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VR Simulation of a Vertiport for Advanced Air Mobility: A Sustainability-Oriented Case Study

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Abstract

Advanced Air Mobility (AAM) is becoming a possible part of future urban and regional transport systems. Vertiports form a central element of AAM, offering the infrastructure needed for electric vertical take-off and landing aircraft. Their placement within cities demands close attention to safety, regulation, infrastructure, sustainability, and public acceptance. This thesis examines how Virtual Reality (VR) can serve as a tool to support the early planning and assessment of a conceptual rooftop vertiport.

The study reviews the present state of AAM, eVTOL aircraft, vertiports, and immersive technologies. European regulatory guidance was analyzed, along with the environmental, social, and economic aspects of sustainability, and the possible roles of VR in urban integration, stakeholder communication, and informed decision-making.

A virtual environment was created using three-dimensional modelling and real-time simulation software. It depicted a rooftop vertiport, the nearby urban area, a destination airport, ground traffic, and an eVTOL flight from take-off to landing. Several viewpoints were added to give an immersive experience through a VR headset.

The application was assessed through a questionnaire completed by participants with relevant expertise. The results indicated an overall positive view of VR, especially for presenting vertiport concepts, aiding early design evaluation, and deepening understanding of urban integration.

The study concludes that VR can supplement traditional planning methods by improving spatial comprehension, stakeholder participation, and sustainability focused evaluation. Still, it should be applied together with detailed engineering studies, regulatory reviews, and real-world testing.

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List of Abbreviations

3D	Three-Dimensional
AAM	Advanced Air Mobility
AFM	Aircraft Flight Manual
AR	Augmented Reality
CSFL	Continued Safe Flight and Landing
EASA	European Union Aviation Safety Agency
EU	European Union
eVTOL	Electric Vertical Take-Off and Landing
FATO	Final Approach and Take-Off Area
MR	Mixed Reality
MTOM	Maximum Take-Off Mass
OFV	Obstacle-Free Volume
SA	Safety Area
SDK	Software Development Kit
TLOF	Touchdown and Lift-Off Area
UAM	Urban Air Mobility
UAS	Unmanned Aircraft Systems
UCW	Undercarriage Width
URP	Universal Render Pipeline
VFR	Visual Flight Rules
VR	Virtual Reality
VRP	Vertiport Reference Point
VTOL	Vertical Take-Off and Landing
XR	Extended Reality

Chapter 1

Introduction

1.1 Background and Motivation

Rapid urbanization and continuous population growth are placing increasing pressure on transportation systems in modern cities. Urban areas face serious challenges related to traffic congestion, air pollution, greenhouse gas emissions, and limited infrastructure capacity. According to the European Commission, more than 70% of the European Union population currently lives in urban areas, where transportation activities contribute significantly to environmental impacts[1].

The transport sector is among the main contributors to climate change and environmental pollution. The European Environment Agency reported that transport accounts for roughly one quarter of the European Union’s total greenhouse gas emissions, while also adding to air and noise pollution in urban environments[2]. In addition, growing traffic congestion negatively affects mobility efficiency, energy use, and economic productivity. According to the European Court of Auditors, congestion in urban areas causes economic losses exceeding €270 billion annually across the European Union[3].

To address these challenges, the European Union has established ambitious sustainability objectives through the European Green Deal, which aims to cut transport-related greenhouse gas emissions by 90% by 2050[4]. Achieving these goals requires the creation of innovative and sustainable transportation systems that can improve mobility while reducing environmental impacts.

In this context, Advanced Air Mobility (AAM) has appeared as a promis-

ing concept for future transportation systems. AAM refers to the use of new aircraft technologies and operational concepts for urban and regional air transportation. One of the main applications of AAM is Urban Air Mobility (UAM), which focuses on passenger and cargo transport within cities using electric vertical take-off and landing (eVTOL) aircraft. These systems aim to deliver faster, more flexible, and potentially more sustainable transportation options while easing the burden on existing ground networks. However, the successful implementation of AAM and UAM depends on the development of appropriate infrastructure, such as vertiports, along with effective methods for assessing their integration within existing urban environments.

1.2 Urban Air Mobility (UAM)

Among the emerging solutions proposed for future sustainable transportation systems, Advanced Air Mobility (AAM) and Urban Air Mobility (UAM) have gained significant attention in recent years. With the number of people living in urban areas rising by about 3% each decade, transportation within cities is expected to become more difficult because of increasing congestion, environmental pressures, and infrastructure constraints[5].

According to the European Union Aviation Safety Agency (EASA), Urban Air Mobility (UAM) is defined as "a safe, secure and more sustainable air transportation system for passengers and cargo in urban environments, enabled by new technologies and integrated into multimodal transportation systems"[5]. UAM stands as one of the main applications of AAM and concentrates on transportation within and around densely populated urban zones.

Urban Air Mobility systems rely on eVTOL aircraft equipped with advanced technologies such as electric propulsion and improved battery systems. These aircraft can operate with a pilot on board or through remote piloting systems. Potential benefits associated with eVTOL transportation include shorter travel times on selected routes, reduced local operational emissions, and improved connectivity between specific urban and regional locations. However, the extent of these benefits depends on factors such as route characteristics, aircraft occupancy, energy sources, infrastructure availability, and integration with existing transport networks [5].

From a sustainability point of view, UAM could contribute to more efficient and environmentally conscious transportation through electric propul-

sion and optimized mobility networks. It may also help ease traffic congestion and improve accessibility between urban centers and nearby regions. However, the implementation of UAM also brings several technical, operational, environmental, and social challenges, including:

- Integration into urban environments and ground infrastructure;
- Safety and security requirements;
- Public acceptance and social perception;
- Regulatory and certification challenges;
- Operational procedures and pilot licensing;
- Noise and acoustic impacts;
- Environmental and sustainability considerations;
- Airspace integration and traffic management.

Among these challenges, developing appropriate vertiport infrastructure remains one of the essential conditions for the successful integration of UAM systems into future cities.



Figure 1.1: Key challenges associated with Urban Air Mobility and vertiport integration (Illustration created by the author based on the literature reviewed in this thesis)

1.3 Vertiports and Urban Integration

The development of UAM systems requires suitable ground infrastructure capable of supporting eVTOL aircraft operations. Among the most important infrastructure elements are vertiports, serving as designated areas for aircraft landing and take-off, passenger handling, charging operations, and traffic management.

According to the European Union Aviation Safety Agency (EASA), a vertiport is defined as "an area of land, water, or structure used or intended to be used for the landing and take-off of VTOL-capable aircraft" [6]. Within the framework of Aerodrome and Vertiport regulations, vertiports are regarded as a category of aerodrome infrastructure [7]. Depending on operational requirements and urban constraints, they may be integrated into rooftops, airports, parking structures, or dedicated urban facilities.

Unlike conventional heliports, vertiports are specifically designed to support emerging Advanced Air Mobility (AAM) operations with lower noise emissions, electric charging capabilities, and greater operational flexibility [7]. These facilities may range from small "vertistops" with minimal infrastructure to larger "vertihubs" capable of supporting passenger services, maintenance activities, aircraft storage, and multimodal transportation connections [8]. Therefore, developing vertiports is essential for enabling future aerial transportation networks and integrating air mobility into existing urban transport systems.

However, integrating vertiports into dense urban environments brings several technical, operational, and environmental challenges. Vertiports must be carefully designed to ensure safe aircraft operations while considering surrounding buildings, obstacle limitation surfaces, noise restrictions, public safety, and compatibility with existing infrastructure [7]. In addition, factors such as downwash effects, emergency response systems, charging infrastructure, passenger accessibility, and energy demand must be evaluated during the design process [8]. These requirements make vertiport planning a multidisciplinary task involving aviation authorities, urban planners, local governments, and infrastructure operators.

Recent regulatory frameworks and prototype technical specifications developed by EASA indicate that future vertiports are expected to become highly integrated and technologically advanced facilities [7]. Due to the complexity of these systems and the need to assess human interaction, spatial perception, and operational workflows, simulation and visualization technolo-

gies are becoming increasingly significant during the design phase.

In this context, due to the complexity of vertiport planning, simulation and visualization technologies may support the assessment and communication of design concepts during the early planning phase.

1.4 Virtual Reality in Vertiport Planning

The planning of vertiports requires attention to a range of technical, operational, environmental, and social factors to ensure their safe and effective integration into future transportation systems. Conventional drawings and three-dimensional models can convey essential technical details, yet they may not fully express the spatial qualities of a proposed vertiport to all stakeholders, especially those without a technical background.

Virtual Reality (VR) provides an immersive way to visualise and experience a proposed vertiport before it is physically built. By placing users inside a simulated environment, VR helps them gain a clearer sense of the vertiport layout, its connection with surrounding infrastructure, and the movement of eVTOL aircraft. It can also help designers and stakeholders detect spatial limitations, test operational scenarios, and share design ideas during the early planning stage[9].

The application of VR is not confined to aviation or urban planning. It has also been used in many other areas where direct training or experimentation could be difficult, costly, or even unsafe. In healthcare, virtual environments let students and professionals practice clinical procedures and develop hands-on skills without putting patients at risk [10]. In higher education, VR helps create interactive learning spaces where students can explore complex topics and gain experience that might be hard to achieve in a standard classroom[11]. In manufacturing, it supports training in assembly, equipment operation, production processes, and workplace safety before users handle actual machinery[12]. These uses show the wider value of VR in offering controlled and repeatable experiences before tasks are carried out in real-world settings.

Furthermore, VR can support stakeholder participation by enabling aviation experts, urban planners, public authorities, researchers, and potential users to explore the same virtual environment from various perspectives. Feedback gathered through these experiences may help assess usability, public perception, urban compatibility, and sustainability-related factors[9].

While VR cannot substitute for detailed engineering analyses, safety evaluations, or regulatory approval processes, it can act as a complementary tool for early-stage visualization, communication, and design review[13]. For these reasons, this thesis investigates the potential application of VR to the simulation and preliminary assessment of a conceptual rooftop vertiport within an urban environment.

The remainder of this thesis is organised as follows. Chapter 2 reviews the current progress in Advanced Air Mobility, eVTOL aircraft, vertiports, and the application of simulation and immersive technologies in this area. Chapter 3 outlines the regulatory framework considered in the study and examines the key sustainability aspects related to vertiport planning and development. It also defines the design criteria used for the conceptual rooftop vertiport. Chapter 4 explains the methodology adopted to build the three-dimensional environment and to develop the VR simulation. Chapter 5 reports the preliminary expert evaluation of the created application, along with the questionnaire results and their discussion. Finally, Chapter 6 summarises the main conclusions and suggests possible directions for future research.

Chapter 2

State of the Art

2.1 Introduction

Advanced Air Mobility is an emerging field that brings together new aircraft technologies, dedicated infrastructure, digital systems, and innovative operational concepts. Understanding its current stage of development requires consideration of eVTOL configurations, vertiport features, and the use of simulation and immersive technologies to support design, evaluation, and public engagement. This chapter reviews these elements and points out the research gap addressed by the present thesis.

2.2 Current Development of Advanced Air Mobility and Vertiports

AAM has moved beyond the initial conceptual phase. Several full-scale eVTOL aircraft have completed piloted and unpiloted flight tests, including vertical take-off and landing, transition to forward flight, operation in controlled airspace, and flights between existing aviation facilities[14]. However, most eVTOL aircraft remain in stages of testing, certification, and operational-readiness work instead of being deployed for regular public passenger transport.

The level of development differs across regions. In Europe, the sector is largely in the aircraft certification and operational integration phase. Current regulatory activities address aircraft certification, pilot training, air opera-

tions, airspace integration, landing-site availability, and energy management [15]. A similar development phase can be seen in the United States, where pilot programmes are used to assess how eVTOL aircraft can be safely integrated into the existing aviation system[16].

China has reached a more advanced operational stage, where limited human-carrying eVTOL activities have received operational authorisation[17]. These activities mainly involve tourism, sightseeing, and flight experiences. Still, regular point-to-point urban passenger transport and large-scale commercial AAM networks are at an early stage.

Alongside the development of eVTOL aircraft, significant progress has also been made in the design, testing, and implementation of vertiport infrastructure. Vertiports have moved from conceptual designs to physical prototypes, demonstration sites, and operational testbeds. Full-scale facilities have been developed in Singapore, the United Kingdom, France, and Italy to test passenger handling, ground operations, charging systems, aircraft-infrastructure interaction, and public experience[18, 19, 20, 21]. Some of these facilities have also hosted crewed eVTOL demonstration flights. More permanent vertiport infrastructure is now being prepared in the United Arab Emirates to support future commercial air-taxi operations [22].

Overall, AAM can at present be described as shifting from experimental development toward early implementation. eVTOL aircraft have shown their capability to fly, and vertiport facilities have been physically built and tested. However, most current projects still remain in demonstration, certification, testing, or operational-preparation phases. Further progress is needed in aircraft certification, infrastructure development, operational procedures, airspace integration, economic feasibility, and public acceptance before large-scale urban passenger networks can be fully established.

2.2.1 Main eVTOL configurations

Electric vertical take-off and landing aircraft (eVTOL) can be classified into three main configuration types: vectored thrust, lift-and-cruise, and wingless multicopter designs[7].

In a **vectored-thrust configuration**, the same propulsion units generate vertical lift during take-off and landing and are then rotated to provide forward thrust during cruise. In forward flight, the wings generate aerodynamic lift. This configuration is generally suitable for longer-distance operations since it offers higher cruise efficiency, though its movable propulsion

system adds mechanical and certification complexity.

In a **lift-and-cruise configuration**, separate propulsion systems are used for vertical and horizontal flight. Dedicated rotors provide lift during take-off and landing, while another propulsion system produces forward thrust during cruise, with the wings generating lift. This separation tends to simplify the design compared with vectored-thrust aircraft, while still allowing a greater range than wingless multicopter concepts.

In a **wingless or multicopter configuration**, fixed rotors provide lift throughout all phases of flight. These aircraft do not rely on wings or rotating propulsion units, resulting in a relatively simple mechanical layout. However, because the rotors must continuously generate lift, multicopter aircraft are generally more suitable for shorter-distance urban operations.

The aircraft model used in this thesis is based on the Volocopter concept, which falls within the wingless multicopter category. This configuration was regarded as appropriate for simulating short-distance urban flight between the rooftop vertiport and the destination site.

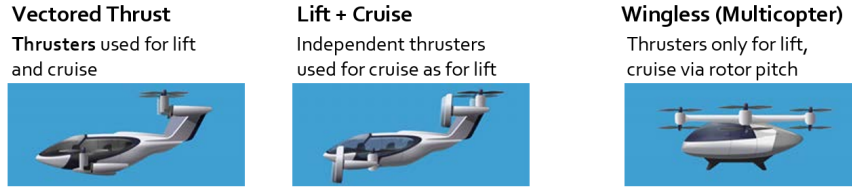


Figure 2.1: Main eVTOL configurations and their typical characteristics. Adapted from EASA [23].

2.2.2 Types of Vertiports

Vertiports can be grouped according to their physical location and operational scale.

