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Application of eVTOL Aircraft in Advanced Air Mobility
Vertiport in Humberto Delgado Airport

(Versão Final Após Defesa)

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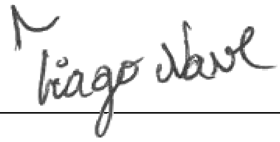

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Resumo

Novas capacidades, fruto de desenvolvimentos tecnológicos, abrem a porta para a Mobilidade Aérea Avançada (Advanced Air Mobility, AAM) integrar o ambiente urbano. Este trabalho ambiciona explorar o potencial de um vertiporto, infraestrutura de solo necessária pela AAM, associada ao Aeroporto Humberto Delgado, ligando-o ao novo Aeroporto Luís da Camões.

Há ainda muitos desafios a superar de forma a implementar uma rota, servida por uma nova categoria de aeronaves, eVTOLs, numa indústria que não tolera qualquer compromisso em segurança operacional. De forma a desbloquear o ciclo de desenvolvimento, várias autoridades aeronáuticas têm vindo a disponibilizar material temporário, aplicável durante esta fase inicial, facto que em conjunto com incertezas relativamente ao acompanhamento do controlo de tráfego aéreo levantam dúvidas sobre os modelos até agora utilizados. De forma a diminuir o impacto dos fatores previamente mencionados, durante o desenvolvimento deste trabalho foi atribuída grande importância as especificações aplicáveis e exposição do publico aos componentes menos desejáveis da AAM, justificou as decisões necessárias e expondo as incertezas identificadas. Alcançando a um layout otimizado ao caso de estudo, foi desenvolvido um modelo que permitisse a simulação do mesmo, de forma a estimar o seu desempenho e identificar os fatores limitantes.

Os resultados atingidos refletem a necessidade ainda por suprir de confirmação das promessas feitas pela AAM, resultando em maior rigor no material de orientação da EASA e impondo restrições significativas ao cenário em estudo. Considerando dados do mês de Agosto 2024, o vertiporto desenvolvido mostrou-se capacitado para servir 0.398% dos passageiros diários do Aeroporto Humberto Delgado, mediante condições como regras de voo visual (Visual Flight Rules, VFR) e o modelo eVTOL VoloCity da Volocopter.

O desempenho previsto é adequado face a procura reduzida, esperada nesta fase inicial com limitada procura por uma ligação direta entre aeroportos. No entanto uma falta de opções de expansão é motivo de preocupação assumindo o sucesso do conceito. A eventual conclusão dos projetos de infraestrutura terrestre já confirmados, precisamente com o objetivo de aumentar as capacidades de transporte dos meios mais convencionais, levará também a concorrência significativa para a AAM.

Palavras-chave

Mobilidade Aérea Urbana (UAM); Mobilidade Aérea Avançada (AAM); Descolagem e Aterragem Vertical Elétrica (eVTOL); Espaço Aéreo Urbano; Vertiporto.

Resumo Alargado

Motivação

O sonho por carros voadores apareceu a mais de um século atrás, com várias tentativas de o concretizar desde o início do século XX, focadas no acrescento de asas aos carros convencionais por meio de um componente amovível. Uma mistura entre carro e avião era claramente considerada como o caminho mais promissor, resultando em sucesso parcial, não comercializável. No entanto em janeiro de 2022, o Air Car da Klein Vision recebeu a certificação tipo na Eslováquia, após rigorosos testes de voo compatíveis com a Agência Europeia para a Segurança da Aviação (EASA) [1]. Mantendo a filosofia de mistura entre carro e avião, representa a tentativa mais próxima do sucesso deste conceito.

Reconhecendo as limitações associadas ao uso de uma pista, infraestrutura limitada e de colocação inconveniente, procurou-se prover os carros voadores com a capacidade de descolagem e aterragem vertical (VTOL), permitindo o uso em zonas urbanas. Alguns projetos mostram-se mais ambiciosos, procurando o uso regional. Baseados no desenvolvimento de uma consciência ambiental por parte do público e o crescimento do mercado de mobilidade por pedido (On-Demand Mobility, ODM), vários conceitos de eVTOL (VTOL elétrico) estão a ser desenvolvidos, principalmente para utilização como táxis aéreos, sendo também apresentadas versões de carga, alimentadas pela visão de empresas como a UBER, que mostrou interesse e expectativas em relação a ideia [2].

Os pontos diferenciadores deste conceito incluem a sua adequação ao ambiente urbano, especialmente quando comparado a operações de helicópteros. Derivado da natureza elétrica dos eVTOLs, estas aeronaves são mais silenciosas e apresentam uma fonte de energia mais fácil de se manusear, permitindo operações mais perto do público em geral, dando uso a um espaço aéreo praticamente inutilizado. Sendo a energia gerada de uma fonte verde, os eVTOLs passam a partilhar essa característica a que é atribuída uma importância crescente com a maior sensibilização ambiental.

Qualquer cenário em que o tempo de transporte seja um fator crítico está sujeito a melhorias com a implementação da AAM. Seja pela velocidade mais elevada ou trajetória aérea mais direta, sem o impedimento do terreno e congestionamentos, o tempo ganho pode revelar-se vital para a vida humana em utilizações médicas ou acelerar a resposta a várias emergências. No entanto, o caso do táxi aéreo visa uma componente menos urgente do dia a dia, reduzindo o tempo gasto em transportes pelo cidadão comum, permitindo o seu uso em outras ocupações, melhorando a qualidade de vida.

Independentemente dos seus benefícios em relação a helicópteros, eVTOLs continuam sujeitos a requisitos específicos para infraestruturas de solo, na forma de vertiportos, uma versão equivalente ao heliporto, que permitem reabastecimento elétrico adequado e gestão de um maior número de passageiros. São ainda aplicados outros termos dependendo da escala da implementação como *vertipad* (1 pad), *vertibase* (cerca de 3 pads) e *vertihub* (até 10 pads), usados tanto pela EASA como McKinsey [3], [4]. Alinhado com as suas necessidades operacionais pode ser necessário apoio na forma de *stands*, espaço para estacionamento mais prolongado, capacitado para assistência geral do eVTOL, e de *gates*, mais especializados ao embarque / desembarque de passageiros [5], [6]. É importante referir que os dois espaços referidos anteriormente podem coincidir, novamente sobre a denominação de *stand*, nomeadamente como aplicado pela EASA [7].

Tal como qualquer infraestrutura uma construção dedicada ao seu propósito é preferível, no entanto de forma a integrar o ambiente urbano, com opções de espaço extremamente limitadas, a conversão total ou parcial de edifícios já presentes é também considerada. De forma geral, como os vertiportos não representam nem o ponto de partida nem de chegada do percurso do utilizador, ligações com outros meios de transporte são entendidas como um requisito obrigatório para o sucesso da AAM, sendo favorecidas por tal opção [8].

Por mais que os benefícios destas aeronaves sejam desejados por muitos, existem obstáculos a superar até serem viáveis. A legislação ainda não contempla esta nova vertente da aviação, necessitando ainda de atenção pelas devidas agências governamentais. No entanto o desenvolvimento legislativo já começou, com material guia já disponibilizado por vários órgãos aeronáuticos, mesmo que abertamente declarados como temporários, permitindo a recolha de dados na base de documentação mais permanente.

A confiança do público tem de ser conquistada, sendo a sua recetividade uma das maiores incógnitas com impacto no sucesso da AAM, facto refletido na ênfase em redução do ruído e segurança por parte dos fabricantes de eVTOLs, fatores de grande relevo como apontado por inquéritos públicos [3], [9]. Não estando as pessoas confortáveis com a proximidade dos eVTOLs os projetos necessários para desenvolver a AAM podem ser bloqueados, motivo desta vertente ser contemplada por vários investigadores.

Este trabalho procura fortalecer as bases necessárias para tirar o máximo partido destas aeronaves, inspirando implementações reais e estudos adicionais relacionados a esta oportunidade diante de nós.

