already reserved or occupied. If the UAM vehicle on the platform is a vehicle of the requested operator, it can be booked directly for the flight and the passengers can proceed to the flight immediately. In this case, they behave according to the previously described procedure. If the vehicle on the platform is from a different operator than the one requested by the passenger, other scenarios arise. If it becomes apparent that the platform will be free again in the foreseeable future, the booking request can be processed, and the platform can be reserved for the next flight. Consequently, a vehicle would be requested according to the process described above. This assumes that a reliable statement about the turnaround time is possible. In case the UAM is parked on the platform, the platform must be reported back as "occupied" or the vehicle must be requested to take off and fly to another parking position, depending on the agreement with the UAM operators. Of course, this step needs to be further elaborated in consultation with the UAM operators.

5. Concept Feasibility

5.1 Spatial Analysis

To estimate the feasibility regarding the availability of suitable parking lots, a spatial analysis is carried out taking a closer look on different cities within Europe. The analysis is based on statistical data from Eurostat, map data from OpenStreetMap, digital elevation models from national agencies and is conducted using QGIS.

City Selection

The city selection is based on the European Union's Urban Audit 2020 [20] to ensure a common data base. This dataset contains statistical information and boundary information on individual cities within the EU, Iceland, Norway, Switzerland, and the United Kingdom. It applies the EC-OECD city definition [21] which differentiates between cities and greater cities. This analysis considers the 20 largest cities and greater cities by population according to [22], as shown in table 2.

Table 2 – Selected Cities for Spatial Analysis and Results of the Horizontal Spatial Analysis

No.	**City**	**Urban Audit Code [20]**	**Population as stated in [22]**	**Year of population data [22]**	**No. of suitable parking lots**	**No. of suitable parking lots per km²**
1	Paris	FR001C1	9,845,879	2017	1,882	0.99
2	London	UK001K2	8,866,541	2018	1,200	0.76
3	Madrid	ES001K1	5,012,504	2019	819	0.66
4	Barcelona	ES002K2	3,701,270	2019	476	0.80
5	Berlin	DE001C1	3,669,491	2020	868	0.97
6	Milan	IT002K1	3,622,641	2020	1,426	1.35
7	Naples	IT003K3	2,855,958	2020	313	0.37
8	Rome	IT001C1	2,808,293	2020	743	0.58
9	Manchester	UK008K1	2,805,684	2018	1,113	0.87
10	Athens	EL001K1	2,622,404	2013	232	0.38
11	West Midlands	UK002K1	2,543,414	2018	914	1.14
12	Bucharest	RO001C1	2,131,034	2018	228	0.95
13	Katowice	PL010K1	1,893,271	2014	740	0.61
14	Lisbon	PT001K1	1,872,036	2020	438	0.69
15	Hamburg	DE002C1	1,847,253	2020	508	0.69
16	Vienna	AT001C1	1,766,746	2014	301	0.73
17	Budapest	HU001C1	1,752,286	2019	377	0.72
18	Stockholm	SE001K1	1,745,766	2018	907	0.62
19	Warsaw	PL001C1	1,735,442	2014	569	1.10
20	Munich	DE003C1	1,484,226	2020	257	0.83

Horizontal Spatial Analysis

The horizontal spatial analysis shall provide an overview of the number of parking lots within the city boundaries that offer a surface area sufficient to fit the proposed UAM platform. OpenStreetMap [23] provides information on parking lots in the form of polygons and tags. The polygons represent the shape of the physical parking lots and the tags provide additional information like access to the facility. Only single level parking lots on the ground which are open to the public or to customers are considered. As described in Chapter 4.1, the platform has a side length of 30 meters. Firstly, an inward buffer of 21 meters, equal to the radius of the platform's outer circle, is created from the parking lot's boundary. If an area remains inside the polygon, as show in blue in figure 4, the UAM platform fits on the parking lot surface regardless its orientation and can be marked as suitable. Secondly, another inward buffer of 15 meters, equal to the radius of the platform's inner circle, is created from the parking lot's boundary. This time, if an area remains inside the polygon (yellow in figure 4), the parking lot might fit an UAM platform. A further analysis, considering the platform's orientation, is necessary. All remaining parking lots can be marked as not suitable.