According to EASA[7], vertiports may be classified as either surface-level or elevated. A vertiport situated on a raised structure on land at a height of 3 m or more is considered elevated. Therefore, this category includes vertiports built on building rooftops or other sufficiently raised structures.

Vertiports may also be grouped according to their size and expected traffic capacity. An EASA study presents three scalable infrastructure types: vertipads, vertibases, and vertihubs[23].

A **vertipad** represents the smallest vertiport configuration and is mainly

focused on the landing and take-off pad itself. It usually contains one or two landing pads and may serve outlying areas, specific points of interest, private users, or suburban transport links.

A **vertibase** represents an intermediate configuration and may be located close to areas with a higher concentration of origins and destinations, such as business districts, retail areas, and major commuting stations.

A **vertihub** is the largest configuration and may contain approximately ten landing pads. These facilities are primarily proposed for major airports, city centres, and key transport corridors.

This size-based classification is conceptual and shows how vertiport infrastructure can be scaled according to traffic demand and urban context. It does not constitute a formal regulatory classification for vertiport certification.

Based on these classifications, the conceptual facility developed in this thesis can be described as a small, single-pad elevated rooftop vertiport. In terms of operational scale, it most closely resembles a vertipad since it includes one take-off and landing area.

2.3 Previous Applications of Simulation and Virtual Reality

Virtual Reality has been used in aviation for many years, mainly for flight training, aircraft and cockpit design, maintenance and air traffic simulations where real operators work within a simulated environment.

During the early development of Advanced Air Mobility, VR was adapted to create configurable test environments for studying eVTOL operations, route following, cockpit interfaces, airspace integration, and interaction between users and automated systems[24, 25]. These simulations made it possible to examine operational concepts safely and gather flight and user-performance data without the need for real aircraft or access to operational urban airspace.

As AAM research progressed, the use of VR broadened from technical flight simulation to human-centred design. Immersive environments were applied to assess vertiport layouts and passenger experience, including circulation, wayfinding, signage, accessibility, and usability. This method allowed potential users to experience the proposed infrastructure and share feedback

before physical construction[26].

The current state of the art goes beyond conventional VR and increasingly includes Extended Reality (XR) technologies, such as Augmented Reality (AR) and Mixed Reality (MR). Present platforms can integrate virtual urban environments, aircraft models, physical controls, operational data, digital twins, and real-time interaction. Their uses include design validation, concept-of-operations testing, training, public familiarisation, stakeholder communication, and operational support[27, 28].

Overall, immersive technologies have developed from specialised technical simulators into broader platforms that support operational analysis, human-centred design, and communication of future AAM systems. Still, most current applications remain experimental. They cannot fully reproduce real flight conditions like acceleration, vibration, wind, and physical risk, and they do not replace engineering calculations, certification, safety assessment, or real-world testing. Instead, they serve as complementary tools for assessing and presenting AAM concepts during the early stages of development.

2.4 Research Gap

Based on the literature reviewed, limited research has examined the combined use of Virtual Reality to represent a regulation-informed rooftop vertiport integrated into an existing urban building. In particular, little attention has been paid to simulations that merge the full departure, flight, and landing phases of an eVTOL operation from both passenger and pilot perspectives, while also accounting for sustainability aspects, public understanding, stakeholder communication, and early design evaluation.

This thesis addresses that gap through the development of a conceptual elevated rooftop vertiport integrated into an existing building. The virtual environment brings together a vertiport layout based on EASA guidance, an eVTOL aircraft model, an urban flight scenario, and immersive passenger and pilot views through a VR headset. The simulation also illustrates the connection between the vertiport, its surrounding urban context, and selected sustainability elements. Feedback from VR participants and experts is gathered to assess the potential of VR as a tool for visualisation, communication, user engagement, and the preliminary evaluation of future vertiport concepts.

Chapter 3

Regulatory and Sustainability Framework

3.1 Aviation Regulation and Its Importance

Regulation can generally be described as the creation of rules, standards, and procedures that guide, control, and organize activities within a specific field. In aviation, regulation holds particular importance because aircraft operations involve significant technical complexity, operational risk, and interaction among aircraft, infrastructure, personnel, passengers, and nearby communities. Aviation regulations aim to reduce the likelihood of accidents by setting shared requirements for aircraft design, airworthiness, maintenance, pilot qualification, infrastructure, operational procedures, and safety management[29].

In addition to safety, aviation regulation promotes standardisation across the aviation system by ensuring that aircraft, airports, operators, air navigation services, and authorities operate within a unified framework. It also supports environmental protection by addressing matters such as noise, emissions, energy consumption, and the sustainable integration of emerging aviation technologies.

The significance of regulation becomes even more pronounced in the context of Advanced Air Mobility (AAM), where new types of electric vertical take-off and landing aircraft are expected to function in or near densely populated urban areas. Unlike conventional aviation activities, AAM demands regulatory focus across several interrelated domains, including vehicle cer-

tification and airworthiness, vertiport design and infrastructure standards, integration with existing urban systems, coordination with air traffic management and digital flight data networks, environmental and sustainability aspects, and social acceptance. These domains are essential because AAM operations must be safely coordinated with buildings, transport systems, public areas, emergency services, and current airspace users. Therefore, a well-structured regulatory framework is necessary to ensure that AAM can be introduced safely, efficiently, sustainably, and with public confidence.

In Europe, the European Union Aviation Safety Agency (EASA) plays a key role in developing technical guidance and future regulatory structures for the safe integration of VTOL-capable aircraft and vertiport infrastructure. One of the most relevant documents for this purpose is the Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category (PTS-VPT-DSN)[7].

EASA states that these prototype specifications are intended as non-regulatory guidance material in the initial phase, while a more complete regulatory framework will be established later. For this reason, the document is particularly relevant to this thesis, as it outlines the main safety and design considerations that should be taken into account when developing vertiport concepts for Advanced Air Mobility operations.

3.2 EASA Vertiport Design Requirements

3.2.1 Overview and Applicability

EASA notes that vertiport regulation will be developed in two main phases. In the first phase, the PTS-VPT-DSN [7] is introduced as non-regulatory guidance material for designing VFR vertiports, or parts of vertiports, intended for manned VTOL-capable aircraft certified in the enhanced category. EASA then intends to create a full regulatory framework for vertiports covered by Regulation (EU) 2018/1139, including requirements for authorities, vertiport operators, vertiport operations, certification specifications, and related guidance material for vertiport design and certification. The document thus applies to VFR vertiports that support manned VTOL-capable aircraft within the enhanced category.

In the EASA framework, the enhanced category [6] is a safety certifica-

tion class for VTOL-capable aircraft that demands higher safety objectives, especially for passenger transport and flights over dense urban areas. In this category, aircraft must be able to maintain safe flight and perform a landing after a critical failure, enabling them to continue to their planned destination or reach another suitable vertiport safely. This makes the enhanced category particularly important for AAM operations, where aircraft may carry passengers and operate above populated regions.

3.2.2 Key Definitions for Vertiport Design

Congested area:

A congested area refers to a part of a city, town, or settlement that is mainly used for residential, commercial, or recreational activities[7].

Aerodrome:

A defined area, including any buildings, installations, and equipment, located on land, water, or a fixed offshore or floating structure, intended to be used fully or partly for the arrival, departure, and surface movement of aircraft[7].

Category Enhanced:

Category Enhanced is a certification category for VTOL-capable aircraft that requires the aircraft to be capable of continued safe flight and landing after a critical failure. This means that even if a serious performance-related failure happens, the aircraft must still maintain controlled flight and land safely, either at the planned destination or at another suitable vertiport. This category is mainly relevant for higher-risk operations, such as passenger transport and flights over congested areas[7].

Category Basic:

Category Basic is a certification class for VTOL-capable aircraft that requires the aircraft to be able to make a controlled emergency landing after a critical performance-related failure. Unlike the enhanced category, it does not demand that the aircraft continue safe flight to its destination or an alternate vertiport, but it must still permit a controlled landing[7].

Obstacle:

Any fixed or movable object, whether temporary or permanent, that could pose a hazard to VTOL-capable aircraft[7].

Safety Area (SA):

An obstacle-free zone surrounding the FATO, meant to lower the risk of damage if a VTOL-capable aircraft unintentionally deviates during approach or take-off[7].

Protection Area:

An area around a VTOL-capable aircraft stand, designed to reduce the risk of damage if the aircraft accidentally deviates from its intended position during stand operations[7].

D-value:

The D-value refers to the diameter of the smallest circle that completely encloses the horizontal projection of a VTOL-capable aircraft when it is in its take-off or landing configuration, with rotors turning if applicable. It is given in metres and rounded up to the nearest tenth. If the aircraft changes its dimensions while taxiing or parking, for instance due to folding wings, separate values such as D_{taxiing} or D_{parking} should also be noted[7].

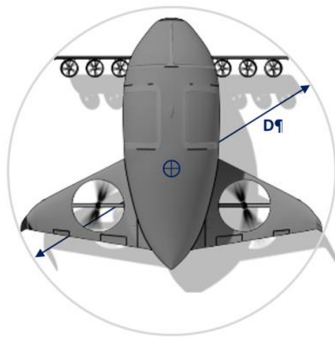


Figure 3.1: Definition of the Design D -value for a VTOL-capable aircraft (source: EASA PTS-VPT-DSN [7]).

Distance DR:

It means the horizontal distance between the VTOL-capable aircraft and an obstacle during take-off. This distance is measured either from the end of the available take-off distance or from the rear edge of the FATO to the obstacle [7].

VTOL-capable aircraft:

A heavier-than-air aircraft, distinct from a conventional aeroplane or helicopter, that can carry out vertical take-off and landing using more than two lift or thrust units to generate lift during take-off and landing[7].

Design VTOL-capable aircraft:

The design VTOL-capable aircraft is the reference aircraft used for vertiport design. It represents the aircraft type, or the mix of aircraft characteristics, that impose the most demanding requirements on the vertiport, such as the largest dimensions, the highest maximum take-off mass (MTOM), and the strictest obstacle-avoidance criteria. These characteristics may come from several aircraft types, not necessarily from a single one[7].

Final Approach and Take-Off Area (FATO):

The FATO is the part of a vertiport used for the final phase of approach and the start of take-off. It should remain free of obstacles, except for necessary safety-related equipment like lighting or firefighting systems, and must be large enough to hold the design VTOL-capable aircraft during its intended operations. Each vertiport should have at least one FATO, and it should be associated with a safety area (SA)[7].

Continued Safe Flight and Landing (CSFL):

The ability of a VTOL-capable aircraft to remain under control and land safely at a vertiport after a failure, possibly using emergency procedures, without requiring exceptional pilot skill or physical effort[7].

Touchdown and Lift-Off Area (TLOF):

The area on a vertiport specifically intended for the touchdown and lift-off of VTOL-capable aircraft[7].

Visual Flight Rules (VFR):

A set of flight rules under which the aircraft is flown mainly by visual reference to the outside environment. VFR operations require adequate visibility and weather conditions that allow the pilot to see and avoid obstacles, terrain, and other aircraft[7].

Vertiport Reference Point (VRP):

The designated geographical position of a vertiport, usually given through coordinates. It serves as the official reference point for identifying the vertiport’s location on maps and in aeronautical information[7].

Vertiport elevation:

The highest point of the Final Approach and Take-Off Area (FATO)[7].

3.2.3 Physical Characteristics of Vertiports

According to EASA, the physical layout of a vertiport is built on several core assumptions and design principles.

First, the Final Approach and Take-Off Area (FATO) is considered to serve only one VTOL-capable aircraft at any given time. This means the landing and take-off zone is arranged for single-aircraft operations, not for multiple aircraft using the same FATO simultaneously. When more than one FATO is positioned near another, EASA assumes they will not be used at the same time unless proper separation distances and safety measures are clearly defined.

EASA defines a vertiport as a set of distinct areas, each serving a particular operational role. These areas form the essential structure of the vertiport and include the FATO, TLOF, aircraft stand, taxiway, ground taxi-route, and air taxi-route. Supporting zones consist of the Safety Area (SA), clearway, and protection area.

Moreover, when designing stands for VTOL-capable aircraft, the placement and size of charging systems should be taken into account. This is particularly significant for AAM operations since many aircraft are electric, and the charging infrastructure can influence the layout, spacing, and ground movement within the vertiport.

Based on these principles, the main physical features of vertiports are outlined to highlight the essential components required for safe VTOL operations[7].

3.2.3.1 Final-Approach and Take-Off Areas (FATOs)

The Final Approach and Take-Off Area (FATO) is a key physical component of a vertiport. According to EASA, it must provide an area free from obstacles, except for essential safety-related items such as visual aids, lighting, roll-over protection, or firefighting equipment. Any essential objects within

the FATO should not rise more than 5 cm above the horizontal plane at the FATO elevation.

A vertiport should have at least one FATO, which can be either solid or non-solid. When the FATO has a solid surface, it must resist downwash effects, offer sufficient bearing strength where needed, ensure proper drainage, and prevent surface hazards. If it is located together with a TLOF, both areas should be continuous and level.

The FATO must be large enough to accommodate the design VTOL-capable aircraft during the final stage of approach and the initial stage of take-off.

The FATO must also be linked to a Safety Area (SA). Its minimum length and width should follow the procedure specified in the Aircraft Flight Manual (AFM), or be 1.5 times the Design D, whichever value is greater[7].

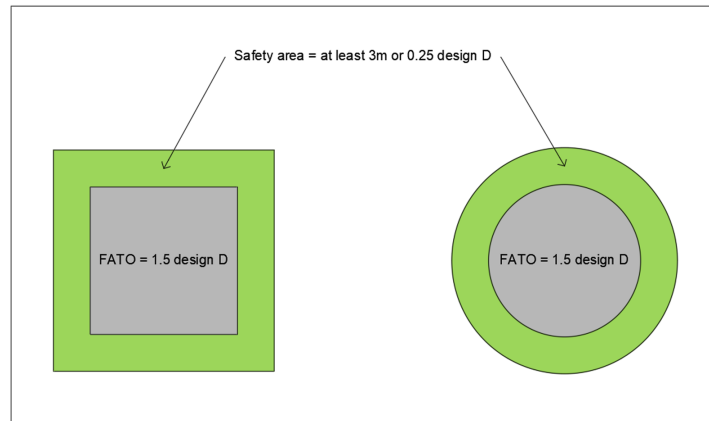


Figure 3.2: FATO and associated Safety Area (Source: EASA PTS-VPT-DSN [7])

3.2.3.2 Safety Area (SA)

The Safety Area (SA) surrounds the FATO and offers extra protection during VTOL-capable aircraft operations. Its main role is to offset possible manoeuvring errors, particularly in difficult environmental conditions. For this reason, the SA must remain clear of obstacles, except for essential safety-related items.

When the SA has a solid surface, it needs to be continuous and level with the FATO. It should also resist downwash effects and ensure proper drainage to prevent operational risks.

As stated by EASA, the SA must extend outward from the FATO edge by at least 3 m or 0.25 Design D, whichever is larger. No movable objects are allowed within the SA during VTOL-capable aircraft operations. Essential objects placed inside the SA must also comply with height restrictions and should not break through an imaginary surface beginning 25 cm above the FATO edge and rising outward at a 5% gradient. Moreover, when the SA is solid, its surface slope should not go beyond 4% outward from the FATO[7].