Objeto e Objetivo

O objeto de estudo desta dissertação são as aeronaves eVTOL em contexto de AAM. Com esta nova opção de transporte no horizonte, é necessário avaliar a adequação das várias opções para uma implementação inicial, quer para fundamentar futuros projetos de vertiportos, quer para aperfeiçoar o processo do seu desenvolvimento.

O objetivo geral deste trabalho é avaliar um *layout* de vertiporto à luz do caso de estudo, determinando a adequação da AAM para responder aos requisitos identificados para o Aeroporto Humberto Delgado. No entanto, para o atingir, objetivos específicos necessitam de ser alcançados, resultando na lista seguinte:

1. Identificar as preocupações do público, tanto como possível utilizador como membro da comunidade circundante à infraestrutura de solo;
2. Avaliar possíveis localizações para implementação de um vertiporto, determinando a mais adequada;
3. Desenvolver o *layout* associado ao vertiporto de acordo com documentação aplicável e o impacto no público;
4. Avaliar o *layout* desenvolvido face ao contexto do caso de estudo.

No entanto, o estudo dos objetivos apontados está sujeito a várias limitações derivadas de indisponibilidade de dados. Nomeadamente, mesmo que algumas afirmações gerais possam ser feitas sobre a vertente económica, a sua presença foi propositadamente minimizada devido à falta de uma base que substanciasse a sua contribuição.

Metodologia

É primeiramente necessária uma revisão literária que conduza a um conhecimento atualizado do estado atual da AAM e futuro pretendido para a mesma. Especial atenção deve ser aplicada as dificuldades no desenvolvimento de um vertiporto e opções aplicadas por outros autores na sua superação.

Como pré-requisito para o desenvolvimento de um *layout*, alguns aspetos necessitam de ser averiguados antes de começar o processo, nomeadamente: caraterísticas da aeronave a servir, requisitos de projeto impostos pelas autoridades aeronáuticas e caraterísticas do local onde se pretende estabelecer o vertiporto.

Compreendendo os dois locais a ligar por um serviço de táxi aéreo, são estabelecidos requisitos e preferências quanto às capacidades do eVTOL, com base nos quais se julgam vários modelos, sendo o mais adequado considerado como referência para o resto do trabalho.

Com a finalidade de identificar as preocupações do público mais relevantes para a implementação de um vertiporto, é realizado um questionário, que em conjunto com os requisitos estabelecidos pela EASA estabelecem as bases para determinar a localização do vertiporto. Candidatos a tal posição são inicialmente estabelecidos com base em imagens de satélite e uma visita ao local.

Tendo alcançado a devida fundação, procede-se com o desenvolvimento do *layout*, expondo e justificando as várias decisões associadas. Finalmente, o resultado é simulado com base numa combinação de Discrete Event Simulation (DES) e Agent Based Simulation (ABS), fornecendo as métricas necessárias à sua avaliação.

Análise dos Resultados

Parte dos primeiros passos, o questionário público confirmou uma dicotomia entre o otimismo e vontade de usufruir dos benefícios esperados da AAM e a exposição aos custos associados na qualidade de vida. De forma geral foi observado um ceticismo face as promessas deste conceito e se os respondentes se enquadrariam no grupo limitado, que dela beneficiaria. Os pontos anteriormente mencionados precisam de ser adequadamente balanceados, permitindo que clientes dispostos a experimentar se tornem recorrentes, estabelecendo uma base para sustentabilidade económica.

A sugestão de vertiporto alcançada mostrou-se capaz de absorver uma componente muito reduzida dos passageiros processados pelo Aeroporto Humberto Delgado. Em contexto de primeiro passo para a AAM em Portugal, por mais que aquém do desejado, apresenta capacidades alinhadas com a base de utilizadores limitada, esperada na fase atual. Mesmo favorecido pelo relativamente pequeno tempo de implementação, a realidade circundante ao aeroporto não só limita o que se poderia atingir numa primeira fase como uma futura expansão de forma a acompanhar um caso de sucesso para o conceito. Estando as alternativas de solo limitadas a médio prazo pela capacidade de travessia do rio Tejo, mediante a conclusão da já anunciada terceira ponte, estas apresentam características mais adequadas ao transporte de um maior volume de passageiros.

Tal conclusão pode ser revertida pela larga margem de progressão ainda viável para a AAM, nomeadamente por uma realidade mais automatizada. No entanto o tempo associado seria refletido no período inicial, em que a AAM apresenta mais benefícios face as alternativas, reduzindo o seu periodo de maior oportunidade.

Conclusões

Sendo a AAM um novo ramo da aeronáutica o presente estudo foi em várias etapas limitado pela falta de disponibilidade de informação relevante, ainda englobado por segredo comercial.

No entanto as limitações sentidas são normais para a fase de desenvolvimento do conceito. A sua superação é apenas possível com novos avanços e uma manutenção do interesse pela AAM, resultando num processo em aperfeiçoamento, cada vez menos dependente de suposições e aproximações. O presente estudo representa uma contribuição para esse mesmo ideal.

A identificação das preocupações do publico, nos vários papeis que este pode tomar, permitiu o desenvolvimento de uma solução baseada em AAM para a ligação entre o atual e futuro aeroporto de Lisboa. Por mais que dentro das devidas limitações, entre as quais a influencia pela ideia atual de cada respondente em vez de uma realidade vivenciada, uma base satisfatória para o desenvolvimento de um vertiporto foi alcançada.

Com os critérios obtidos foi decidida a localização, desenvolvendo-se o respetivo *layout*, resultando num vertiporto enquadrado às condições atuais do caso de estudo. Para avaliar o vertiporto desenvolvido foi elaborado um modelo de simulação de onde se obtiveram as métricas necessárias para o julgar face ao pretendido.

Os resultados demonstraram uma adequação para o cenário inicial acompanhado de restritas opções de expansão, em grande parte resultantes do alto requisito de área por trás da AAM. No entanto, assim que as alternativas de transporte baseadas em vias terrestres deixem de estar restringidas pela capacidade de travessia do rio Tejo, é previsível que estas assumam em maior parte a ligação entre aeroportos.

Investigações Futuras

Como mencionado anteriormente são ainda possíveis várias melhorias tanto para os eVTOLs como vertiportos, sendo que a direção dos esforços deve ser derivada de uma maior compreensão tanto de vertiportos como de eVTOLs. Para tal vários pontos beneficiariam de atenção por trabalhos futuros:

- Efeitos da proximidade entre o público e eVTOLs, especialmente se baseado em experiências reais, mesmo que em ambiente controlado;
- Comparação de vários eVTOLs, ligando as suas capacidades a componentes chave de desenho e configurações do sistema propulsivo;
- Derivado dos dados obtidos pelos limitados projetos de vertiportos, elaborados no subcapítulo 2.2.4 (Vertiports), uma proposta de dimensionamento dos elementos do vertiporto especifica para eVTOLs, possivelmente variável com as características dos mesmos;
- Estudo económico da AAM, uma vertente capaz de tornar a tornar inacessível a maior parte da população, contrariando as ambições da mesma. Tal deve analisar o peso de cada componente no valor pago pelo utilizador.

Abstract

Technological developments allowed air mobility to enter the urban environment, expanding urban mobility to a new dimension and originating Advanced Air Mobility (AAM). The present work explores the potential of a vertiport, AAM's ground infrastructure, associated with Humberto Delgado Airport, allowing its connection to the new Luís de Camões Airport.

There are still many obstacles in the path to implementing a route taken by a recent category of aircraft, eVTOLs, in an industry that does not accept safety compromises. Various aeronautical authorities have released documentation to guide the development of vertiports. Yet, their transitional nature alongside the uncertainty around accordingly expanding air traffic control (ATC) and other operational uncertainties leads to significant doubt of the longevity of the models used so far. Aiming to reduce the impact of the many uncertainties, a vertiport implementation was sought while pondering proper specifications and public exposure to the negative side of AAM, pointing out identified sources of uncertainty and explaining the decision process for each step. Reaching a recommended layout for the case of study, a simulation model was then elaborated to estimate its performance, identify bottlenecks and confirm assumptions made during the layout design phase.