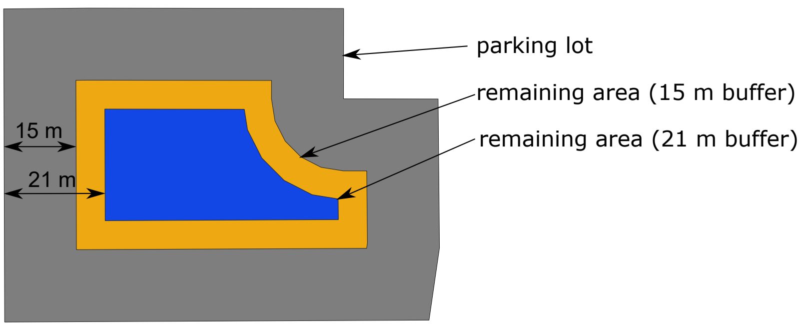


Figure 4 – Example parking lot with inward buffers of 15 meters and 21 meters

For the further analysis, a square with sides of 30 meters in length, equal to the platform's side length, is created around the pole of inaccessibility. The pole of inaccessibility is the most distant internal point from a polygon's boundary [24]. It marks the center of the circle with maximum radius that fits inside the polygon and shall give an indication for a possible center of the platform. To identify the suitable parking lots, an algorithm adapted from [25] is used to determine if the platform can be oriented to fit the parking space. The algorithm applies a golden section search to determine the angle that minimizes the difference area (area of the square that is not within the parking lot's boundary). If the difference area equals zero, the platform, represented by the square, fits on the parking lot, and can also be marked as suitable. The number of suitable parking lots regarding its surface is listed in table 2. Further, it contains the number of suitable parking lots per square kilometer allowing a comparison between the selected cities.
The results show that the number of suitable parking lots greatly varies between 228 in Bucharest and 1,882 in Paris due to the different urban area. Instead, the parking lot density varies between 0.37 suitable parking lots per square kilometer in Naples and 1.35 in Milan with a mean value of 0.79.

Vertical Spatial Analysis
Besides the horizontal spatial analysis, obstacle height limitations in the surroundings of the platform must be considered. For this vertical spatial analysis, a digital surface model (DSM) of the city provides the basis and includes elevation data of buildings, vegetation, and natural elevations.
Table 3 gives an overview of the considered cities as a DSM is available. Further, it lists the meta data of the DSMs. The year of the dataset points to the year the elevation data has been captured. The resolution of the DSMs is between 1 meter and 0.5 meters meaning there are 1 to 4 data points per square meter.

ICAO Annex 14 states the need for obstacle limitation surfaces for heliports, as shown in Chapter 3.4. In this analysis, only the immediate surrounding shall be considered as VTOLs will most probably have different requirements regarding their take-off and landing sites. It shall be determined whether obstacles within 100 meters from the safety area boundary of the platform exceed a certain threshold. For this analysis, the slope of 12.5% is applied and an obstacle limitation surface extending in all directions from the safety area boundary is assumed. Firstly, an outward buffer of 11.5 meters, equal to the radius of the platform's safety area, is created around the pole of inaccessibility of the parking lots marked as suitable during the preceded horizontal spatial analysis and which are covered by the DSM. The obstacle limitation surface with a total length of 100 meters is discretized equally into 20 annuli with a width of 5 meters, as shown in figure 5.