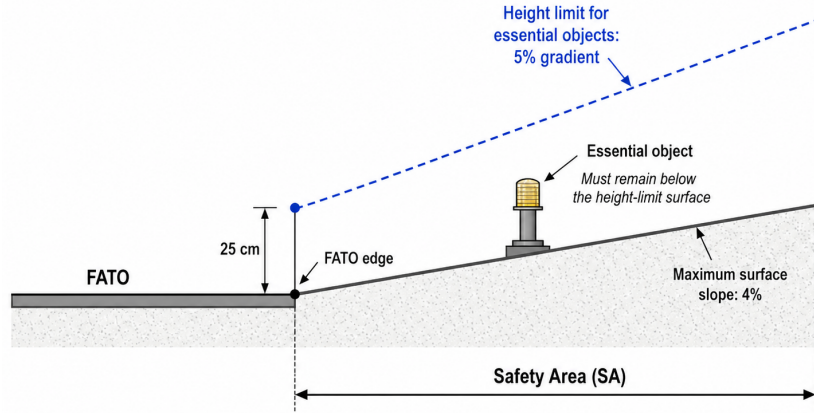


Figure 3.3: Safety Area geometry and height limitations(Author’s own elaboration based on EASA PTS-VPT-DSN [7])

3.2.3.3 Downwash Protection

Downwash protection is a key part of vertiport design since VTOL-capable aircraft can create strong airflow during hover, take-off, and landing. According to EASA, the Aircraft Flight Manual (AFM) must include the downwash value measured around the aircraft under specific hover conditions. This figure helps determine whether the Safety Area (SA) offers enough protection against downwash effects.

EASA gives initial guideline values for the maximum downwash velocity for various types of areas, as shown in figure 3.4. These values help assess the

influence of downwash on passengers, flight crew, public zones, roads, apron equipment, and nearby structures. Still, the evaluation should also take into account local factors such as wind, vegetation, pedestrian or bicycle paths, light structures, and any relevant local regulations.

If the downwash value stated in the AFM goes beyond the recommended limits, an extra downwash protection area should be established. This area must ensure that the downwash velocity at its boundary stays below the advised maximum value. Depending on local wind patterns, the protection area might need to stretch beyond the standard 2D circle. When the Safety Area is not solid, the downwash protection area can overlap with the SA. For elevated vertiports, the protection area might also need to extend below the FATO level. In those cases, a safety assessment should be performed to decide whether this extra protection is required [7].

Maximum downwash velocity	Type of area
60 km/h	for areas of a vertiport traversed by flight crew, or passengers, boarding or leaving an aircraft
60 km/h	for public areas, within or outside the vertiport boundary, where passengers or members of the public are likely to walk or congregate
80 km/h	for public areas where passengers or others are not likely to congregate
50 km/h	for public roads where the vehicle speed is likely to be 80 km/h or more
60 km/h	for public roads where the vehicle speed is likely to be less than 80 km/h
80 km/h	for any personnel working near an aircraft
80 km/h	for equipment on an apron
100 km/h	for buildings and other structures

Figure 3.4: Initial guidelines for the maximum downwash velocity per type of area (Source: EASA PTS-VPT-DSN [7]).

3.2.3.4 Protected Side Slope

According to EASA, a vertiport must have at least one protected side slope that extends outward from the edge of the Safety Area (SA). This surface rises at a 45-degree angle and continues for a distance of 10 m. Its function is to offer extra obstacle protection around the FATO and SA, helping reduce the chance of interference between VTOL-capable aircraft and nearby objects during operations.

The protected side slope must stay clear of any obstacle penetration. In

other words, buildings, equipment, structures, or any other objects should not intrude into this protected surface, ensuring a safe operational area around the vertiport[7].

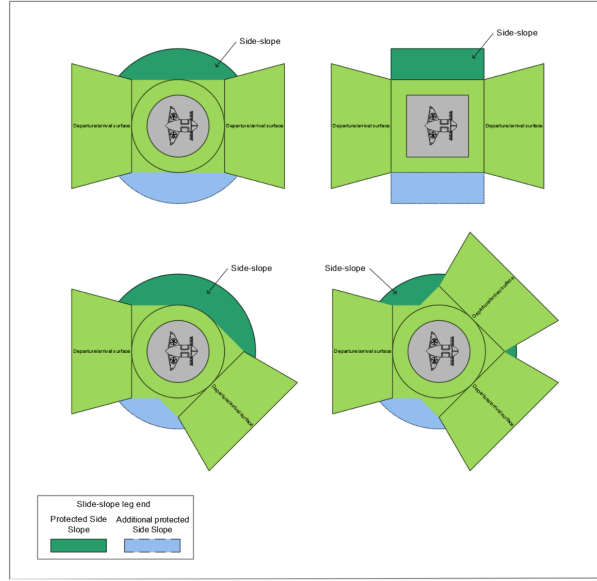


Figure 3.5: Different configurations of protected side slopes around the FATO and Safety Area (Source: EASA PTS-VPT-DSN [7]).

3.2.3.5 VTOL-capable Aircraft Clearway

A VTOL-capable aircraft clearway is an additional area that can be provided to support take-off performance, though EASA specifies that its inclusion is not required. When it is included, the clearway must remain free of obstacles, except for essential safety-related items, and should provide enough space for the design VTOL-capable aircraft to accelerate near the surface and reach its take-off safety speed.

If the clearway has a solid surface, it needs to be continuous and level with the FATO and Safety Area (SA), resistant to downwash forces, and free of hazards if a forced landing becomes necessary. When the clearway is elevated, it must also allow sufficient clearance above all obstacles.

The clearway should start at the outer edge of the Safety Area or, if elevated, directly above or below that edge. Its width must not be less than the total width of the FATO and the related Safety Area. For solid clearways,

the ground slope should remain within the limits set by EASA to prevent operational hazards during take-off [7].

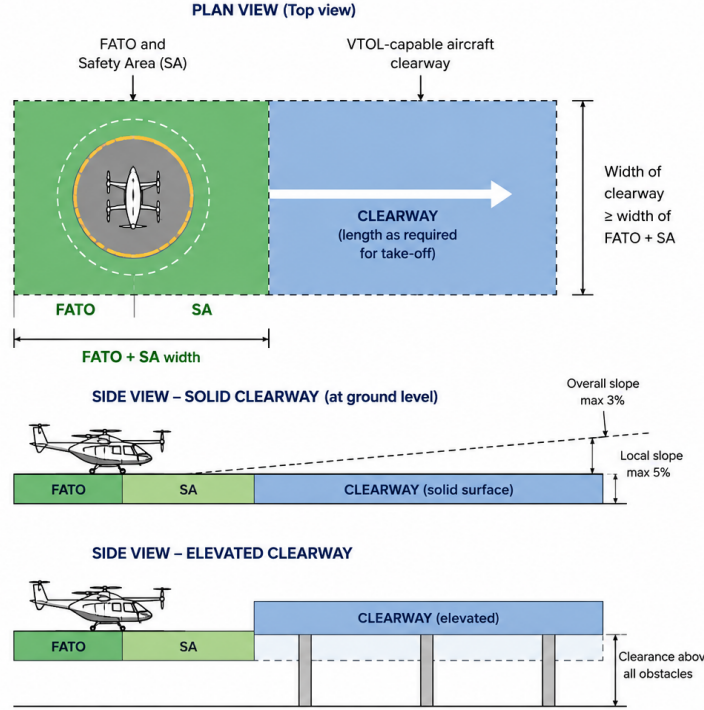


Figure 3.6: Schematic representation of a VTOL-capable aircraft clearway in relation to the FATO and SA (Author’s own elaboration based on EASA PTS-VPT-DSN[7].)

3.2.3.6 Touchdown and Lift-off Area (TLOF)

A vertiport must include at least one Touchdown and Lift-Off Area (TLOF) wherever the aircraft’s undercarriage is meant to touch down or lift off. The TLOF may be connected with a FATO, a taxiway, or an aircraft stand.

This area must be free of obstacles and large enough to hold the undercarriage of the most demanding VTOL-capable aircraft. Its surface should have adequate bearing strength for dynamic landing loads, enough friction to prevent skidding, resistance to downwash, proper drainage, and no irregularities that could affect aircraft stability.

The minimum TLOF dimensions should be $0.83 D$, or those specified in the Aircraft Flight Manual (AFM), whichever is greater. For an elevated ver-

tiport, a TLOF within a FATO must be large enough to contain a circle with a diameter of at least 1 Design D. When located within a FATO, the TLOF should normally be centered on it, while one within an aircraft stand should be centered on that stand. Clear markings should indicate the touchdown point and any maneuvering restrictions[7].

3.2.3.7 VTOL-capable Aircraft Taxiways and Taxi routes

VTOL-capable aircraft taxiways are prepared surfaces meant for ground movement, either under the aircraft's own power or with ground-handling equipment. They must remain clear of obstacles, able to bear taxiing loads, and, where needed, resistant to downwash. They should also be designed to provide proper drainage. The minimum width is generally twice the undercarriage width (2 UCW).

Ground taxi-routes are protected corridors used when the aircraft moves on its landing gear. They should be centered on the taxiway and have a minimum width equal to 1.5 times the overall width of the largest aircraft expected to use them. No mobile objects should be present within the route during aircraft operations.

Air taxi-routes are meant for aircraft movement slightly above the surface in low hover, usually at a ground speed below 37 km/h (20 kt). Their minimum width should be twice the overall width of the largest aircraft intended to use them. When combined with a taxiway, the air taxi-route should be centered on it[7].

3.2.3.8 FATO Location in Relation to Other Operational Areas

The distance between two FATOs should be determined through a safety assessment to ensure that nearby operations do not compromise VTOL-capable aircraft safety. The assessment must take into account the type of operation, approach, and departure path orientation, balked landing procedures, aircraft downwash data, and the need to prevent overlap between the related Safety Areas.

A separation distance of 60 m can serve as an initial reference for simultaneous operations involving relatively light aircraft, though the final distance should be adjusted according to the characteristics and performance of the VTOL-capable aircraft.

When a FATO is located near an aerodrome runway or taxiway, the

minimum separation distance should be chosen according to the aircraft mass categories given in figure 3.7. These distances are mainly intended to reduce the risk of wake turbulence. FATOs should also not be placed near taxiway intersections, holding points, or areas affected by jet-engine turbulence or aircraft wake vortices. Local conditions and other relevant aerodrome design requirements should be taken into account as well[7].

If aeroplane mass and/or VTOL-capable aircraft mass are	Distance between FATO edge and runway edge or taxiway edge
up to but not including 3 175 kg	60 m
3 175 kg up to but not including 5 760 kg	120 m
5 760 kg up to but not including 100 000 kg	180 m
100 000 kg and over	250 m
Note: The values specified in this table are primarily intended to mitigate risks of wake turbulence encounters. In addition to this table, when positioning a FATO intended to be used simultaneously with a nearby runway or taxiway, attention should be given to other CS ADR-DSN requirements such as the minimum runway strip width. Local environment should be taken into account when setting the separation between the FATO and nearby infrastructure elements to ensure the safety of simultaneous operations.	

Figure 3.7: Minimum separation distance between FATOs (source: EASA PTS-VPT-DSN [7]).

3.2.3.9 Obstacle-Free Volume (OFV)

The Obstacle-Free Volume (OFV) is a protected airspace above the vertiport that must stay clear of any obstacles. This requirement is particularly significant for vertiports situated in urban or obstacle-dense areas, as it ensures safe vertical take-off and landing operations.

The dimensions and form of the OFV are determined by the vertical take-off and landing procedure described in the Aircraft Flight Manual (AFM). The volume rises vertically from the FATO and Safety Area to the low hover height (h_1), then expands gradually until it reaches the high hover height (h_2), forming a funnel-like protected space. The main parameters defining the vertical take-off and landing procedure and the Obstacle-Free Volume are summarised in the following table.

Table 3.1: Vertical take-off and landing procedure parameters

Parameter	Min/Max	Short description
h_1	–	Low hover height.
h_2	$\geq h_1$	High hover height.
TO_{width}	$\leq 5D$	Width at h_2 .
TO_{front}	$\leq 5D$	Front distance at h_2 .
TO_{back}	$\leq 5D$	Back distance at h_2 .
$FATO_{\text{width}}$	$\geq 1.5D$	Width of the FATO.
$FATO_{\text{front}}$	$\geq 0.75D$	Front distance on the FATO.
$FATO_{\text{back}}$	$\geq 0.75D$	Back distance on the FATO.
θ_{app}	$\geq 4.5\%$	Slope of the approach surface.
θ_{dep}	$\geq 4.5\%$	Slope of the departure surface.

Source: Adapted from EASA PTS-VPT-DSN [7]

The FATO width must be at least $(1.5D)$, while the front and rear distances from the aircraft centre must each be at least $(0.75D)$. At the high hover height, the width, front distance, and rear distance of the procedure volume must not exceed $(5D)$. The approach and departure slopes must each be at least 4.5% . To form the complete OFV, an additional $0.5D$ is added on each side of the procedure volume at h_2 . Therefore, the total width becomes $(TO_{\text{width}} + 1D)$, while the front and rear distances become $(TO_{\text{front}} + 0.5D)$ and $(TO_{\text{back}} + 0.5D)$, respectively. The entire OFV must remain free from obstacles. A larger Safety Area may be required where local wind or turbulence conditions create additional risks[7].

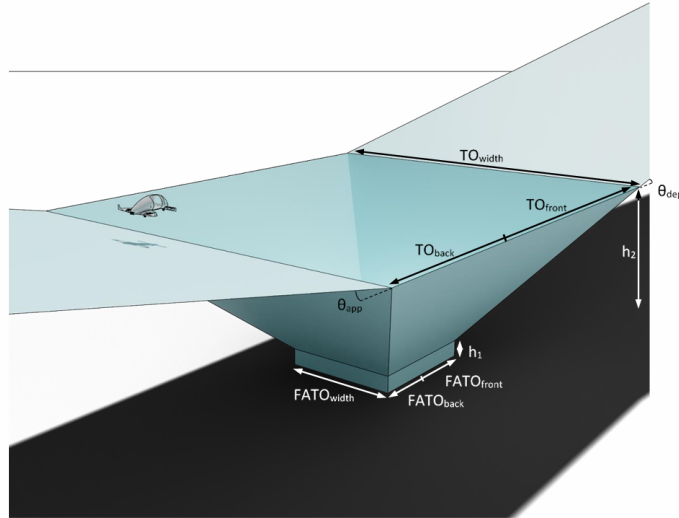


Figure 3.8: Schematic representation of the obstacle-free volume (Source: EASA PTS-VPT-DSN [7]).

3.2.3.10 Visual Aids, Markings, and Lighting

Visual aids assist pilots in locating the vertiport, recognizing its operational boundaries, maintaining the correct approach or departure path, and positioning the aircraft safely. As stated by EASA, the primary visual aids consist of wind direction indicators, identification markings, FATO and TLOF markings, touchdown position markings, operational limitation markings, and lighting systems.