The reached conclusions reflect a lack of validation of the claims surrounding AAM, translated on rigorous EASA guidance material for vertiport design, restricting the options for a vertiport associated with Humberto Delgado Airport. Considering data from August 2024, the developed vertiport, under various limitations such as visual flight rule (VFR) conditions and considering Volocopter’s VoloCity as the eVTOL, proved capable of serving 0.398% of the airport's daily processed passengers.

The proposed vertiport’s performance can be seen as adequate for the expected demand on this initial stage, with few passengers seeking a direct connection between the airports and not taking another means of transport. On the other hand, expansion options are lacking, compromising the capacity of ground infrastructure in case of the concept's success. Additionally, as soon as infrastructure projects seeking an expansion of ground transport capabilities are completed, while still many years in the future, AAM may face serious competition from the more conventional transport means.

Keywords

Urban Air Mobility (UAM); Advances Air Mobility (AAM); Electrical Vertical Take-off and Landing (eVTOL); Urban Airspace; Vertiport.

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List of Acronyms

AAM	Advanced Air Mobility
ABS	Agent Based Simulation
AFM	Aircraft Flight Manual
AQI	Air Quality Index
ATC	Air Traffic Control
CASA	Civil Aviation Safety Authority
DES	Discrete Event Simulation
EASA	European Union Aviation Safety Agency
EU	European Union
eVTOL	Electrical Vertical Take-off and Landing
FAA	Federal Aviation Administration
FATO	Final Approach and Take-off
GIS	Geographical Information System
ODM	On-Demand Mobility
PA	Protection Area
RAM	Regional Air Mobility
SA	Safety Area
TLOF	Touch-down and Lift-off
UAM	Urban Air Mobility
UBI	Universidade da Beira Interior
VFR	Visual flight Rules
VTOL	Vertical Take-off and Landing
WHO	World Health Organization

Chapter 1

1 Introduction

1.1 Motivation

The desire for flying cars goes back beyond a century, with multiple attempts at fulfilling the idea at the start of the 20th century, centred mainly on a removable component that added wings, showing a clear bias towards a mix of car and plane, perceived as the more promising path, leading to a partial success unable to provide a legally usable product. At least that was the case until January 2022, when the Air Car of Klein Vision was type-certified in Slovakia, after rigorous flight testing compatible with the European Aviation Safety Agency (EASA) [1]. The Air Car remains a mix between car and plane, without removable components specific to flight and is but one of the modern attempts to satisfy the flying car dream.

Other efforts, recognising the limitations brought by the requirement of a runway, sought to create aircraft with vertical take-off and landing (VTOL) capabilities, catered for use in urban areas. Others aspire to reach beyond, onto regional use. Adding the development of an environmental consciousness by the public and significant market share of on-demand mobility (ODM) solutions, various eVTOL (electric VTOL) concepts are being developed, mainly for use as air taxis, while cargo versions are also presented, fuelled by the vision of companies like UBER, that showed interest and expectations for the concept [2].

The differentiating factors of this concept lie in their suitability for the urban environment, especially compared to helicopters. Being quieter and having an easier to handle energy source, they can operate closer to the public in a barely occupied airspace. If charged with green energy, eVTOL become a green transportation method, an essential characteristic given the ever-growing environmental conscience of the public, that also contributes to cleaner air in heavily populated areas.

Any application where a reduction in transportation time has significant returns will benefit the most of AAM. Be it by having a higher speed or a more direct trajectory by air, not impeded by terrain or traffic congestions, these time reductions may prove vital for human life, in medical uses, or represent significant gains, speeding repairs and reducing downtimes of critical infrastructure. The air taxi use case aims to confront the considerable portion of the day people spend on transport, especially by car, seeking to free up time for other uses, improving the quality of life.

However, these eVTOL aircraft do not abdicate the existence of support infrastructure for their operations, in general being under the same requirements as helicopters, needing an equivalent version of the helipad with proper recharging capabilities, alongside passenger and cargo management aligned with the greater scale of operations expected compared to heliports. These infrastructures have the commonly accepted denomination of *vertiport*, with more specific denominations depending on the scale yet to achieve consensus. For reference, EASA and McKinsey use the terms *vertipad* (1 pad), *vertibase* (around 3 pads) and *vertihub* (up to 10 pads) [3], [4]. Following scale, the ability to support operations should increase in the form of *stands*, space for parking that permits the servicing of the aircraft without interfering with traffic and *gates*, used for passenger / cargo pick up and drop off [5], [6], being important to note that both spaces may represent the same area, referred again as stand, namely in EASA documentation [7].

Even if the construction of a dedicated building can be advantageous, integrating with the urban environment, where space options are extremely limited, is possible by converting unused buildings or repurposing only the top floors. The combination of vertiports with other transport means, necessary to cover transportation to and from vertiports, as these do not represent neither the start nor finish points of the users trip, is therefore perceived as a mandatory requirement for the success of UAM, being achievable by such means [8].

Many desire the benefits of these aircraft, yet much still needs to be done to see them come to reality. Governmental agencies have yet to adequately develop legal requirements for their operation, whether for individual or commercial use. Much of what has been publicised is labelled as temporary and subject to significant changes, dependent on data collection from limited initial applications, permitted on a case-by-case evaluation.

Public trust needs to be earned, their reception being one of the most significant variables to AAM's success, reflected in the major focus on noise reduction and safety features advertised by manufacturers, both being among the top concerns referred on public enquiries [3], [9]. Something as simple as being uncomfortable with aircraft flying too close for passersby's comfort can block the projects required to kickstart the future, reason why related subjects are the focus of many researchers.

This work represents a contribution to the foundations required to bring out the most of these wonderful aircraft, inspiring actual implementations and further studies on the opportunity now before us.

1.2 Object and Objectives

The object of this dissertation is eVTOL Aircraft in AAM. With this new transportation option on the horizon, the suitability of initial cases for implementation needs to be assessed to substantiate future vertiport projects and polish their development process.

The overall goal of this work is to assess a vertiport layout in light of the case of study, determining the suitability of AAM to address the identified requirements for Humberto Delgado Airport. However, in order to achieve it, many specific objectives need to be reached, leading to the following goals:

1. Identify public concerns, both as possible users and elements of the community surrounding the ground infrastructure;
2. Assess possible areas for a vertiport implementation, determining the most suitable location;
3. Development of an associated vertiport layout in accordance with design guidelines and public impact;
4. Assess the recommended layout under the context of the case of study.

The stated objectives will, however, be studied under some scope limitations derived from data availability. Namely, while some general statements can be presented on the subject of economics, its presence was purposely minimised due to the lack of a proper base to substantiate its contribution.

1.3 Methodology

First, a literary review needs to take place, leading to up-to-date knowledge on the current state of AAM and the one pretended to be in the future. Both, an idea of the challenges faced during the development of vertiports and how other authors surpass them lay the groundwork for said process to be carried out for the pretended case of study.

For this work's case of study, which aims to suggest a vertiport layout associated with Humberto Delgado Airport, the following aspects need to be ascertained before a layout can be designed: the characteristics of the aircraft it is expected to serve, design requirements imposed by aeronautical authorities and the characteristics of the location where the vertiport is being established, be it of the terrain itself or the impacted surroundings.

Understanding the two locations to be connected by an air taxi service, requirements and preferences for the capabilities of the eVTOL can be established. Based on this, various models can be judged, with the most suitable being considered a reference for the rest of the work.

A public survey aimed at identifying the most critical public concerns, relevant design requirements by EASA and some initial considerations derived from other works were exposed, establishing a base for developing criteria used to assess the suitability of selected options for the vertiport location. Such options are obtained by a combination of on site visits and satellite images, from which the most suitable is then selected.

Having addressed all requirements for the layout design, the relevant decisions behind the design are then exposed and justified. Finally, the layout is simulated based on a mix of Discrete Event Simulation (DES) and Agent Based Simulation (ABS), providing the metrics by which it can be judged.