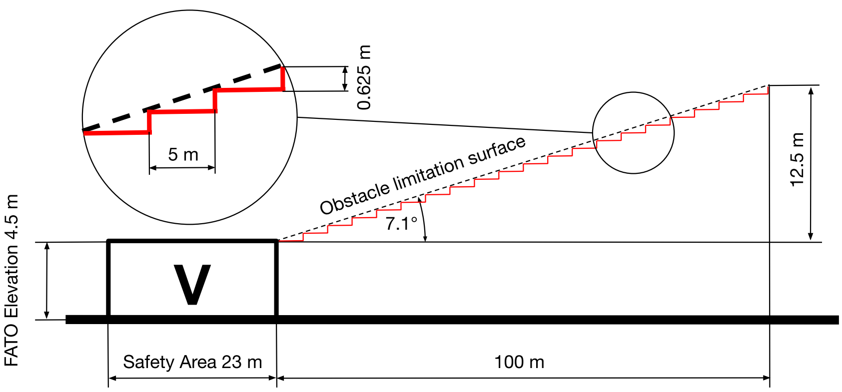


Figure 5 – Discretized obstacle limitation surface (red) for the vertical spatial analysis

For every annulus, a zonal statistic is carried out which provides information on the maximum elevation in this area. This maximum elevation can be subtracted from the minimum elevation within the safety area to get the maximum obstacle height relative to the parking lot surface. All parking lots whose surrounding buildings, vegetation etc. do not exceed the specified obstacle height limitations, also considering the platform height of 4.5 meters, are regarded as suitable locations for the platform. The results from this analysis are listed in table 3. It shows the amount of parking lots that are covered by the DSM and the resulting number of suitable parking lots per city.

Table 3 – Metadata of Digital Surface Models and Results of the Vertical Spatial Analysis

City	Year of dataset	Resolution	Vertical Accuracy	Data Source	No. of parking lots within DSM coverage	No. of suitable parking lots
London	2017	1 m	+/- 15 cm	[26]	1,147	62
Barcelona	2016	0.5 m	+/- 20 cm	[27]	476	30
Berlin	2020	1 m	N/A	[28]	865	6
Manchester	2017	1 m	+/- 15 cm	[26]	1,061	77
West Midlands	2017	1 m	+/- 15 cm	[26]	884	66
Vienna	2007	0.5 m	+/- 10 cm	[29]	301	2

The results show that the number of suitable parking lots decreases significantly compared to the results of the horizontal spatial analysis. For Vienna, only two parking lots could be identified as suitable whereas for Manchester 77 parking lots offer a sufficient area to fit a platform and do not show buildings or vegetation higher than the obstacle limitation surface in the immediate surrounding.

Limitations

It must be pointed out that in this analysis the obstacle limitation surface has been applied to all directions. However, ICAO Annex 14 only demands a heliport to meet the obstacle elevation limitations in two directions. Following a separate safety assessment, a single direction obstacle limitation surface may also be legitimate.

Also, the discretization of the slope with annuli of 5 meters can lead to a maximum vertical error of 0.625 meters compared to the continuous slope. The DSMs of London, Manchester and West Midlands do not fully cover the city as defined in the Urban Audit. Therefore, not all suitable parking lots resulting from the horizontal spatial analysis could be considered in the vertical spatial analysis. These circumstances could have led to more parking lots being identified as not suitable. Most of the DSM data was captured within the last five years, except the DSM of Vienna which was captured in 2007. However, new buildings could have been built or torn down in a parking lot's surrounding in the meantime resulting in outdated elevation data.

5.2 Current Challenges and Next Steps

The results of the spatial analysis show promising platform locations on parking lots within the urban area of large European cities. However, there are still aspects that must be addressed in further analyses to verify the suitability of a platform location.

Due to the lack of dedicated requirements for vertiports, only an initial study following the requirements for heliports was carried out. New legal requirements for vertiports would require a refined horizontal spatial analysis in case of changes regarding the FATO or safety area dimensions and a refined vertical spatial analysis in case of different obstacle limitation surfaces.

Also, it must be examined how the pillars of the platform can be integrated into the existing parking lot to minimize the impact on the individual parking spots and driveways.

As urban air mobility represents a new infrastructure component, new regulations in respect to airspace will come into effect. The effects of these regulations on the suitability of take-off and landing sites for air taxis must be examined. Besides the spatial and legal requirements, strategic and operational aspects must be considered. It needs to be further examined whether the location can contribute to the infrastructure strategy of the city or region.