Wind Direction Indicator

A vertiport must include at least one wind direction indicator that displays the local wind direction and offers a general sense of wind speed. It should remain visible to the pilot during flight, hovering, and ground movement, and it must be placed away from airflow disruptions created by nearby structures or aircraft downwash.

For a surface-level vertiport, the wind direction indicator should have a minimum length of 2.4 m, with diameters of 0.6 m at the larger end and 0.3 m at the smaller end. For an elevated vertiport, the minimum length is 1.2 m, with diameters of 0.3 m and 0.15 m. It should have a clearly visible color, such as white, orange, or alternating contrasting colors, and should be

illuminated when the vertiport is used at night.

Vertiport Identification Marking

The vertiport identification marking should consist of a white letter "V" placed inside a blue circle. Its purpose is to show the presence of a vertiport and its intended function. The marking is usually located at or near the center of the FATO. For an elevated vertiport, it should be placed within the FATO or TLOF. It must also be aligned so that the letter can be read from the preferred final approach direction.

FATO Identification Marking

This marking helps distinguish between different FATOs when a vertiport includes two or more landing and take-off areas. It is generally not required for runway-type FATOs, where other designation markings are used instead. The marking should be placed inside the FATO and positioned so that it can be easily read from the preferred final approach direction. Each FATO must be identified by a sequential number, starting from 1, displayed inside a blue circle with a diameter of 175 cm.

Maximum Allowable Mass Marking

This marking indicates the maximum aircraft mass that the vertiport can safely handle. When needed, it should be placed within the FATO or TLOF and arranged so that it is clearly visible from the preferred final approach direction. The maximum allowable mass should be shown in tonnes, rounded to the nearest 100 kg, and written to one decimal place followed by the letter "t". The marking should contain a two- or three-digit value and use a color that contrasts clearly with the background. For non-runway-type FATOs, the minimum character height is 90 cm when the D-value is between 15 m and 30 m, and 60 cm when the D-value is below 15 m. Larger markings should be used when the D-value exceeds 30 m.

Taxiway and Air Taxi-Route Markings

Taxiway and air taxi-route markings provide visual guidance for VTOL-capable aircraft movement. Their center lines should be marked by a continuous yellow line, 15 cm wide, on paved surfaces. On unpaved surfaces, flush yellow markers about 1.5 m long and 15 cm wide should be used, with maximum spacing of 30 m on straight sections and 15 m on curves. When an air taxi-route shares a taxiway, the same taxiway center-line marking is

used. For night operations, markers should be illuminated or retroreflective.

Vertiport Lighting

Vertiport lighting ensures safe night-time operations by helping pilots identify the vertiport, follow the designated approach and departure paths, distinguish the main operational areas, and position the aircraft accurately. Lighting systems should provide adequate visibility, allow intensity adjustment according to conditions, and be arranged to reduce glare and confusion with nearby urban lights[7].

3.3 Sustainability Considerations for Vertiports

Vertiport sustainability can be evaluated through three main pillars: environmental, social, and economic sustainability. Each of these pillars includes several important aspects that need to be taken into account during site selection, design, construction, and operation.

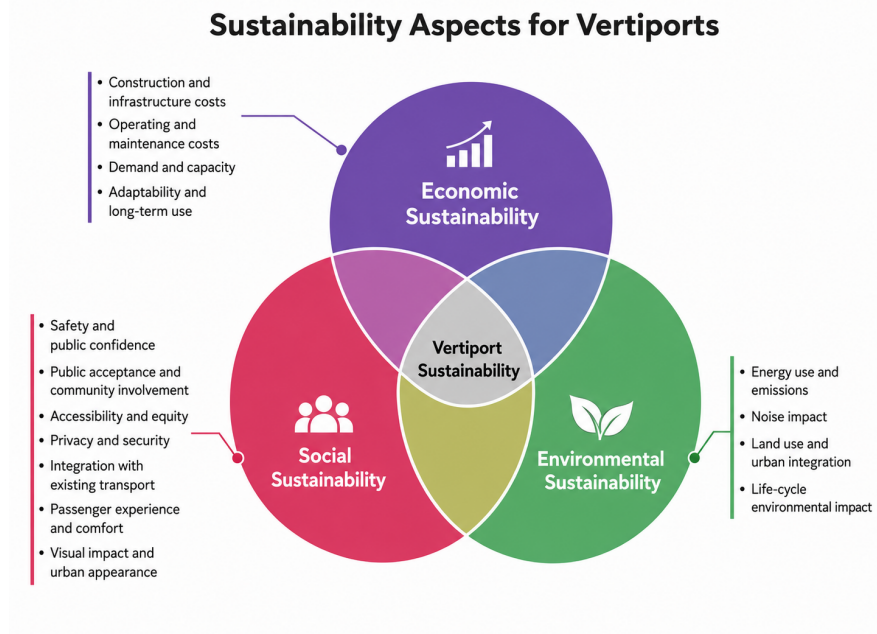


Figure 3.9: Three pillars of sustainability (Author's own elaboration)

3.3.1 Environmental Sustainability

Environmental sustainability in vertiport development involves several inter-related aspects, including energy consumption, emissions, noise, land use, and life-cycle impacts.

Vertiports require electricity for aircraft charging, lighting, communication systems, and passenger facilities. For this reason, the source of electricity is very important. Electric aircraft may produce no direct emissions during flight, but emissions can still result from electricity generation and battery production. Therefore, renewable or low-carbon energy should be preferred whenever possible[30, 31].

Noise is among the most significant environmental issues linked to vertiports. Take-off, landing, hovering, and frequent aircraft movements can disturb those living or working nearby. Because of this, the vertiport’s location, flight routes, operating times, and number of daily operations should be planned with care to limit noise exposure [23, 31, 32].

A vertiport should make efficient use of space and avoid occupying land unnecessarily. Rooftops, airports, parking decks, or existing transport hubs can sometimes be reused instead of building entirely new facilities. Still, the chosen site must remain appropriate regarding structure, accessibility, safety, and its influence on the surrounding area[31, 32, 33].

Environmental sustainability should not focus only on aircraft operations. It also needs to account for battery and equipment production, construction materials, maintenance, component replacement, waste generation, and final disposal. Taking a life-cycle view gives a fuller picture of the true environmental impact[30, 31].

3.3.2 Social Sustainability

Social sustainability in vertiport development involves several interconnected aspects, including safety, public confidence, community involvement, accessibility, equity, privacy, transport integration, visual impact, and passenger comfort.

Safety and public confidence are central to a socially sustainable vertiport. It should ensure safe aircraft operations, smooth passenger movement, reliable emergency access, and clear operational procedures. Public confidence is also important because people are less likely to accept or use a system that they do not consider safe[23, 32, 34].

Public acceptance and community involvement are also important. Vertiports may create concerns about noise, safety, privacy, visual impact, and changes in neighborhood activity. Local residents, authorities, transport operators, and other stakeholders should therefore be informed and involved in the planning process. Early communication can help identify concerns and strengthen trust[23, 31, 32].

Accessibility and equity should also be considered. The vertiport should be accessible to different types of users, including people with reduced mobility. It is also essential that the benefits and negative impacts are shared fairly. One community should not face most of the noise or disturbance while gaining very few mobility or economic advantages[31, 32].

Privacy and security represent further social considerations. Urban air mobility may raise privacy concerns because aircraft and vertiports can operate close to homes, offices, schools, and other private spaces. Flight paths, cameras, passenger information, digital systems, and data collection should therefore be managed carefully. Vertiports should also be protected from unauthorised access, physical threats, and cyberattacks. Privacy and security measures are vital for protecting users and nearby communities and for building public trust[31, 32, 34].

Integration with existing transport is another important aspect of social sustainability. A vertiport should be connected with public transport, pedestrian routes, cycling infrastructure, taxis, and road networks. Good connections reduce first- and last-mile difficulties and make the service easier to reach for more users. Poorly connected vertiports may increase car traffic and limit the wider mobility benefits of the system[31, 35].

The visual impact and urban appearance of the vertiport should also be considered. Vertiports, aircraft movements, lighting, rooftop structures, and supporting equipment may alter the appearance of the surrounding area. This can influence the quality of life of residents and the visual character of neighborhoods, historic areas, or public spaces. Therefore, the design should be carefully integrated into the existing urban environment, using appropriate location, scale, materials, lighting, and architectural solutions to reduce visual disturbance and support public acceptance[23, 31, 32].

Finally, passenger experience and comfort are essential elements of social sustainability. A vertiport should provide clear access routes, understandable information, comfortable waiting areas, efficient boarding procedures, and suitable facilities for different users. Noise, vibration, waiting time, perceived safety, accessibility, and the overall comfort of the journey may affect passengers' willingness to use the service and their acceptance of Advanced Air Mobility[23, 34].

3.3.3 Economic Sustainability

Economic sustainability in vertiport development involves several interconnected aspects, including construction and infrastructure costs, operating and maintenance expenses, passenger demand, capacity, adaptability, and long-term viability.

Construction and infrastructure costs should be considered from the beginning of the planning process. Vertiport development may require structural work, charging systems, passenger facilities, safety equipment, communication networks, and utility connections. These costs should be considered from the beginning, especially for rooftop vertiports where reinforcement, lifts, and emergency access may be necessary[32, 33, 35].

Operating and maintenance costs are also important for ensuring that a vertiport remains affordable over time. Key costs include electricity, staffing, inspections, maintenance, security, insurance, and replacing equipment. A simple and efficient design can help reduce unnecessary costs[32, 35].

Demand and capacity should be evaluated together when determining the appropriate size of the vertiport. A facility that is too large could be costly and underused, while one that is too small might cause delays and restrict future operations. Demand and capacity should therefore be studied together[32, 34].

Finally, adaptability and long-term use are essential for economic sustainability. Vertiport design should be flexible enough to respond to future changes in aircraft size, charging systems, traffic levels, automation, and regulations. Adaptable infrastructure can reduce the need for costly reconstruction and improve long-term viability[31, 32, 33].

3.3.4 How VR Supports Sustainability

Virtual Reality can support sustainability-oriented vertiport planning by allowing proposed designs and operations to be explored before physical implementation. Its contribution can be considered across the environmental, social, and economic pillars:

3.3.4.1 Support for Environmental Sustainability

VR can help show how a vertiport fits within the surrounding urban environment. Different locations, rooftop layouts, building shapes, approach paths, lighting systems, and nearby sensitive areas can be displayed and compared. This may help identify possible concerns early, such as those related to land use, visual impact, and the proximity of residential buildings, schools, hospitals, or public spaces.

VR may also be combined with external noise, energy, or emissions models to present environmental data in a clearer and more accessible way. However, VR alone cannot calculate noise exposure, energy consumption, emissions, or life-cycle impacts. These aspects need separate quantitative assessment methods[30, 32].

3.3.4.2 Support for Social Sustainability

Public Familiarity, Acceptance, and Trust

VR can help people become familiar with future vertiports and Advanced Air Mobility before these systems are physically introduced. Since most citizens have never encountered a vertiport or an eVTOL flight, an immersive simulation can make the concept easier to grasp and less uncertain. Users can observe the rooftop vertiport, the aircraft, the boarding process, the flight, and the surrounding urban environment.

This experience can support public acceptance by allowing residents, passengers, experts, and authorities to form more informed opinions. It also offers an opportunity to collect feedback about safety, comfort, privacy, noise, visual impact, and the general acceptability of the project[23, 31, 32].

Passenger Experience, Safety, and Accessibility

VR can simulate the passenger journey from entering the building to landing at the destination. This helps users assess comfort, orientation, perceived

safety, waiting areas, boarding procedures, and accessibility for people with different needs[9, 32].

VR can show how rooftop vertiport elements might appear within the surrounding urban environment. Residents and planners can therefore judge whether the proposed design matches the character of the area or causes visual disturbance. The simulation can also help users understand the relationship between the vertiport, flight paths, nearby homes, offices, schools, and other private spaces, supporting discussion about privacy and visibility. Sound may also be included to give an initial impression of aircraft and vertiport noise[23, 30, 32].

Urban and Transport Integration

VR can display how the vertiport connects with existing buildings, roads, pedestrian routes, public transport, taxis, and cycling infrastructure. This helps planners and users decide whether the facility is easy to reach and fits appropriately within the surrounding area. It can also support the comparison of rooftop locations and different access solutions before construction. Good urban and transport integration can improve accessibility.

Overall, VR can support social sustainability by making future vertiports more understandable, allowing people to experience the proposed system, gathering informed feedback, and encouraging passenger-centred design. Its main contribution is therefore the improvement of public familiarity, acceptance, trust, and stakeholder participation before physical implementation[23, 32].

3.3.4.3 Support for Economic Sustainability

VR can support economic sustainability by helping designers detect layout, access, circulation, or infrastructure problems before construction begins. Finding these issues early may reduce the need for costly design changes or physical modifications later on[32, 34].

Nevertheless, VR cannot directly determine construction costs, operating costs, passenger demand, revenue, or financial viability. These aspects require economic, market, and operational analyses. VR should therefore be used as a complementary planning and communication tool rather than as a complete sustainability assessment method[34, 35].

3.4 Design Criteria Applied in This Case Study

The conceptual rooftop vertiport developed in this thesis was dimensioned in accordance with the EASA Prototype Technical Specifications for the Design of VFR Vertiports, PTS-VPT-DSN[7]. Since this is a non-binding prototype material, the resulting layout should be regarded as a preliminary conceptual design rather than a certified vertiport.

3.4.1 Rooftop characteristics

The proposed vertiport is located on the rooftop of the Engineering Campus building in Forlì. The available rooftop measures about 40 m by 23.5 m, giving a total plan area of roughly 940 m². Since the operating surface is positioned more than 3 m above ground level, it is considered an elevated vertiport according to the EASA definition.

For the purposes of the VR simulation, the rooftop was assumed to provide a paved and approximately level surface. However, the structural load-bearing capacity, exact surface slope, drainage characteristics, and resistance to aircraft downwash were not experimentally assessed. These aspects would require dedicated structural and operational studies before real implementation.

3.4.2 Design aircraft

The VR aircraft is based on the Volocopter concept. Since certified operational data and a public Aircraft Flight Manual were unavailable, the manufacturer's specification sheet [36] was used to approximate the aircraft and vertiport dimensions. The Volocopter has two seats, a height of 2.7 m, a rotor-rim diameter of 11.3 m, and an approximate MTOM of 1,000 kg. These values were used only to approximate the aircraft dimensions and the related vertiport design parameters.

3.4.3 Determination of the Design D-Value

According to the EASA PTS-VPT-DSN, the design D-value is defined as the diameter of the smallest circle enclosing the horizontal projection of the aircraft in its take-off or landing configuration. Since the Volocopter has a

circular rotor rim with a diameter of 11.3 m, the Design (D)-value adopted for the preliminary vertiport calculations was: $D = 11.3$ m

3.4.4 FATO and TLOF Dimensions

According to PTS-VPT-DSN [7], the minimum length and width of the FATO should correspond to the aircraft-specific dimensions prescribed in the Aircraft Flight Manual (AFM) or $1.5D$, whichever is greater. Therefore, the preliminary FATO dimension was calculated using the D-based criterion:

$$\text{FATO} = 1.5D = 1.5 \times 11.3 = 16.95 \text{ m} \quad (3.1)$$

Consequently, a nominal FATO dimension of approximately 17 m was adopted for the conceptual design.