A visual representation of the dependencies between steps corresponding to the case of study can be found at Figure 1.

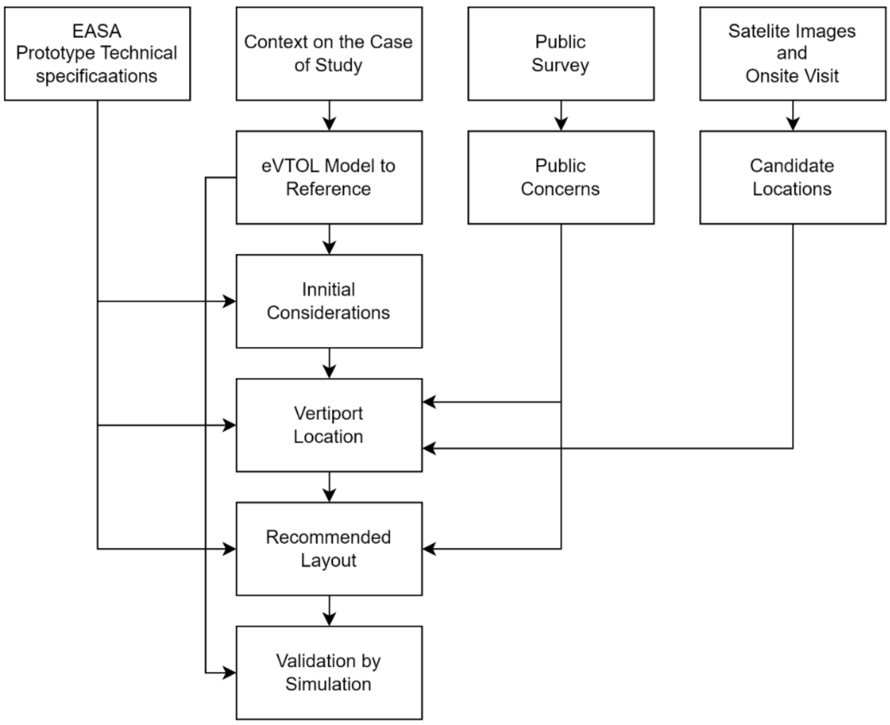

Figure 1 – Case of study methodology. Source: Own elaboration.

1.4 Dissertation Structure

This dissertation contains five chapters, which are presented in the following order: Introduction, State of the Art, Case of Study, Result Analysis and Conclusion.

The first chapter, **Introduction**, contains the motivation behind this work, what it seeks to achieve and the methods used. Lastly, an overview of the content of each chapter of this document is provided.

Chapter 2, **State of the art**, describes the hopes for urban air mobility (UAM) and the research it depends upon: vertiport placement, vertiport capacity estimation, operational optimisation, demand estimation methods, public concerns and ways to address them. Additionally, both eVTOL and vertiport projects are mentioned to better understand the current stage of AAM implementations.

The **Case of study**, chapter 3, starts by providing context on the Humberto Delgado Airport, based on which a suitable eVTOL to reference is chosen, followed by the results of a survey on public concerns. An overview of vertiport requirements under EASA guidelines is provided, establishing the base for layout requirements and element dimensioning, followed by initial considerations on vertiport design. After the previous groundwork, possible vertiport locations are identified and assessed, with a vertiport layout being developed for the most suitable one. Lastly, the recommended layout is simulated, providing the operational metrics used to evaluate its suitability for the intended use case.

A **Result analysis** is presented in chapter 4, scrutinising the simulation results of the recommended implementation and their viability to serve the needs of the airport's future.

Finally, a **Conclusion** is presented in chapter 5, reflecting on the obtained solution, addressed hurdles and perceived difficulties in which future studies are of benefit.

Chapter 2

2 State of the Art

2.1 Introduction

This chapter aims to explain the basics of AAM, namely how it can be implemented, what it can do for the public and why it is worth researching. Starting with how AAM fits in the current state of urban transportation and addresses present and future concerns, followed by an explanation of the key characteristics of the vehicles (eVTOL), a cornerstone of AAM, just like the ground infrastructure (vertiports) addressed right after. A summary of advantages is provided, followed by present obstacles to bring this concept to life and ending with current projects to address these issues.

2.2 Urban Transportation

Transport of both people and cargo stands as the core of the economy, representing either a transaction in on itself, being 5% of European GDP, or a facilitator for one, besides being directly related to the quality of life [10]. Many economic booms can be related to an evolution of transportation means, possible by facilitation of commerce, as was the case with the train, plane and subway. The previous examples were born from an identified necessity and matching technological evolution. Current urban transportation, reaching its capacity limits, can be seen as such a necessity. Given the difficulties of simply expanding available infrastructure and services, be it from the considerable cost or lack of space in the packed urban environment, the engineering community has to face quite the challenge.

2.2.1 Growing Demand

In 2018, 55% of the world's population was concentrated in urban areas, a number expected to grow to 68% by 2050 [11], [12]. While the biggest growth is foreseen in Asia and Africa, Northern America and Europe will still face a significant challenge, already having 82% and 74% of its population in urban areas respectively (data of 2018) [11].

The consequences of this tendency are already felt all around the world. Of the world's residents "4.2 billion people living in cities suffer inadequate housing and transport, poor sanitation and waste management, and air quality that fails WHO guidelines (…) Other forms of pollution, such as noise, water and soil contamination, so-called urban heat islands, and a lack of space for walking, cycling and active living"[1] [12] (world health organisation, WHO) are also present, now the focus of growing concerns by the population as quality of life becomes a priority. We are therefore at a time when "the world (...) has a unique opportunity to guide urbanisation and other major urban development trends in a way that protects and promotes health"[2] [12].

Dealing with this trend is relatively simple for the expanding peripheries of cities, which are still to be saturated and have room for the necessary compromises to accommodate infrastructure related to both rail and road-based solutions. The biggest problem faced by public planners is how to deal with works from their predecessors. City centres, alongside other points of interest (like airports) have already been developed to their fullest, in some cases beyond the immediate surroundings, making expansions of current infrastructure to accommodate the increasing demand either highly restricted with a limited impact or lack of feasibility. Limited by ground and underground solutions, "lifting the transportation offer into the third dimension by introducing UAM may be a promising step towards an improvement"[3] [13].

2.2.2 Current State

Aligning with public values is considered a requirement for success, as a smooth implementation is highly dependent on public opinion and acceptance. A manifestation of that is the green nature of the eVTOL vehicles catered for AAM use. The public's environmental consciousness is on the rise due to the way the consequences of global warming are getting closer, becoming "our" problem rather than "theirs".

The type of pollution where an improvement can be felt by using AAM is air pollution. "Air pollution is the largest environmental health risk in Europe and significantly impacts the health of the European population, particularly in urban areas"[4], being linked to 238 000 premature deaths in Europe alone (data referring to 2020) [14]. While a source of most controlled air pollutants, road transport was the larger contributor to emissions of nitrogen oxides (37%) in 2020 [15], a component known to weaken the body's defences against respiratory conditions, particularly concerning given the fact that all member countries reported levels, above WHO standards, of such component alongside ozone [16]. The percentage of the European population exposed to air pollutants in concentrations above both European and WHO standards (2021) is presented in Figure 2. Being mostly on the good and moderate rating, in terms of air

[1] https://www.who.int/health-topics/urban-health#tab=tab_1
[2] https://www.who.int/health-topics/urban-health#tab=tab_1
[3] [Page 1, Lines 2:3 of the abstract]
[4] https://www.eea.europa.eu/publications/air-quality-in-europe-2022

quality index (AQI), Europe can still improve and keep making the world better, despite southern Asia representing a more pressing problem, where measurements ranging from unhealthy to hazardous are common.