A recent study by the EASA on the societal acceptance of UAM in Europe [4] found environmental aspects and noise pollution to be the biggest concerns when it comes to air taxis. First concepts exist to reduce the perceived noise by the citizens. One of them is to define routes for the UAM vehicles that follow existing roads or train tracks [9]. The EASA [4] identified several cities which offer corridors for noise avoidance. Among them are 10 cities considered in the horizontal spatial analysis. Regardless, the construction of a platform within an urban area remains an individual case that demands individual location assessments. A spatial analysis using OpenStreetMap and DSM data cannot replace an on-site assessment of the location and its surrounding. Nonetheless, this analysis was able to prove the existence of potentially suitable locations in a variety of cities. Also, it can be regarded as a starting point as it helps filtering the most promising sites.

6. Conclusion

This paper outlined the fundamental requirements in terms of system context and legal requirements for a take-off and landing platform built onto an existing parking lot. Based on existing heliport regulations, the minimum platform diameter for a selected reference eVTOL has been calculated to 23 m. It is expected to see dedicated regulations for vertiports soon, which could lead to necessary adjustments.

A first design concept has been derived from the platform requirements. To ensure a safe and secure operation, additional components have been identified and integrated into the concept. This keeps the footprint on the ground to a minimum but increases the overall space requirement for the platform to 30 m × 30 m.

Further, the possible operation scenarios describing the interaction between the platform and the eVTOL, as well as the passengers have been analyzed and outlined. It remains unanswered what kind of charging infrastructure is needed by the eVTOL and how the charging will proceed. It must be clarified whether an autonomous charging is possible and what implications this might have on the turnaround sequence. As no designated parking stand is planned in this concept, only one eVTOL can use the platform at a time. Therefore, it must be further analyzed how eVTOLs that are on the platform and do not have a mission are treated in case another eVTOL intends to use the platform.

It must be pointed out that the integration of the platform into the existing infrastructure as well as the digital infrastructure comprising data exchange between the platform, the eVTOL itself, air traffic control, the UAM operator and others remain topics for further research. As stated earlier, the key drivers for digital infrastructure and flight operations are likely going to be the UAM manufacturers which is why the concept needs to be adapted to meet future standards. At this point, it is challenging to give answers to all mentioned aspects as information and technical details from UAM manufacturers and operators are limited.

Furthermore, UAM manufacturers are still developing concepts for their own vertiports. As the industry is in an early stage, specific information on features, requirements, dimensions, or surrounding infrastructure is not yet publicly available. UAM manufacturers and other companies have presented layouts for vertiports, but early designs seem to focus primarily on larger infrastructure, that is, vertihubs and vertibases.

As an outcome of the present study, an initial spatial analysis based on the regulations for heliports identified up to 77 suitable parking lots in a large city in Europe, even with a conservative approach. McKinsey [8] estimates the need for small-sized take-off and landing platforms at 5 to 10 for large and densely built-up cities with a high-income population, like London. With further location assessments due, the construction of landing platforms on existing parking lots could be a promising contribution to a city's UAM infrastructure. Many ground infrastructure concepts today include the integration of landing areas on top of high-rise buildings, at airports or the new construction of vertiports in open spaces or waterfront locations. This could be difficult in densely build-up cities since vacant spaces are rarely available. Integrating platforms into buildings also proves difficult in historically grown cities, as these concepts rely on sufficiently large flat roofs rather than the gable or hip roofs common in such cities.

Of course, the concept presented in this paper could also be used in other parts of the world. Europe was chosen as an example for the spatial analysis as there is a great number of historically grown cities where the concept feasibility is assumed to be most critical. The proposed concept is designed to efficiently use the already limited space in urban areas. Thus, this is especially attractive for modern but historically grown, densely build-up cities.

Nonetheless, this concept can only be regarded as an addition to the UAM infrastructure and can only work in conjunction with other vertipads, vertibases and vertihubs.

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8. Copyright Statement

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