The general minimum TLOF dimension is $0.83D$. For the selected aircraft:

$$0.83D = 0.83 \times 11.3 = 9.38 \text{ m} \quad (3.2)$$

However, for an elevated vertiport where the TLOF is located within the FATO, the TLOF should contain a circle with a diameter of at least one design D-value. The governing minimum dimension is therefore:

$$\text{TLOF} = 1D = 11.3 \text{ m} \quad (3.3)$$

The TLOF was positioned concentrically within the FATO in the conceptual layout.

3.4.5 Safety-Area Dimensions

The safety area surrounding the FATO should extend outward by at least 3 m or $0.25D$, whichever is greater:

$$0.25D = 0.25 \times 11.3 = 2.825 \text{ m} \quad (3.4)$$

Since 3 m is greater than 2.825 m, a 3 m safety-area extension was adopted around the FATO. The overall dimension of the FATO and its associated safety area was therefore:

$$\text{SA} = 16.95 + 2(3.0) = 22.95 \text{ m} \quad (3.5)$$

This corresponds to an approximately 23 m total protected operating footprint.

3.4.6 Obstacle-Free Volume

Because the proposed vertiport is located on an elevated rooftop in an urban environment and the simulated operation includes a vertical take-off and landing phase, the obstacle-free volume concept was considered appropriate for the conceptual design. According to the EASA PTS-VPT-DSN, the OFV provides protected airspace above and around a vertiport for vertical take-off and landing procedures in obstacle-rich environments.

However, detailed OFV dimensions normally depend on aircraft-specific procedure parameters provided in the Aircraft Flight Manual. Since the relevant Aircraft Flight Manual is not publicly available, an aircraft-specific OFV could not be verified. The EASA Reference Volume Type 1 was therefore used only as an illustrative design assumption and should not be interpreted as evidence of certified compliance.

Table 3.2: Reference Volume Type 1 parameters and calculated dimensions, adapted from EASA PTS-VPT-DSN [7].

Parameter	EASA value	Calculation for $D = 11.3$ m	Result
Low-hover height, h_1	3 m	Specified by EASA	3 m
High-hover height, h_2	30.5 m	Specified by EASA	30.5 m
TO_{width}	$3D$	3×11.3	33.9 m
TO_{front}	$2D$	2×11.3	22.6 m
TO_{back}	$2D$	2×11.3	22.6 m
$FATO_{\text{width}}$	$2D$	2×11.3	22.6 m
$FATO_{\text{front}}$	$1D$	1×11.3	11.3 m
$FATO_{\text{back}}$	$1D$	1×11.3	11.3 m
Approach slope, θ_{app}	12.5%	Specified by EASA	12.5%
Departure slope, θ_{dep}	12.5%	Specified by EASA	12.5%

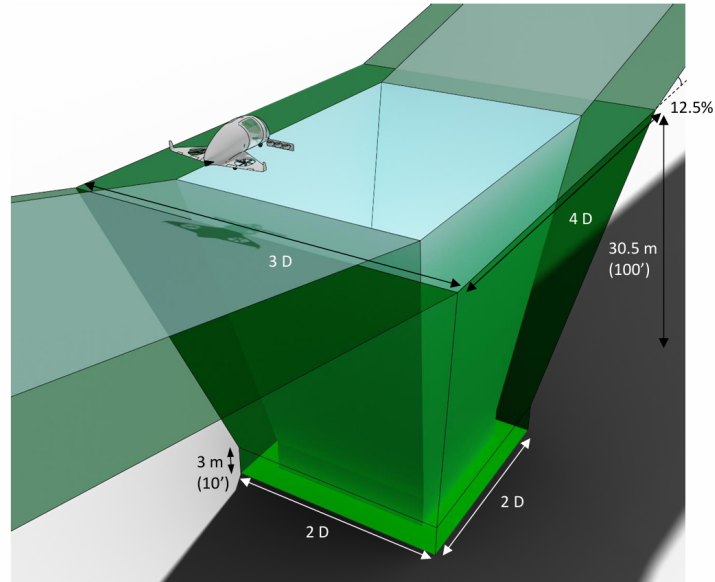


Figure 3.10: Reference Volume Type 1 dimensions (source: EASA PTS-VPT-DSN[7])

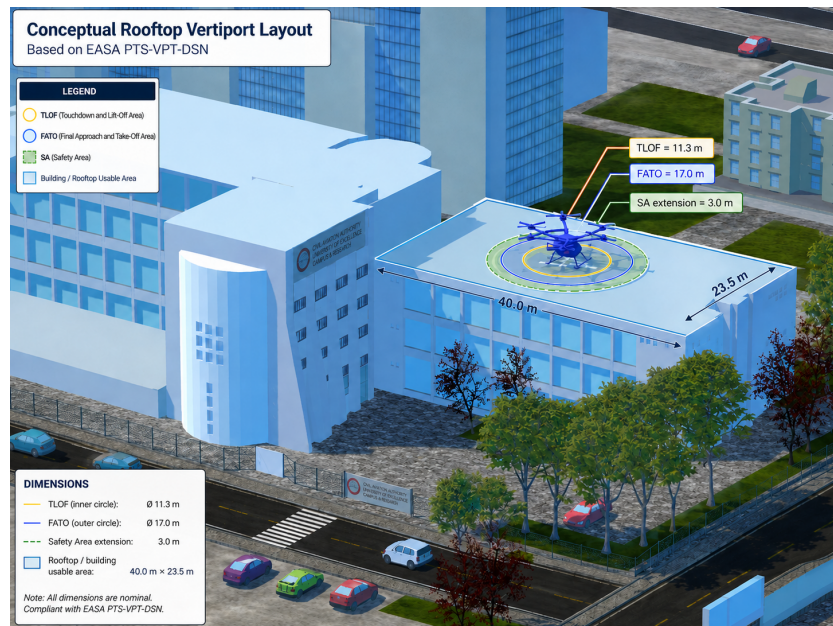


Figure 3.11: Conceptual rooftop vertiport layout showing the TLOF, FATO, safety area, and building dimensions.

3.5 Conclusion

The main regulatory and technical factors in vertiport development were examined together with the environmental, social, and economic pillars of sustainability. Planning a vertiport demands careful attention to safety, infrastructure, urban integration, sustainability effects, and long-term feasibility before any construction starts. Virtual Reality can assist the early planning stage by improving design visualization, evaluating passenger experience, supporting stakeholder communication, and gathering public feedback. It can thus help create a clearer understanding of future vertiports, even though detailed technical and quantitative analyses remain essential for real-world implementation.

Chapter 4

Methodology and VR Simulation Development

4.1 Introduction

This chapter outlines the methodology used for developing the virtual reality (VR) simulation of the vertiport. The process follows a clear workflow that starts with 3D modeling and moves through system setup, asset integration, and interaction implementation. The goal is to create a realistic and functional simulation environment to assess vertiport design in an urban setting. The overall development process consists of seven main phases, as illustrated in Figure 4.1.

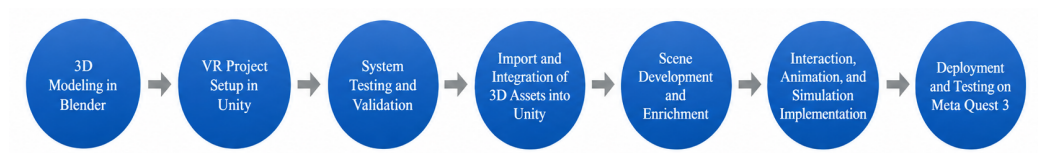


Figure 4.1: Workflow of the VR Simulation Development Process

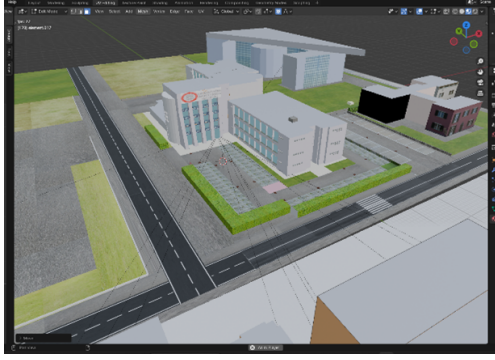
4.2 3D Modeling of the Vertiport Environment

4.2.1 Study Area and Modeling Approach

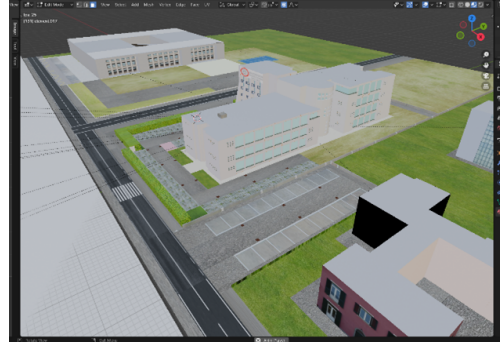
The vertiport simulation was developed within an urban context, located on the Engineering Campus of the University of Bologna in Forlì, with a proposed flight connection to Forlì Airport. For vertiport infrastructure located within or close to an aerodrome, the separation between the FATO and nearby runways or taxiways should be assessed according to the applicable EASA and local operational conditions[7]. The surrounding urban context includes academic buildings, road infrastructure, nearby educational facilities, residential areas, and airport-related infrastructure, making it a representative environment for evaluating vertiport integration within an existing urban setting.

The selection of this area enables the evaluation of vertiport integration within a dense urban environment, representative of future Advanced Air Mobility (AAM) scenarios. The study area was also selected because it was familiar and easily accessible for research purposes, allowing the main buildings, spatial relationships, and environmental characteristics to be directly observed and compared during the modelling process. As no existing vertiport infrastructure is currently available at either location, the model represents a conceptual design integrated into a real-world setting.

The 3D modeling process was carried out using Blender (version 4.0) [37], an open-source 3D creation software widely used for modeling, rendering, animation, and digital asset development. Blender was selected due to its flexibility, compatibility with Unity[38], and suitability for creating optimized models for real-time VR applications. In addition, Blender supports a wide range of plugins and add-ons that extend its functionality. In this project, the Prisma Kit add-on [39] was used to facilitate the generation of urban elements such as buildings, streets, and environmental components, improving both modeling efficiency and spatial accuracy.



(a) View 1



(b) View 2

Figure 4.2: Initial 3D base model of the Engineering Campus.

4.2.2 Modeling Development, Refinement, and Export

To ensure accurate dimensions and spatial relationships, the Prisma Kit add-on, a Blender plugin for generating urban buildings and environmental elements [39], was used to import buildings, streets, and other urban components with appropriate scaling and positioning.

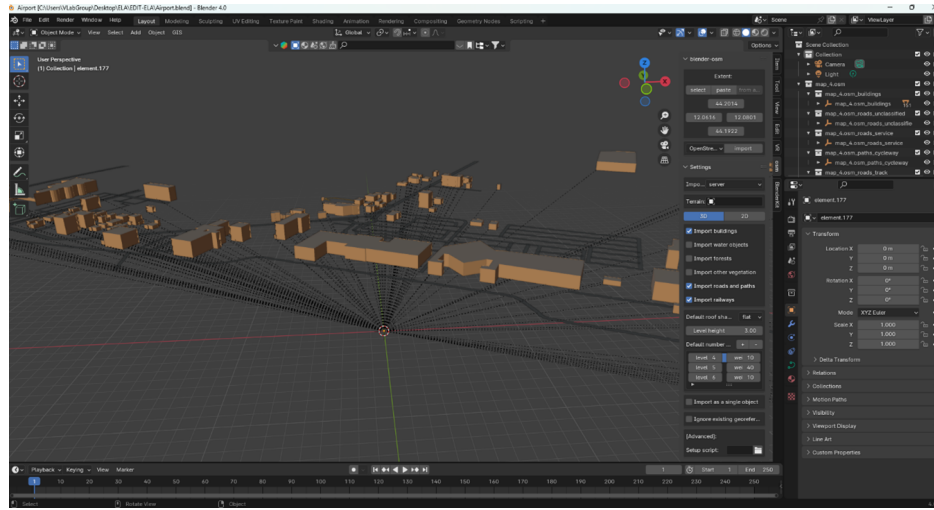


Figure 4.3: Prisma Kit add-on in Blender for building and environment generation.

Following this, the main campus buildings were adjusted, and new structures, such as laboratory buildings near the main engineering building, were added

to improve the detail and realism of the environment.

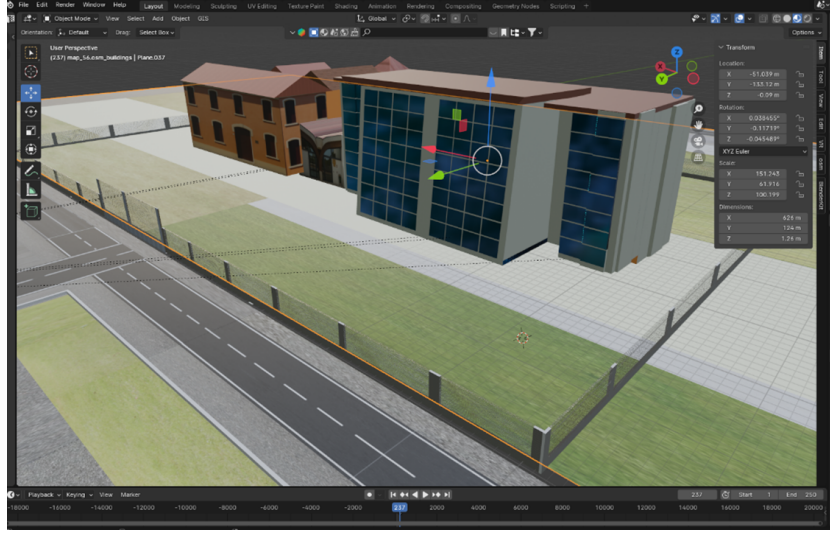


Figure 4.4: Creation of laboratory buildings to enhance the realism of the vertiport model.

In addition, the vertiport landing pad was developed according to the dimensional requirements and regulatory considerations described in Chapter 3. This approach ensured that the proposed infrastructure remains consistent with current standards for Advanced Air Mobility (AAM) operations.

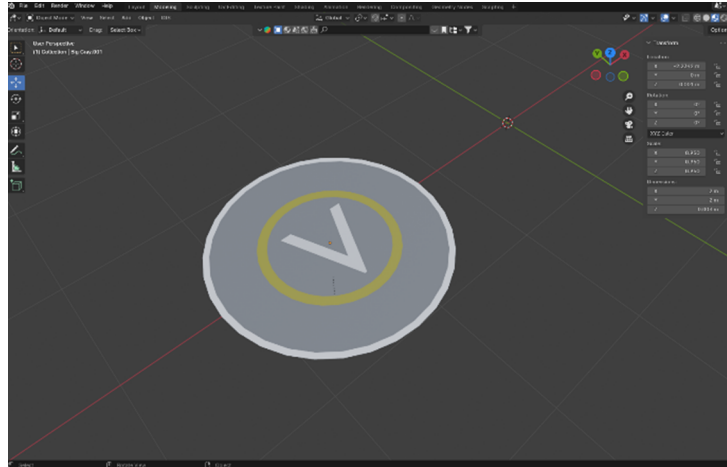


Figure 4.5: Modeling of the vertiport landing pad.