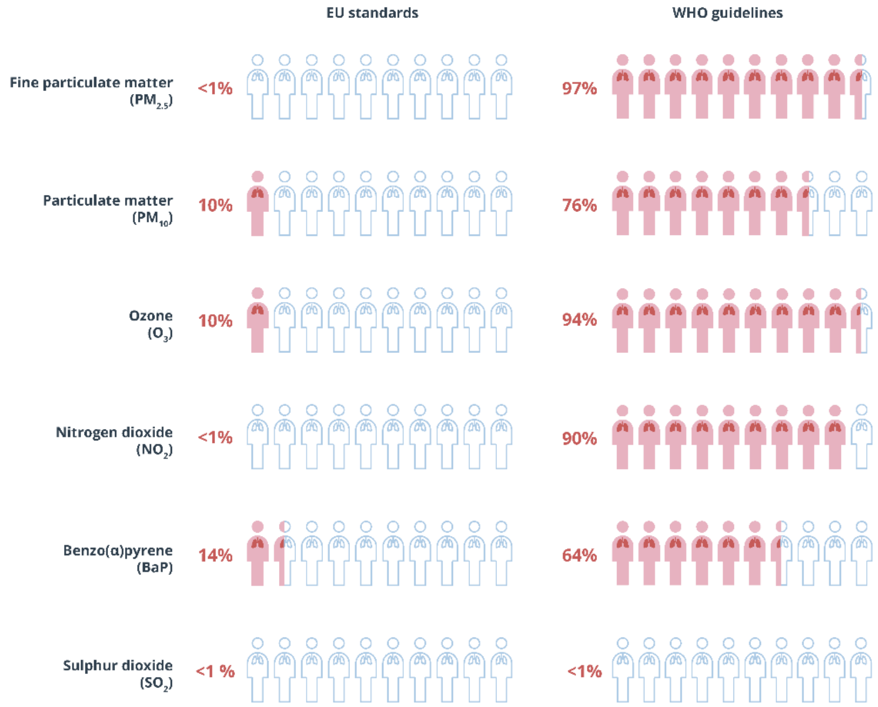

Figure 2 - Share of the EU urban population exposed to air pollutant concentrations above specific EU standards and WHO guidelines in 2021. Source: [16]

Noise pollution represents a high level of unwanted sounds that interfere with common actions like thinking, working, talking and sleeping, being detrimental to quality of life and even causing long-term harm to health. One of the more recognisable forms of noise are the sounds from road, rail, and air traffic, all already connected to physiological and psychological stress, a contributor to heart disease. As expected, the consequences are more predominant in the urban environment, where more noise sources concentrate. Despite being deemed unavoidable by the general population, steps can be taken to combat noise pollution. Many cities have laws limiting noise in residential areas, even if under questionable enforcement. Progress has also been made in limiting noise along flight paths, while not considered a priority compared to air pollution. Taking note of this reality, eVTOLs are being designed to produce limited noise, at a level compared with other ground vehicles, representing a significant reduction in comparison with more established aircraft [17].

Millions of hours are used daily for transport needs around the world, with many commutes extending well beyond necessary due to factors like traffic. INRIX global traffic scoreboard (2022) [18] ranked urban areas in accordance with hours of delay per driver throughout the year by comparing peak and off-peak traffic conditions. London had the worst delays, representing 156 hours of lost time, followed by Chicago with 155 hours and Paris with 138 hours. The two biggest cities of Portugal, Lisbon and Porto, had a value of 64 hours and 40 hours respectively. For a better perspective, per year, the average driver in London could lose up to six and a half days to traffic and in Lisbon, over two and a half days. These numbers represent time away from family, costing money in fuel and not contributing to the economy, increasing stress levels of both drivers and those surrounding the traffic. Many city centres are implementing a traffic restriction policy, whereby access by private cars and the time spent in the area are heavily limited. Such measures aim to improve the quality of the area, diminishing noise and emissions associated with road vehicles. Such is achieved by transferring users from personal to public transport, reducing the number of vehicles on the road and freeing space from supporting infrastructures (car parks or gas stations) to projects that contribute to quality of life, like gardens and stores. While a good implementation results in no loss for the business owners, such initiatives are often met with opposition from both the public, who are afraid of a more complicated access, and the store owners, who are fearful of losing customers and income [19]. Situations like these may benefit from the introduction of AAM, as the presence of one more transport alternative contributes to assuring both parties. The expected infrastructure conversion can even be an opportunity for a vertiport implementation, opening an alternative otherwise not present.

2.3 Advanced Air Mobility

AAM can be defined as an initiative in the field of aviation to connect cities across urban and regional areas making use of eVTOL aircraft [20], enabling consumers to access on-demand air mobility, delivery of goods and emergency services as part of an integrated and connected multimodal transportation network [21]. It can be divided into UAM and Regional Air Mobility (RAM) depending on the area / range of operations.

2.3.1 UAM

Technological developments in energy storage and electric propulsion caused major investments in developing new eVTOL aircraft, catered for use in urban environments. Centred around such aircraft, UAM is defined as an "air transportation system for passengers and cargo in and around urban environments"[5] [3]. Despite the long history of helicopters, they are unable to play the same role as the recent eVTOL aircraft, being more expensive to operate, energy inefficient, and undesired in many urban areas due to the high level of noise. All problems addressed by eVTOL aircraft, resulting in the cost

[5] [Executive Summary, Page 3, Lines 3:4]

per mile of an helicopter being up to 1.5 the initial counterpart by an eVTOL [22]. For the previously explained reasons, these new vehicles are expected to replace helicopters and bring flights closer to the ground.

Multiple markets are being evaluated considering the new capabilities brought by eVTOL aircraft, the more prominent ones being as an airport shuttle or air taxi. The airport shuttle case refers to offering a service to, from, or between airports along fixed routes, while the air taxi is expected to service on-demand point-to-point passenger services throughout urban areas [8].

The air taxi use case, while envisioned a long time ago, was brought back by a UBER white paper [2], where on demand door to door trips making use of both ground and air transportation were envisioned. The necessity of ground infrastructure for take-off and landing prevents a full air trip and originates the named "last mile" problem, whereby the first and last legs of the trip may not be serviced by UAM and instead by additional ground means [2], [23]. Companies like UBER have shown interest in UAM due to their ability to cover the ground segments, providing the means to book a door-to-door trip instead of separate bookings for each component of the journey. Still, minimising the relatively slow ground component can be seen as reducing travel time, making UAM a more attractive option for customers, reason why a suitable number of vertiports at desirable locations, either close to start / finish points of a trip or at a hub favourable for further travel is a largely agreed upon requirement for the success of UAM [3], [5], [8], [13], [24].

To properly develop UAM an integrated approach encompassing air vehicle technology, UAM infrastructure, and the corresponding business models for its operation are required [25].

2.3.2 RAM

Of the many electric aircraft in development, some have a publicised range that opens the door to use beyond UAM, into RAM. UAM and RAM share many similarities at their core, yet diverge in target market and vehicle and infrastructure requirements. In a RAM use case, the VTOL capabilities may be forsaken in favour of greater efficiency and capacity alongside lower operating costs, making use of electric versions of planes [26]. However, should direct access to a city be desired to the point of justifying the trade-offs for VTOL capabilities, a situation where UAM and RAM overlap takes form.

2.3.3 eVTOL Aircraft

New technological developments pave the way for passengers and goods transport, provided by eVTOL vehicles and introduce the UAM concept [5]. Providing a variety of configurations, be it in terms of seating / cargo capacity, range, or energy resupply method, the variety of eVTOL models allows the coverage of multiple market segments.

Despite the many differences, the helicopter is the closest equivalent technology in use today. Helicopters are, however, too noisy, inefficient, polluting, and expensive for mass-scale use [2]. On the other hand, the economics of manufacturing eVTOLs is expected to become more akin to automobiles than aircraft [2], promising shorter journeys, lower fares, lower traffic noise, and less pollution [26]. The most differentiating factor remains the prospects for the future. While there are projects to electrify and automate helicopter piloting, these are, in the end, conversions of a product developed without such characteristics in mind, causing foreseeable inefficiencies compared to the eVTOL purposely designed for it.