For the aircraft model, a base model of the Volocopter developed at the University of Bologna as part of previous student team projects was selected as a reference. The Volocopter represents a well-known Urban Air Mobility passenger vehicle designed for short-range urban transport and vertiport operations. The model was further refined in Blender to better suit the requirements of the simulation, improve its visual integration and compatibility with the overall environment, and support the implementation of the aircraft animation in Unity.

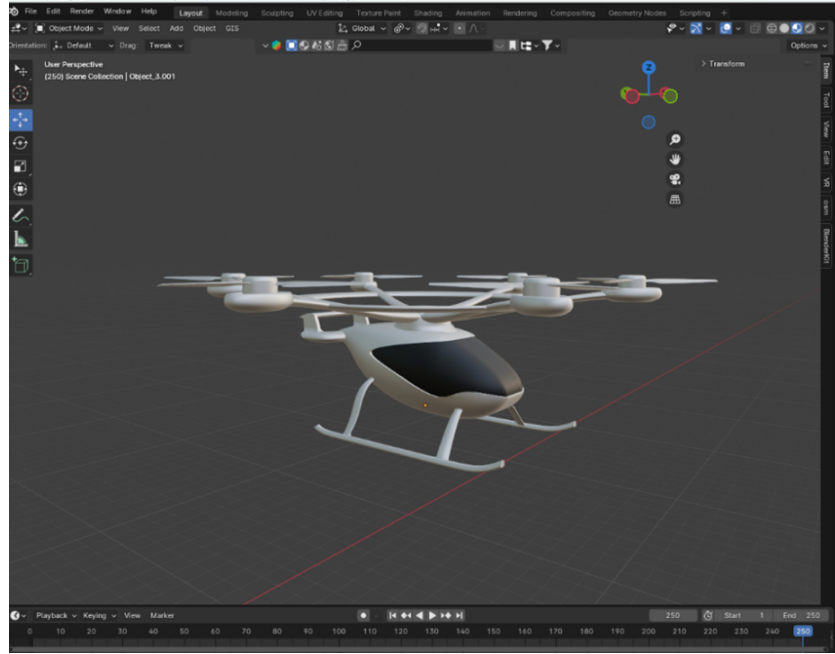


Figure 4.6: 3D model of a Volocopter used in the simulation.

During the modeling process, attention was given to maintaining a balance between geometric detail and computational efficiency to ensure compatibility with real-time VR simulation. Finally, the completed models of the buildings, vertiport elements, and surrounding environment were exported and imported into Unity for further development and integration into the simulation.

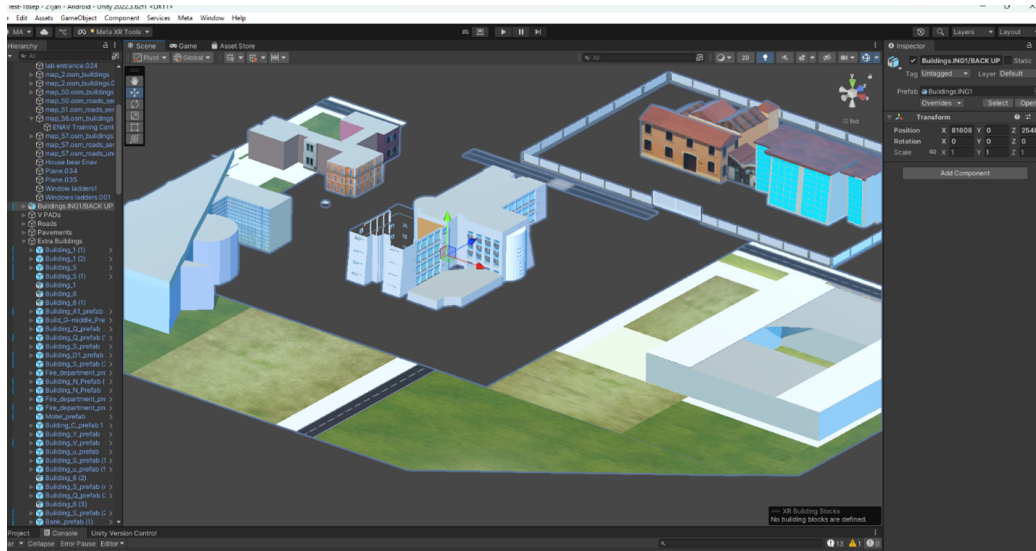


Figure 4.7: Exported models imported into Unity for simulation.

4.3 VR Project Setup and Template Configuration

The VR simulation environment was developed using Unity 2022.3.62f1, part of the Unity 2022 Long-Term Support release [38], selected due to its extensive VR development ecosystem, compatibility with Meta Quest hardware, support for XR frameworks, and suitability for real-time interactive simulation. Blender (version 4.0), previously introduced for 3D modeling, provided compatibility for efficient asset transfer into the simulation environment. Unity Hub was used to install the required Unity Editor version, along with Android build support necessary for Meta Quest deployment. A new 3D project was created using the Universal Render Pipeline (URP) to ensure efficient rendering performance in VR.

4.3.1 XR Configuration and SDK Integration

To enable virtual reality functionality, the OpenXR plugin was installed and configured. The Meta XR Software Development Kit (SDK), including core and interaction components, was integrated into the project. These tools

provided essential features such as headset tracking, controller input, and interaction systems.

4.3.2 Project Configuration and Validation

The project setup was finalized using the Meta XR Project Setup Tool and validation system. These tools were used to automatically detect and fix configuration issues, ensuring that the project was fully compatible with the Meta Quest 3 hardware and capable of running correctly in a VR environment.

4.3.3 Scene Initialization and Interaction Setup

Basic VR components were added to the scene using preconfigured building blocks. This included the camera rig for user perspective and interaction systems for hand tracking and controller-based input. These elements formed the foundation for user interaction within the virtual environment.

4.3.4 System Testing and Validation

After completing the setup, a simple test scene was created to verify system functionality. A cube with a rotation animation was implemented and used as a test object. This allowed validation of key features, including rendering in the headset, tracking accuracy, controller input, and interaction performance. Testing was performed using Meta Quest Link to connect the headset to the development environment.

4.3.5 Preparation for Further Development

Once all core functions were confirmed to be working correctly, the project was considered ready for the next stages, including the import of 3D vertiport models and the development of the full simulation environment.



Figure 4.8: Meta Quest 3 headset used for VR simulation.

4.4 Import and Integration of 3D Assets

Following the successful setup and validation of the VR template, the 3D models of the vertiport environment were imported into Unity. This included the buildings, surrounding areas, and infrastructure previously developed in Blender.

During the import process, several technical issues were encountered, particularly related to materials, textures, and geometry integrity. Some materials were not correctly transferred, resulting in missing or incorrect surface appearances. In addition, certain textures required reassignment, and some building models appeared partially distorted or broken due to compatibility differences between the two software environments.

To address these issues, a series of refinements was carried out within Unity. Materials were reconfigured, and new textures were applied where necessary to restore visual consistency. Additional elements, such as building details and logos, were created and integrated to improve realism. Minor geometric adjustments were also performed to correct any structural inconsistencies.

These refinements ensured that the imported models were visually accurate and technically suitable for further development within the VR simulation environment.

4.5 Scene Enrichment and Asset Development

After completing the refinement of the imported building models, additional assets were integrated into the scene within Unity to enhance the realism and functionality of the environment. These assets were sourced from the Unity Asset Store [40] and included elements such as streets, pavements, green areas, trees, parks, local buildings, parking areas, fences, aircraft, and airport facilities, as well as urban furniture.

The integration of these assets played a key role in transforming the scene from a basic structural model into a complete and interactive simulation environment, supporting a more accurate visualization of vertiport operations.

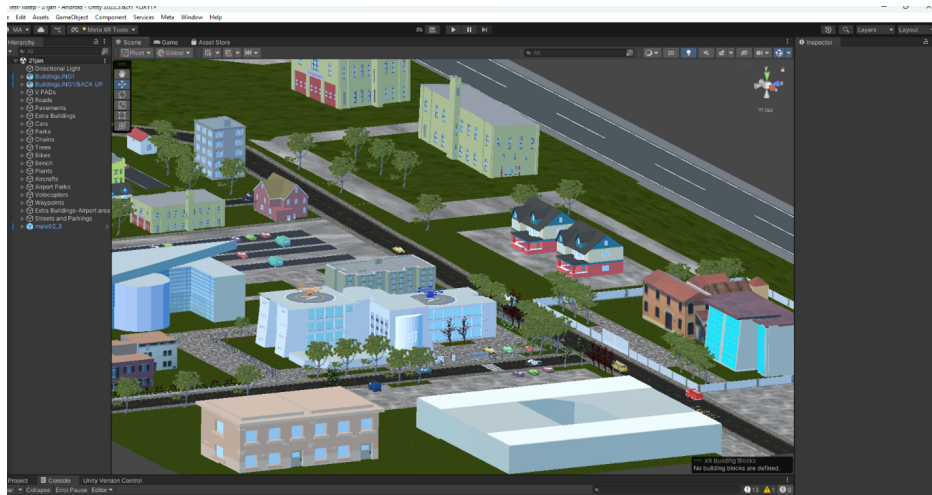


Figure 4.9: Final model integrated in Unity.

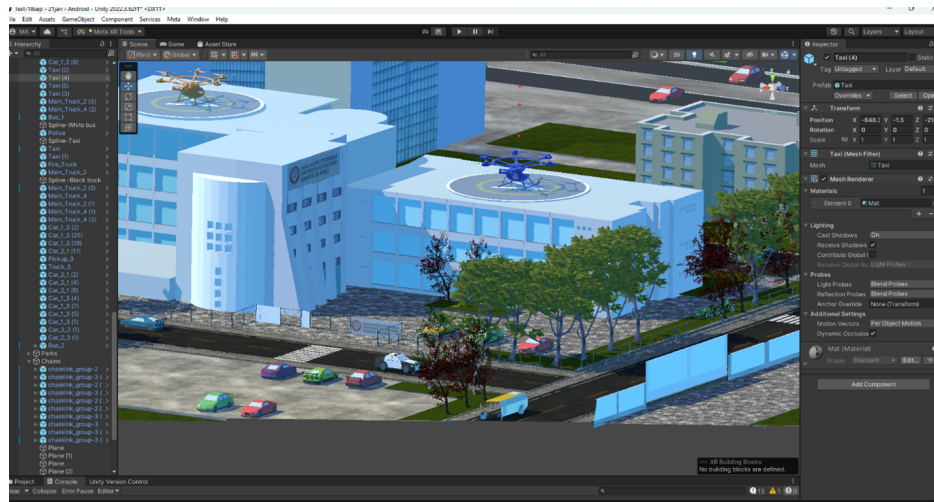


Figure 4.10: Final VR vertiport model integrated in Unity.

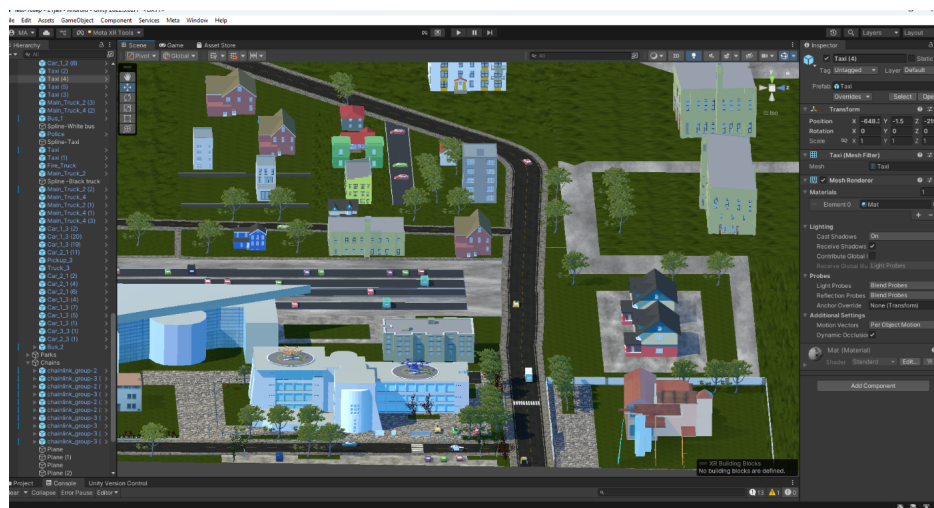


Figure 4.11: City-scale (top) view of the final VR vertiport model.



Figure 4.12: Laboratory-level view of the final VR vertiport model.

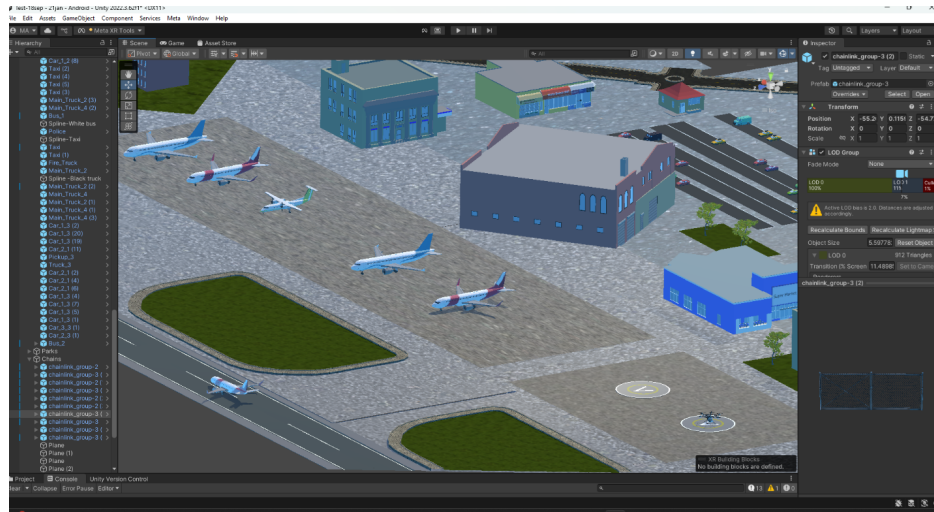


Figure 4.13: Airport area view of the final VR vertiport model.

4.6 Interaction, Animation, and System Implementation

After completing the scene assembly, animation, and interaction systems were implemented to simulate real-world dynamics within the environment. The

simulated mission is divided into three main phases: vertical take-off, forward flight over the city, and vertical landing. In the first phase, the eVTOL takes off vertically from the rooftop vertiport at the Engineering Campus in Forlì. In the second phase, it moves forward along a predefined route toward Forlì Airport. During this part of the journey, the user can observe the campus, buildings, roads, ground traffic, public spaces, and the surrounding urban area from either the passenger or pilot viewpoint. In the third phase, the eVTOL reaches the airport, positions itself above the designated landing pad, and lands vertically. The complete journey lasts approximately seven minutes, including all three phases

Two main approaches were used to control the movement of ground vehicles and eVTOL within the Unity environment.