A key point for achieving the vision of UAM is the automation of the vehicles. Lack of maturity and real-world validation maintain scepticism over eVTOL in urban areas without pilots on board and significant automation. For that reason, a first implementation of UAM would require pilots, a comprehensible imposition by authorities present at the base of all legal documentation for the construction of vertiports [7], [27], applicable only for cases with an on board pilot flying under VFR. Not to say legislation is the only reason pushing projects to not start without on board pilot capabilities, distrust by the public on the yet proven technology is a significant factor pointed out in all works on predicting demand / willingness to try flying on an eVTOL aircraft, connected with the perception of safety [2], [3], [8], [9], [23]. As people grow accustomed with gradual increases in automation, the presence of a pilot should eventually be forfeited, a process that should follow the key phases outlined at [28]:

- No automation or human assistance – Present state, computer systems may help reduce the pilot workload and provide certain safeguards while unable of any control of the aircraft;
- Partial and conditional automation – The pilot is now on the ground, able to pilot the aircraft from a distance but on-board automation systems control most activities;
- High automation – While remotely supervised there is no longer a dedicated pilot, replaced by a supervisor in charge of multiple aircraft;
- Full automation – All human presence as a safeguard is lifted.

Between purposely created companies like Lilium, Volocopter, Ehang and Archer and already known names in aeronautics such as Airbus and Embraer, all with their own design choices, aircraft with varying performances and capacities are in development, optimised for cruise efficiency, required hover power, vehicle control, design simplicity, payload, turnaround time and vehicle cost. Most aimed to certify the respective aircraft at most in 2024. Unfortunately, be it for development delays, the impact of COVID-19, or other factors, the only eVTOL type certified to date is EHang's EH216-S, while doing so only by Chinese authorities [29].

To achieve such variety different propulsion configurations are employed [2], [3]:

- Vectored Thrust – Can refer to either prop-rotors or jets that can rotate following the requirements of the flight stage, providing both lift and thrust throughout the flight:
  - Lower motor weight and aircraft drag;
  - Optimised for both hover and cruise;
  - Lift provided by wings during cruise for high efficiency, range and speed;
  - Higher design complexity.
- Lift + Cruise – The vertical lift and forward thrust are provided by separate, non-articulating propulsors:
  - Higher motor weight and aircraft drag;
  - Maintains the redundancy benefits of the multicopter without the need for collective or cyclic actuation;
  - The presence of wings permits a higher speed in cruise;
  - Suitable for medium range;
  - Lower design complexity.
- Wingless (multicopter) – The propulsion units are fixed in position and create lift all the time:
  - High redundancy with simple controls;
  - Significantly quieter than helicopters;
  - Lower maintenance and lightweight;
  - Significantly slower and with a smaller range than the other alternatives;
  - Simplest concept.

2.3.4 Vertiports

"The buzz about vehicles flying above hides the infrastructure challenge below"[6] [4].

According to EASA SC-VTOL-01, a vertiport can be defined as an "area of land, water, or structure used or intended to be used for the landing and take-off of VTOL aircraft"[7] [30]. These structures are akin to heliports or airports, demarking both the take-off and landing locations for eVTOL aircraft, being as much of a key factor for the success of AAM as the aircraft themselves. The implementation of a vertiport must take in consideration most of the same factors as all other airport infrastructures, location, land availability and construction costs, throughput capacity (passengers and aircraft), restrictions derived from the surrounding environment (weather and airspace), impact on the local community, connection with the network of other vertiports, accessibility and supporting services [23].

It is important to note that early-stage regulations for the design of vertiports have been published by both EASA [7] and FAA [27], tying most dimensions to the diameter of the smallest circle that encompasses the aircraft. The reason for the transitioning nature of these documents is clearly explained by the FAA: "There is currently limited demonstrated performance data on how VTOL aircraft operate. Research efforts are underway to better understand the performance capabilities and design characteristics of emerging VTOL aircraft. The FAA will develop a performance-based AC on vertiport design (…) as additional performance data is gleaned (…)"[8] [27].

A literary review of approaches to determine both vertiport location and capacity was already performed by [5], serving as a base for the explanations given next.

2.3.4.1 Location

In terms of the location of vertiports, a decision must be achieved while balancing three impacting factors: Interconnection with further means of travel (due to the previously explained "last-mile" problem), local conditions and surrounding buildings, and physical spaces for construction / conversion.

While exceptions may exist, the rule remains that vertiport locations do not coincide with the passengers' starting / finishing point of travel. As such, choosing a suitable location

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[6] [Opening quote]
[7] [Subpart A - VTOL.2000 Applicability and definitions – (b), (8)]
[8] [Page 3, Lines 7:10]

that maximises the served area while minimising access times plays a significant role in the desirability of the offered service.

Due to the high development of desirable locations, a purpose build building may not be an option, so when considering the location, the presence of possible convertible structures needs to be taken into account, be it parking garages, shopping malls, transport nodes, floating barges or rooftops [2]. Additionally, local weather and airspace availability should pose as small an obstacle for uninterrupted operations as possible. One of the more influential factors for these aspects is surrounding buildings, to which an overflight limit may be imposed, alongside operating hours restrictions due to noise impact on an urban context. Surrounding buildings also impact the wind, a concern on its own, together they can lead to the “canyon effect” [31] especially prominent in the heterogeneous structure of the urban environment.

Depending on the corporate decision, the expandability of the implementation can be considered when deciding the vertiport’s location, even with some trade-offs. The same can be said about operation resilience.

There are three main approaches to determine desirable vertiport locations for a network, these being geographic information systems, algorithms and optimisation problems [5]. All of them differ in the required input data, merits of the reached solutions and how close they can get to a realistic implementation. Explained in more detail in the following paragraphs, the referred methods are but part of the start of determining the location of a vertiport. The “solutions” they present need to be further processed with important factors not considered up to that point, many with variable importance dependent on the resulting area of influence. The most restrictive of these being the presence of available land or a suitable rooftop in the immediate area around the solutions presented, usually applied as a secondary filter [23], [32].

Geographical information systems (GIS) are employed to process multiple types of spatial data [5], that is pondered using arbitrary weights commonly defined after consulting experts. For determining a suitable location for a vertiport, relevant data to consider may include socioeconomic data (ex: income, population density,…), closeness to a point of interest (ex: city square, historical monument, airport,…), presence of previous usable infrastructure (in general airport or heliport), restrictions to the airspace (ex: no fly zones, overfly minimum altitude,…), among others.

Algorithmic approaches are in general derived from the k-means algorithm. This algorithm groups the inputted points into the specified number of (k) non-overlapping clusters. While the most common method starts with selecting a random set of points (numbering k) and running the algorithm, actual applications either repeatedly run the algorithm for multiple random starting points, comparing the outputs, or make use of a "warm start", selecting the starting points (not necessarily part of the inputted points) in accordance with pertinent information for their goals, akin to an "educated guess"[5], [33]. This last case of non-random starting points is named k-means++. Examples of works that made use of the k-means approach are found in [2], [5], [34]. The metric to grade vertiport placement options may be catered to specific goals like minimising medium travel time or costs and should be accompanied by critical thinking, confirming the size of each cluster and even number of clusters in light of the desired final result. Due to the limitations on factors considered by the algorithm, applying additional filters to the results may be necessary. An example of both options is found in [32], where the metric used pertained to closeness to high income individuals, further filtered using an available land dataset. The k-means algorithm follows the next steps:

1. Specify the number of clusters (k);
2. Select the starting points, numbering k, as centroids for different clusters;
3. Assign the remaining points to the closest cluster centroid;
4. Calculate a new centroid for each cluster using all assigned points;
5. Repeat steps 3 and 4 until the defined stopping criteria is reached. It may include at least one of the following:
    a. The centroids for each cluster stop changing;
    b. Each point remains assigned to the same cluster;
    c. A maximum number of iterations is reached.

Objective-based approaches seek to optimise the solution in accordance with an objective function defined on a case-by-case basis in a way that best describes the objectives of the implementation. The most applied objectives are maximising travel time savings, revenue, demand coverage by the vertiport or minimising travel costs. While defining the objective function, multiple previously exposed options may be combined and even pondered under different weights.