1. **Ground Vehicle Movement:** For ground vehicles, a spline-based method was applied. Predefined spline paths were created to represent road networks, and vehicles such as cars were programmed to follow these paths. This approach allowed smooth and continuous movement, ensuring realistic traffic flow throughout the simulated urban area.
2. **eVTOL Movement:** For the aircraft, a custom flight path system was developed. A sequence of waypoints, defined using empty objects, was created to represent the flight trajectory between the Engineering Campus and Forlì Airport. A movement script was implemented to enable the aircraft to take off from the vertiport, follow the defined path, and land at the designated landing pad. This method provided controlled and repeatable flight behavior within the simulation.

In addition to movement systems, audio elements were integrated to enhance the realism and immersion of the VR environment. Ambient urban sounds, including traffic noise, were sourced from online audio libraries[41]. Due to the limited availability of authentic eVTOL audio recordings, a helicopter sound sample was used as an approximate representation of aircraft operation within the simulation [42]. These audio elements contributed to creating a more immersive and realistic user experience. Overall, the implementation of animation, movement systems, and audio significantly improved the dynamic behavior and realism of the VR simulation.

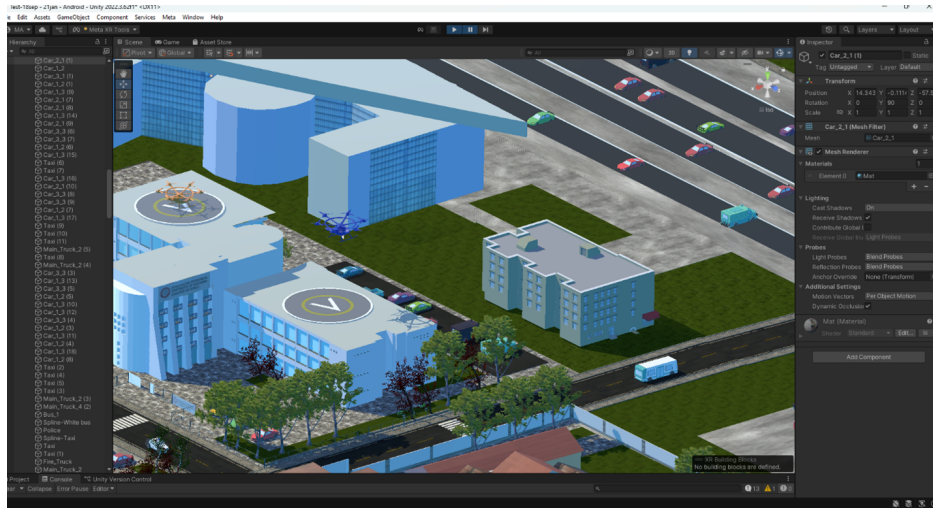


Figure 4.14: Volocopter flying over the simulated city.

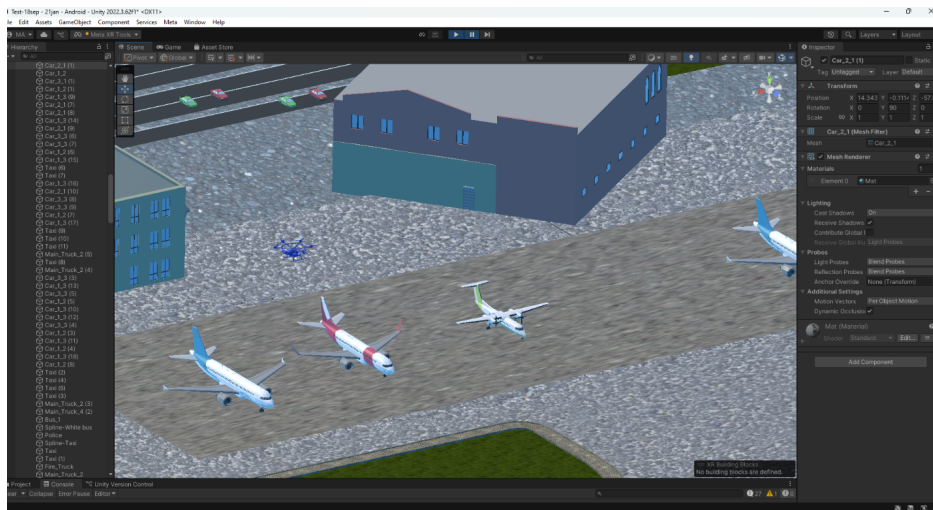


Figure 4.15: Volocopter flying over the airport.

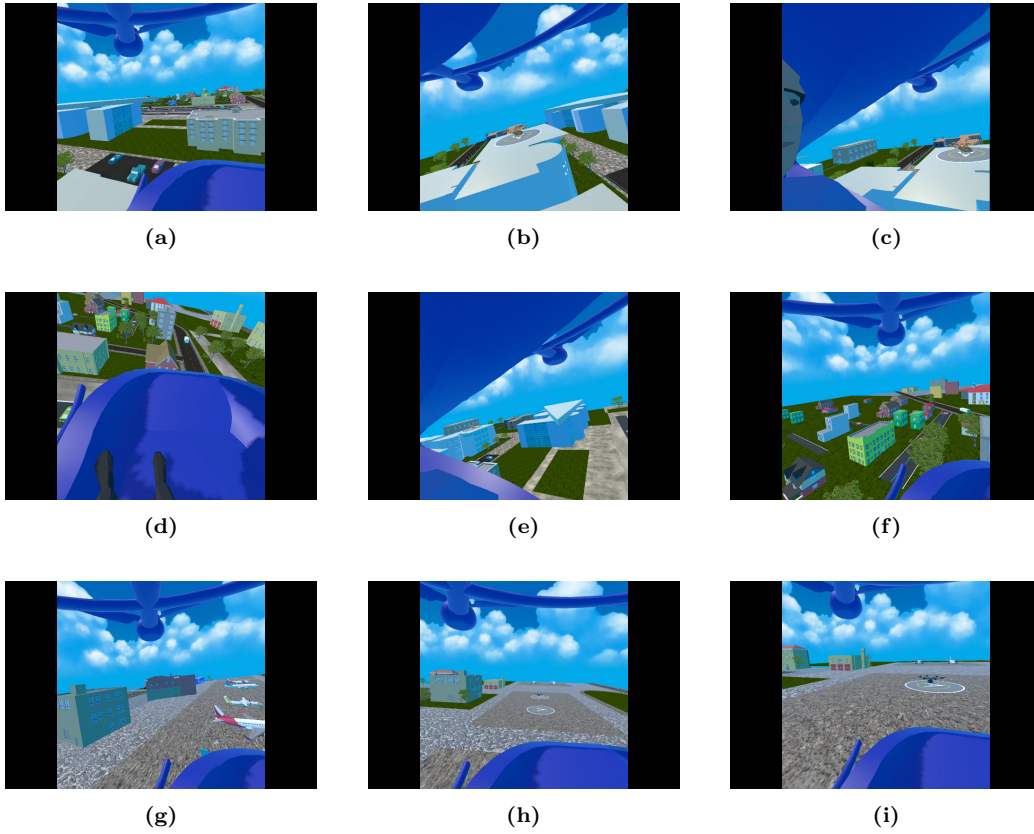
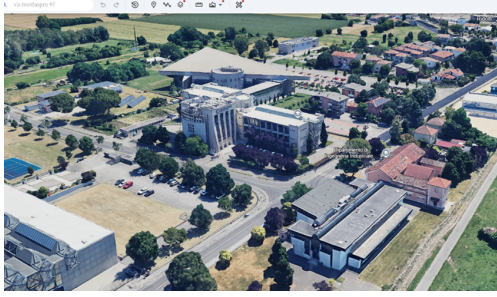


Figure 4.16: Multiple views from inside the Volocopter during flight over the city in the VR simulation: (a) Campus view; (b) Vertiport landing pad view; (c) Pilot perspective; (d) Interior view of the Volocopter; (e) Engineering campus and navigation view; (f) City overview; (g) Airport area view; (h) Vertiport pads within the airport; (i) Landing approach view.

The model was developed to closely match the real-world environment while considering the technical constraints of VR simulation.



(a) Google Earth image



(b) VR simulation model

Figure 4.17: Comparison between real-world satellite imagery and the VR model.

4.7 Conclusion

This chapter presented the development of the VR-based vertiport simulation using Blender for 3D modeling and Unity for real-time implementation. The system was successfully configured for Meta Quest 3, enabling interactive visualization and testing. The results of this work are discussed in the next chapter.

Chapter 5

Results and Discussion

5.1 Introduction

Evaluating a developed application is essential for determining whether it effectively communicates its intended purpose and meets the needs of its potential users and stakeholders. Expert feedback can offer perspectives that might not surface during the development process and can help pinpoint the main strengths, weaknesses, and areas for improvement of the application.

For this reason, a preliminary expert evaluation was carried out to assess the potential use of the developed VR vertiport simulation in Advanced Air Mobility and vertiport planning. The evaluation included experts with relevant academic or professional experience, who reviewed the application after watching a video presentation of the simulation. This chapter outlines the objectives and procedure of the evaluation, presents the main questionnaire findings, and discusses their significance for the future development of the application and for early-stage vertiport planning.

5.2 Objectives of the Expert Evaluation

The questionnaire was designed to assess the possible use of Virtual Reality in Advanced Air Mobility and vertiport planning, as well as to gather feedback on the simulation created for this case study. The evaluation centered on three main goals.

The first goal was to investigate experts' opinions on how VR might assist in planning and evaluating vertiports, improve communication among

stakeholders, and support more sustainable decision-making.

The second objective was to gather the experts' perspectives on the main challenges associated with vertiport implementation. The evaluators were asked to identify the challenges they considered most relevant based on their academic or professional experience. They were also asked whether VR could help visualise, assess, or communicate these challenges during the early stages of vertiport planning.

The third goal was to collect feedback on the developed simulation and determine potential enhancements for future versions of the application.

5.3 Evaluation Methodology

5.3.1 Expert Recruitment and Selection

The evaluation was conducted with four expert evaluators selected on the basis of their academic or professional experience in fields related to aviation, Advanced Air Mobility, unmanned aircraft systems, and other relevant technical areas. Their backgrounds were considered suitable for providing an informed assessment of the proposed VR application and its possible role in vertiport planning. They also represented different age groups and genders, providing a range of perspectives for evaluating the case study.

The experts were contacted directly through academic and professional networks and were invited to participate voluntarily in the evaluation. Before completing the questionnaire, they received a brief explanation of the purpose of the study, the developed simulation, and the type of feedback that was requested.

5.3.2 Evaluation Procedure

Because the expert evaluators were based in different geographical locations and could not all access the Meta Quest 3 headset directly, the evaluation was conducted remotely. A video presentation of the VR simulation was therefore created to give all experts a consistent view of the developed application.

The video displayed the main features of the virtual environment, such as the rooftop vertiport, the nearby urban surroundings, the eVTOL take-off, the flight between the two sites, and the final landing at the destination. It

also included several viewpoints within the virtual space, allowing evaluators to observe the simulation from both passenger and pilot perspectives.

The experts first viewed the video and then filled out an online questionnaire created with Microsoft Forms. Each evaluator submitted the questionnaire independently. Participation was voluntary, and the gathered responses were used solely for the purposes of this thesis.

5.3.3 Questionnaire Design

The expert questionnaire was created using Microsoft Forms and was structured to collect both quantitative and qualitative feedback. It included questions about their professional background, their opinions on the usefulness of VR for planning, communication, and sustainability-oriented decision-making. Additional questions focused on the main challenges of vertiport implementation and possible improvements to the simulation. Most responses were collected using a five-point Likert scale [43], together with multiple-choice and open-ended questions. The complete questionnaire is provided in Appendix B.

6. This VR simulation could support decision-making by helping compare different vertiport design solutions from a sustainability point of view. *

1 2 3 4 5

Strongly disagree Strongly agree

7. In your opinion, which challenges related to Advanced Air Mobility could this VR simulation help to evaluate, communicate, or better understand? *

(You can select multiple answers.)

- ☐ Integration into urban environments and ground infrastructure
- ☐ Safety and security aspects
- ☐ Public acceptance and social perception
- ☐ Regulatory and certification aspects
- ☐ Operational procedures
- ☐ Noise pollution and acoustic impact
- ☐ Environmental protection and sustainability concerns
- ☐ Airspace integration and traffic management
- ☐ Other

8. Among the challenges listed above, which one do you consider the most challenging, and how do you think VR could help address it? *

Enter your answer

Figure 5.1: Example page of the questionnaire.

5.4 Results

The questionnaire responses were reviewed using quantitative and qualitative approaches. The quantitative analysis considered the three five-point Likert-scale questions and the multiple-choice questions, while the qualitative analysis focused on the explanations, comments, and recommendations provided through the open-ended questions. Since the evaluation involved only four experts ($n = 4$), it was intended primarily as an exploratory feedback exercise to identify initial strengths, limitations, and opportunities for improvement. Therefore, the findings should not be interpreted as a formal validation of the application or as statistically generalizable results.

5.4.1 Quantitative Results

Table 5.1 summarises the responses to the three Likert-scale statements. Ratings of 4 and 5 were considered positive, a rating of 3 was considered neutral, and ratings of 1 and 2 were considered negative.

Table 5.1: Summary of the Likert-scale responses from the expert evaluators ($n = 4$).

Statement	Positive (4–5)	Neutral (3)	Negative (1–2)	Mean
VR can support the design and development of future vertiports	3	0	1	4.00
VR can support sustainability-oriented decision-making by helping compare different vertiport design solutions	2	1	1	3.75
The developed VR application is useful for supporting future vertiport planning and AAM development	3	0	1	4.00

As shown in Table 5.1, the statements concerning the usefulness of VR for vertiport design and the usefulness of the developed application both received

an average rating of 4.00 out of 5. The statement concerning sustainability-oriented decision-making received an average rating of 3.75.

7. In your opinion, which challenges related to Advanced Air Mobility could this VR simulation help to evaluate, communicate, or better understand?

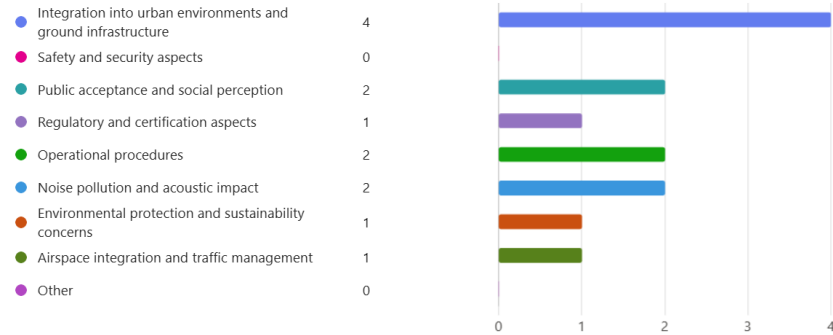


Figure 5.2: Experts' opinions on the AAM and vertiport challenges that the developed VR simulation could help to evaluate.

As shown in Figure 5.2, integration into urban environments and existing ground infrastructure was selected by all four experts. Public acceptance, operational procedures, and noise impacts were each selected twice, while the remaining challenges received fewer selections.