2.3.4.2 Demand

As with any service, it is in the interest of stakeholders to properly dimension all aspects of an implementation, be it fleet, vertiports and all supporting infrastructure, not to leave business opportunities unexplored while limiting the initial investment, a step required to make AAM cheaper and therefore more attractive as it has yet to prove itself. In the initial stage for AAM, a correct demand estimation is instrumental for realising the envisioned future.

Standard methods used by airlines are mostly not applicable to AAM. The most common are historical data, qualitative methods and quantitative methods [35]. Historical data works based on such data with which it is possible to identify patterns, trends and seasonality, despite having the drawback of being influenced by past occurrences not applicable in the future because of weather, holidays, political instability, among others, being important to process the inputted data with such abnormalities in mind. Qualitative methods are the most promising for use in UAM, as they are based on the opinions of stakeholders and experts rather than numerical data. The benefit of this method is the ability to consider intangible aspects like marketing, branding and loyalty programs. Lastly, quantitative methods use mathematical and statistical models, usually applied to relevant data, establishing relations between factors (ex: population, cost, income, seasonality) in the process. The reliance on suitable data, mostly of a historical nature, makes it very suitable for established and stable markets, the opposite of AAM.

As part of estimating demand, all relevant factors need to be identified and considered, in accordance with the type of service planned. The most common among the literature are time (saved and of day), cost, distance, safety (personal, environmental, operational), security (physical and cyber) and noise [23]. However, the factors go beyond these, as schematised in Figure 3, where nature allows their grouping into trip, motivation and acceptance-related groups.

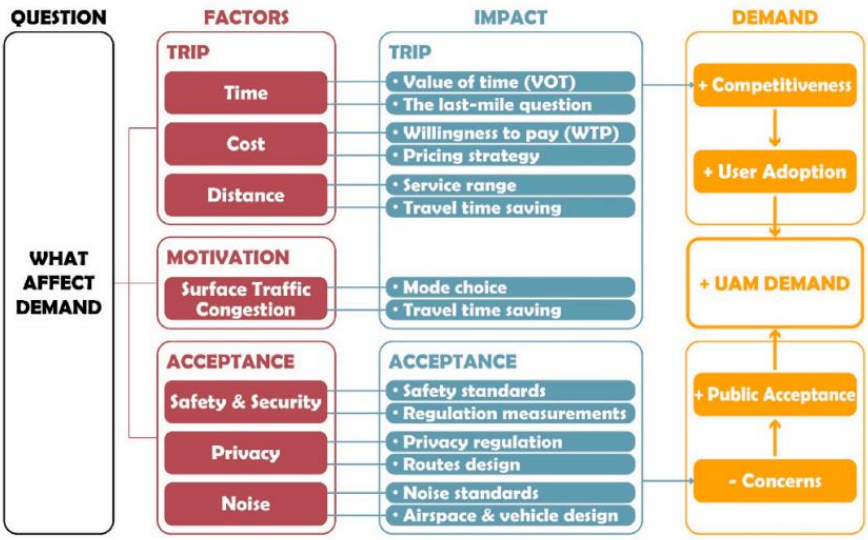


Figure 3 - Different kinds of factors that affect the demand in UAM. Source: [23]

The research of demand can, however, be done at multiple scales from the market as a whole down to a specific city / region. For the former, mostly preference surveys are used, while for the latter quantitative data-based methods are prevalent, allowing the basis for infrastructure dimensioning and placement [23], important as a large part of the attractiveness of AAM lies in the dimension of the vertiport network. For this last case, making use of recent technological developments, the application of machine learning algorithms [34] is also a novel possibility worthy of attention.

In some particular cases, the presence of associated transport infrastructure can be used as reference for the dimensioning of vertiports, as done in [36]. For example, the dimensioning method for airport infrastructure, recommended by ICAO [37] – cited by [36], is to consider the 30th busiest day of the year, a possibility for a vertiport associated with an airport.

2.3.4.3 Layout

The elements that comprise the vertiport are the pads (for take-off and landing), the stands (for aircraft parking) and the gates (for passenger and cargo loading / unloading, normally associated or considered to contain a stand). The layout must be designed following the surrounding airspace and be capable of coping with the projected passenger demand and eVTOL throughput in a way that minimises the footprint and impact on the surrounding community. For that, EASA [7] considered the largest dimensions, maximum take-off mass and most critical obstacle avoidance criteria of the various eVTOL the vertiport is intended to serve as the essential parameters to consider while designing the infrastructure.

The current prototype vertiport specifications [7], [27] already introduce some decisions with an impact on the layout, both in terms of stands and touch-down and lift-off (TLOF) pads, mostly related to the possible overlap of protection areas (PA) from adjacent elements with an impact on simultaneous operations further explored in the following sub-chapter. For now, this information is relevant due to the ability to design the stands either in accordance with a D-value or specific geometry, restricting the eVTOL models permitted in a particular stand and even changing its geometry, as well as a minimum separation between adjacent elements.

To assess the vertiport capacity, many of the available studies have focused on the time needed for eVTOL to clear TLOF pads during arrival and departure procedures, a value ranging from 60s to 180s [5] across the literature. In fact, the vertiport capacity depends on the time required for take-off and landing as well as the vertiport layout, pads need to be clear for use by the next eVTOL as quickly as possible and all the elements of a vertiport must be appropriately organised to maximise capacity [5] and vehicle flow.

The predictions of the capacity can be made using various techniques the most common one being Integer Programming, as is the case on [2], [6], [38], where the considered operational concept is programmed and then repeatedly solved to maximise the objective function where a reward is specified for each arrival and departure completed. To do so it takes various variables as input, dependent on the characteristics of the considered aircraft and layout, such as taxi time between elements.

A simpler model was also introduced by [39] allowing a comparison between the surface and TLOF pad capacity, which is of great use for comparing a sizable number of layouts despite the oversimplification of more than the simplest options.

At [6], the sensibility of various layouts to the number of each component (gate, stand, pad) was studied from an operating point of view, seeking more than a break-even throughput with balanced arrivals and departures. The findings highlight the importance of the gate to TLOF pad ratio for balanced operations and presence of staging stands (longer duration parking) for unbalanced ones. Finding a correct balance between the number of gates and pads is akin to balancing the surface and pad capacity, ensuring enough of each element for fluid operations without one being a bottleneck and the other underutilised, effectively utilising all resources and avoiding overspending. The most efficient ratio varies with the considered times for each segment associated with the element, increasing the arrival or departure time decreases the optimum ratio of gates per pad, while increasing the turnaround time increases the optimal ratio of gates per pad, the opposite being also true. Variations in taxi time do not see a global relation with the gates to pad ratio, as the effect varies with operation policies, explained in the following section.

In general, the decision on what layout to apply is too dependent of the specific case for general conclusions to be made even in mostly similar scenarios. The process should therefore mostly follow the steps of defining all restrictions (required capacity, maximum cost, ground and air operation restrictions, among others), obtain layout candidates considering all possible options and respective numerical modelling, ending with the most realistic simulation possible, be it with integer programming or simulation tools (ex: *Anylogic* [40]) for all relevant scenarios.

2.3.4.4 Operation

The lack of a full-scale implementation of a vertiport network leaves the operational requirements necessary for an optimised and safe operation at the theoretical stage. Many operational decision options and respective conditions are yet to be defined by the authorities. In the case of EASA [7], the vertiport rules will be developed in two stages, the first, already published and being used as a reference for this work, portrays only prototype technical specifications (non-regulatory) for vertiports operating under VFR and manned VTOL aircraft certified in accordance with the special conditions for small VTOL aircraft [30]. The second stage intends to clarify all necessary vertiport rules and requirements, be they regarding authority, operators, and operations, alongside certification specifications and guidance material for vertiport design and certification.