9. From your point of view, who could benefit most from this type of simulator?



Figure 5.3: Experts' opinions on the stakeholder groups that could benefit most from the developed VR vertiport simulator.

Figure 5.3 shows that urban and transport planners, citizens and local communities, and researchers and students were considered the main potential beneficiaries of the simulator, with three selections each.

5.4.2 Qualitative Results

The open-ended responses provided further insight into the main challenges of AAM and vertiport implementation, the stakeholder groups that could benefit from the simulator, and possible improvements for future versions.

Two main challenges emerged from the responses: public acceptance and regulatory certification. Two evaluators pointed to public or societal acceptance as a major concern and suggested that VR could help citizens better grasp future operations, the interaction between aircraft and the urban environment, and the possible effects on local communities. In this sense, VR could help build transparency, public trust, and more informed participation. The other two evaluators pointed to regulation and certification as key challenges. One expert remarked that VR cannot provide the technical evidence needed for aircraft or infrastructure certification, since the represented conditions remain simulated. Still, VR was regarded as useful for supporting the development of operational procedures and training activities.

The stakeholders most often mentioned in the open-ended responses were urban planners, researchers, and citizens or local communities. Urban planners and researchers could use the simulation to study the relationship between a proposed vertiport and the surrounding infrastructure, while local communities could gain a clearer sense of future AAM operations and their possible impacts.

The main suggestions for improvement involved increasing the level of environmental detail, adding more aircraft, improving the realism of the flight trajectory, and showing a more complete passenger journey. One expert proposed that the passenger perspective might be more relevant than the pilot's and that future versions could include the full journey, from booking and accessing the vertiport to boarding, flight, landing, and arrival at the final destination. The realism of the flight path was also questioned, especially the direct route over parked aircraft at the airport. Future versions should therefore take into account more realistic approach and departure paths, separation from other aircraft, and airport operational constraints.

Overall, the qualitative feedback was positive about the general concept and the virtual tour, while identifying important improvements related to

environmental realism, passenger experience, aircraft movement, and operational accuracy.

5.5 Discussion and Final Evaluation

Taken together, the quantitative and qualitative findings indicate that the main value of the developed VR application lies in supporting early-stage visualisation, communication, and discussion of vertiport concepts. The feedback suggests that VR can make a proposed vertiport and its connection with the surrounding environment easier to grasp, especially before any physical infrastructure is built.

Urban integration appeared as the most significant potential use of the simulation. A rooftop vertiport must be considered in relation to the building it occupies, nearby roads, public spaces, transport networks, and other urban functions. By showing these components within the same three-dimensional space, VR can help planners and stakeholders better perceive spatial relationships, share design proposals, and compare alternative solutions during the initial planning stage.

The results also point to the possible contribution of VR to stakeholder engagement and social sustainability. The identification of planners, researchers, and local communities as potential users implies that the application could be valuable not only for technical experts but also for individuals less familiar with Advanced Air Mobility. Seeing a proposed scenario visually may support clearer communication, more informed participation, and a stronger understanding of issues related to public acceptance and urban compatibility.

The evaluation, however, has notable limitations. It involved only four experts and served as an exploratory feedback activity rather than a formal validation study. Moreover, the evaluators examined the application through a video instead of directly using the Meta Quest 3 headset. As a result, elements such as immersion, comfort, interaction, and usability could not be fully evaluated. Even with these constraints, the evaluation offered practical guidance for refining the application and showed its promise as an early-stage visualisation and stakeholder communication tool.

Chapter 6

Conclusions and Future Work

6.1 Conclusion

This thesis examined the use of Virtual Reality in the design and study of a conceptual vertiport for Advanced Air Mobility. The main aim was to analyze how Virtual Reality can assist vertiport planning and the development of Advanced Air Mobility, especially in improving comprehension, aiding decisions, and encouraging a more sustainable integration of these systems within urban settings.

The chosen case study focused on an eVTOL flight between a rooftop vertiport and a nearby airport. The key regulatory requirements were reviewed, and the main vertiport dimensions were defined through calculations based on the characteristics of the selected aircraft and the applicable regulatory guidance.

The study also examined how VR could support the environmental, social, and economic dimensions of sustainability by improving the understanding of potential impacts and supporting more informed decisions in vertiport planning. Together, these elements formed the technical and conceptual foundation for developing the model.

The application was built using Blender and Unity and was experienced through the Meta Quest 3 headset. The final virtual environment included the main components needed to represent the vertiport, the nearby urban area, and the aircraft's movement along the designated route. The simulation offered an immersive view of the proposed journey and allowed the project to be observed from multiple perspectives.

The preliminary feedback provided by the expert evaluators indicated that participants generally viewed VR as a helpful tool for understanding vertiports and Advanced Air Mobility. In particular, the feedback suggested that an immersive environment can help users grasp how a vertiport might interact with surrounding buildings, transport systems, public spaces, and existing infrastructure. The results also highlighted the potential of VR to support dialogue among experts, planners, authorities, and the public.

In conclusion, this study indicates that VR can serve as a useful supporting tool in the early stages of future vertiport projects. It allows complex ideas to be experienced and understood before construction and can assist in considering technical, environmental, and social factors. Still, it should be applied together with detailed engineering studies, regulatory evaluations, and other established planning approaches.

6.2 Future work

Based on the experience gained during the development of this project, an important direction for future work would be to create a new scenario from the viewpoint of people outside the vertiport. This might include pedestrians walking along nearby streets, individuals using adjacent public spaces, and residents who live or work close to the site. Such a scenario could help examine how vertiport operations are perceived within the surrounding urban environment, especially regarding noise, visibility, safety, and public acceptance.

Future evaluations should also include a larger group of participants from the general public, along with more experts who can directly experience the application through VR. Bringing in people from diverse backgrounds would offer a wider understanding of public perceptions and make it possible to compare the views of specialists with those of individuals who have limited prior knowledge of Advanced Air Mobility.

The vertiport model could be refined by adding additional design, operational, and safety features in line with the relevant EASA guidance. This would make the simulation more detailed and realistic, allowing the chosen location to be assessed with greater precision.

The virtual environment could also be integrated with an air traffic and vertiport operations simulator. Such integration would make it possible to reproduce multiple aircraft movements, arrival and departure sequences, traf-

fic flows, scheduling constraints, separation requirements, and interactions within the surrounding airspace. This would expand the application from a single predefined mission to a more dynamic operational environment.

At a later stage, if the vertiport is physically developed or suitable operational data becomes available, the VR environment could be connected to real-time and historical data. The combination of the virtual model, VTOL simulation, traffic simulation, and operational data could support the development of a digital twin capable of representing actual conditions, testing alternative scenarios, monitoring vertiport operations, and supporting planning and decision-making.

Further developments should also take into account the suggestions provided by the expert evaluators. These include increasing the level of environmental detail, introducing more aircraft and dynamic traffic, improving the realism of the flight route, clarifying interface elements, representing a more complete passenger journey, and comparing different vertiport locations and configurations. Together, these improvements could transform the current conceptual application into a more advanced tool for design evaluation, operational analysis, stakeholder engagement, and sustainability-oriented vertiport planning.

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Appendix A

The following script was used to control the waypoint-based movement of the aircraft in the Unity simulation.

```
1 using UnityEngine;
2
3 public class FollowThePath : MonoBehaviour
4 {
5     [Header("Waypoints (drag transforms here)")]
6     [SerializeField] private Transform[] waypoints;
7
8     [Header("Movement")]
9     [SerializeField] private float moveSpeed = 2f;
10    [SerializeField] private float arriveDistance = 0.03f;
11    [SerializeField] private bool loop = true;
12
13    [Header("AR / Parenting")]
14    [Tooltip("If true, moves in local space.")]
15    [SerializeField] private bool useLocalSpace = false;
16
17    [Header("Debug")]
18    [SerializeField] private bool logOnDevice = false;
19
20    private int waypointIndex = 0;
21    private Rigidbody rb;
22
23    private void Awake()
24    {
25        rb = GetComponent<Rigidbody>();
26    }
27
28    private void Start()
29    {
30        if (waypoints == null || waypoints.Length == 0)
31        {
```

```

32         Debug.LogError("[FollowThePath] Waypoints array
33             is empty.");
34         enabled = false;
35         return;
36     }
37     waypointIndex = Mathf.Clamp(waypointIndex, 0,
38         waypoints.Length - 1);
39 }
40 private void Update()
41 {
42     if (rb == null) MoveStep(Time.deltaTime);
43 }
44 private void FixedUpdate()
45 {
46     if (rb != null) MoveStep(Time.fixedDeltaTime);
47 }
48 private void MoveStep(float dt)
49 {
50     if (waypointIndex >= waypoints.Length) return;
51
52     Vector3 currentPos = useLocalSpace ? transform.
53         localPosition : transform.position;
54     Vector3 targetPos = useLocalSpace ? waypoints[
55         waypointIndex].localPosition : waypoints[
56         waypointIndex].position;
57
58     Vector3 newPos = Vector3.MoveTowards(currentPos,
59         targetPos, moveSpeed * dt);
60
61     if (rb != null)
62         rb.MovePosition(newPos);
63     else
64         transform.position = newPos;
65
66     RotateTowardsWaypoint(waypoints[waypointIndex], dt);
67
68     float dist = Vector3.Distance(newPos, targetPos);
69     if (dist <= arriveDistance)
70     {
71         waypointIndex++;
72     }
73 }

```

```

71         if (waypointIndex >= waypoints.Length)
72         {
73             if (loop) waypointIndex = 0;
74             else enabled = false;
75         }
76     }
77 }
78
79 private void RotateTowardsWaypoint(Transform
    targetWaypoint, float dt)
80 {
81     Vector3 direction = targetWaypoint.position -
        transform.position;
82     direction.y = 0;
83
84     if (direction.magnitude > 0.1f)
85     {
86         Quaternion targetRotation = Quaternion.
            LookRotation(direction);
87         transform.rotation = Quaternion.Slerp(transform.
            rotation, targetRotation, moveSpeed * dt);
88     }
89 }
90 }

```

Appendix B

This appendix contains the questionnaire used in the study, which was prepared to collect the expert evaluators' feedback and opinions regarding the VR vertiport simulation.



Feedback Survey on the Experience of a VR Vertiport Simulation for Advanced Air Mobility

This questionnaire is part of the Master's thesis research conducted by a student of the **Mechanical Engineering for Sustainability** programme at the **University of Bologna**. The study investigates the potential of **Virtual Reality (VR)** as a tool for vertiport simulation within the context of **Advanced Air Mobility (AAM)**.

Advanced Air Mobility is an emerging transportation concept that aims to integrate innovative air services, including electric Vertical Take-Off and Landing (eVTOL) aircraft, into urban and regional mobility systems. In this context, vertiports will serve as key infrastructure for the take-off, landing, and operation of these aircraft.

The VR application developed for this research presents a conceptual vertiport located at the Engineering Campus of the University of Bologna in Forlì. The simulation allows users to experience the departure of an eVTOL aircraft from the rooftop of the Engineering building, followed by a flight over the urban environment and a landing at Forlì Airport. The purpose of this questionnaire is to collect feedback from experts regarding the usefulness and effectiveness of the VR application, particularly in relation to public acceptance, passenger experience, sustainability, and future development opportunities for Advanced Air Mobility systems.

Your contribution is highly valuable to this research, for evaluating the potential role of Virtual Reality in the planning, design, and communication of future vertiport infrastructures.

There are no right or wrong answers. We kindly ask you to respond honestly based on your experience with the simulation. Participation in this questionnaire is voluntary.

All responses will be collected and analysed anonymously and will be used exclusively for academic research purposes as part of the above-mentioned Master's thesis. No personally identifiable information will be disclosed, and all data will be treated confidentially and processed in accordance with applicable privacy regulations.

EN: Feedback survey on the experience of a VR vertiport simulation for Advanced Air Mobility (AAM) - University of Bologna

1.Participant Background

1. Name and surname (optional)

6/30/26, 1:44 PM

Feedback Survey on the Experience of a VR Vertiport Simulation for Advanced Air Mobility

2. **Age:** *

- ☐ Under 18
- ☐ 18-24
- ☐ 25-34
- ☐ 35-44
- ☐ 45-54
- ☐ 54-65
- ☐ 65 or above
- ☐ Prefer not to say

3. **Gender** *

- ☐ Woman
- ☐ Man
- ☐ Other
- ☐ Prefer not to say

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4. What is your background? *

- ☐ Engineering-Aviation fields
- ☐ Engineering-Non Aviation fields
- ☐ Air Traffic Management
- ☐ Vertiport developer
- ☐ Drones and Unmanned Aerial Systems (UASs)
- ☐ Sustainability field
- ☐ Urban planning
- ☐ Technical field
- ☐ VR expert
- ☐ Transport expert
- ☐ Environmental expert
- ☐ AI expert
- ☐ Education
- ☐ Medical field
- ☐ Lawyer
- ☐ Humanities and social sciences
- ☐ Regulatory field
- ☐ Health field
- ☐ Programmer
- ☐ Computer science
- ☐ Economics
- ☐ Geography
- ☐ Physics
- ☐ Prefer not to say
- ☐ Other

2.Simulation Experience and Feedback

For the following statements, please use a scale from 1 to 5

1 = Strongly disagree

2 = Disagree

3 = Neutral

4 = Agree

5 = Strongly agree

5. This type of VR simulation can support the design and development of future vertiports. *

1	2	3	4	5
---	---	---	---	---

Strongly disagree

Strongly agree

6. This VR simulation could support decision-making by helping compare different vertiport design solutions from a sustainability point of view. *

1	2	3	4	5
---	---	---	---	---

Strongly disagree

Strongly agree

...

7. In your opinion, which challenges related to Advanced Air Mobility could this VR simulation help to evaluate, communicate, or better understand? *

(You can select multiple answers.)

- ☐ Integration into urban environments and ground infrastructure
- ☐ Safety and security aspects
- ☐ Public acceptance and social perception
- ☐ Regulatory and certification aspects
- ☐ Operational procedures
- ☐ Noise pollution and acoustic impact
- ☐ Environmental protection and sustainability concerns
- ☐ Airspace integration and traffic management
- ☐ Other

8. Among the challenges listed above, which one do you consider the most challenging, and how do you think VR could help address it? *

--

9. From your point of view, who could benefit most from this type of simulator? *

(You can select multiple answers.)

- ☐ Vertiport designers and engineers
- ☐ Urban planners and transport planners
- ☐ Airport and vertiport operators
- ☐ Public authorities and regulatory bodies
- ☐ Citizens and local communities
- ☐ Researchers and students
- ☐ eVTOL manufacturers and operators
- ☐ Emergency, safety, and rescue services
- ☐ Investors and infrastructure developers
- ☐ Other

10. Among the stakeholders listed above, which one do you think could benefit the most from this VR simulator, and how could it support their work or decision-making? *

Final Evaluation and Suggestions

11. Overall, this VR application is useful for supporting future vertiport planning and Advanced Air Mobility development. *

1	2	3	4	5
---	---	---	---	---

Strongly disagree Strongly agree

12. What would you add or improve in this VR application? *

13. Please write any final comments, suggestions, or opinions you may have.

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