Already presented choices to be made considering both operational and layout implications are outlined in [7]. A stand's geometry may be decided based either on a D-value or the aircraft's geometry. Additionally, the respective PA of adjacent stands can overlap under the condition that only one of them may have moving objects (aircraft included) at a given time. Whether or not the ability to turn is desired, suitable clearances need to be applied. Lastly, dependent once again on the ability to operate simultaneously, a certain distance between FATOs needs to be guaranteed, determined by a safety assessment (the value of 60 m separation is the recognised reference for helicopters with MTOW of 3 175 kg).

As studied at [6], fully independent operations between adjacent TLOF pads are the scenario where maximum throughput is achieved, as this policy brings the most TLOF pad capacity out of an additional pad, representing saved time at both ground and air operations. It comes, however, at the cost of a bigger footprint due to the required separation, as discussed in the previous paragraph. In comparison, fully dependent operations entail many restrictions to an additional pad, as the inability to perform take-off and landing operations if other pads are under use restricts gains to possible saved time during the stand – pad taxi. A critical remark is that having multiple pads feed the same gates allows for increased operational robustness and can be the decisive factor for the implementation of a second pad under fully dependent operations, despite the negligible gains compared with independent operations.

2.3.5 Advantages

The success of UAM naturally depends on what it can improve for users and new options it introduces in contrast with already present modes of transportation. Most of the improvements brought by AAM can be attributed to the use of aerial vehicles. Flying can be seen as a distinguishing point that allows for more direct routes at higher speeds, which translate into time savings for users while making the time spent a more enjoyable experience. Being developed with the future in mind, eVTOLs also make part of the current effort to move away from fossil fuels in favour of greener alternatives [2].

EASA [3] foresees transport 1 500 times safer (on a passenger kilometre basis) due to more strict requirements for air transport and a 73% reduction in transportation times between medical facilities. City to airport transfers can save from 15 min to 40 min, with similar values foreseen for work - home commutes. It is also an economic opportunity, representing a projected market of 4.2 b€ with 90 000 related jobs, by 2030.

The more discrete nature of AAM, in terms of infrastructure, facilitates initial deployments and expansions, as despite the high price of each vertiport from a network it still undercuts the extensive roads or rail with accompanying bridges and tunnels posed as an alternative [2]. The option of converting existing buildings also lowers the difficulty of adoption.

2.3.6 Obstacles to Implementation

No matter how much humanity envisioned and desired the capabilities brought by AAM, now that an implementation is possible, public surveys show that alongside the desire to try, an underlying tendency to limit exposure by the consulted individuals can be glimpsed, resulting in the more common concerns on safety, noise, security and environmental impact [3]. Addressing all these is key to gaining public trust and acceptance, requirements for a successful implementation and operation.

The uncertainties around ground infrastructure are also introducing friction to the development process. The lack of non-transitory regulations [7] prevents trust in the longevity of constructed vertiports and the presence of sufficient safety barriers during operations, standing against confidence by investors and users. The various underlying studies in which infrastructure is dimensioned and designed can themselves be put in question as the lack of real data leads to multiple assumptions by the authors [23] and sabotages confidence in the conclusions, yet to be validated in the real world. Even the choice of location needs to be done with care, as rather surprisingly, land used for ground infrastructure causes a far more meaningful impact on welfare than in mode choice [41].

The task of predicting demand is further complicated by the high elasticity of mode choice for transportation with pricing [41], results that support initial use by mainly high-income households that would see welfare gains despite an opposite reaction in low-income households. That is a problem due to the adverse response in public acceptance as all would be exposed to the disadvantages of UAM while only the more affluent individuals enjoy the benefits [3]. The problem is not for a UAM implementation to be viable as even in a small premium market the infrastructure network can at least break even [4], the problem is operating under costs that allow access to medium or even low-income households. McKinsey [4] pointes out options such as ancillary sources of revenue (represents about half the income of airports), private and corporate investments (on ports at their headquarters or personal estates), public-sector subsidies, priority of small-scale and retrofit projects, among others.

Despite the established goal of fully autonomous operations, due to concerns from users and regulations, a first stage should include an on board pilot, them being one of the biggest challenges. Autonomous operations can take more than a decade and, in the meantime, pilots need to be convinced to invest significant money and time to perform a specialised job openly declared as temporary [28].

Another future concern is the lack of air traffic management (ATM) at the required scale for the envisioned fully developed AAM. The automation of ATC is seen as a requirement to cope with the predicted increase of pressure on the service, raising almost the same concerns as the automation of eVTOLs. The sector's current focus lies in bringing a manual version of AAM to life before gradually upgrading to an automated version, not on ATM that stands essentially without progress, expected to only see more attention when the current largely limited capabilities get closer to their limits.

2.4 Active projects

2.4.1 eVTOL Aircraft

From already established aeronautical companies like Airbus to purposely created ones like Volocopter and Lilium, many eVTOLs projects are being unveiled to the public. The variety of eVTOLs is essential to provide aircraft catered for various market segments, as limiting the costs involved is a requirement for still sceptical investors, wanting to limit risks, and consumers, who benefit from prices accessible to a larger share of the population.

Many companies aim straight to the pretended autonomous flight stage and, therefore, do not require a pilot on board. As the initial implementations are expected not to be autonomous, the list of eVTOL models presented below (Table 1) favours models with on board piloting capabilities.

Table 1 - eVTOL models and characteristics. Source: Own elaboration.

Company Model	Seating Capacity	Range [km]	Cruise Speed [km/h]	MTOW [kg]
Volocopter VoloCity	Pilot + 1 Passenger	35	100	900
Lilium Lilium Jet	Pilot + 4-6 Passengers	175	248	3 175
Ehang EH216-S	2 Passengers (no pilot)	35	100	620
EVE Air Mobility EVE	Pilot + 4 Passenger	100	(Not Disclosed)	1 000
Ascendance Atea	Pilot + 4 Passenger	400	200+	2 000

2.4.2 Vertiports

At the initiative of Volocopter, at the 6th October 2022 the first crewed eVTOL test flight in Italian airspace took place, marking the start of operations of the AAM testing vertiport, hosting an interactive booking process. Additionally various tests for both ground and air operations are to be carried out [42].

On November 10th, 2022, as a test bed for future UAM endeavours, the first fully integrated vertiport terminal in Europe was commissioned by Group ADP, Skyports and Volocopter. Located on the outskirts of Paris, this project enables testing for vehicle integration, ground movement and charging procedures, flight scheduling, situation awareness, information exchange, and passenger journey through the terminal, including boarding [43]. Data required to overcome many of the current barriers is expected from this project.

Under an initiative of Skyports, an agreement for the development of UK's first vertiport testbed, at Bicester Motion, Oxfordshire has been reached in hopes of pioneering mobility technology, more specifically the next generation of electric, low-noise aviation [44]. Contributing to vertiport network planning and demonstrations, the project will achieve more stakeholder engagement.

The first conditional approval for a vertiport, in Blackstone, Virginia, has been granted by the FAA under the request by NAVOS Air, now pending licensing by the Virginia Department of Aviation [45]. The Blackstone Army Airfield serves both the public and military and is now seeing a project for a vertiport seeking to research an end-to-end concept of operations specifically for UAS and AAM uses.

EHang launched at the 26th December 2023 the UAM operation demonstration centre, in Guangzhou China, as the first step to provide aerial sightseeing services. Built in only 4 months, the vertiport includes a single pad, catered for EHang's EH216-S, single sitter, pilotless eVTOL, hangars, command and control centre, passenger waiting area and service centre, on 4 600 square meters [46].

Many other projects, in addition to the ones previously mentioned, already exist or are planned. Initiatives like these and the research results they bring represent steps forward, breaking the limits of theory into the realm of practice and providing insights into improvements for eVTOLs, vertiports and the many processes surrounding their use.

2.5 Conclusion

This chapter started by covering many aspects on the base of the enthusiasm over AAM, namely the current state of urban transportation and its impact on quality of life and how AAM takes them into account.

AAM and the two components it integrates (UAM and RAM) were then introduced, alongside the pillars of this concept, eVTOL aircraft and vertiports. The problems faced in the design of vertiports were then explained, mentioning the current methods applied by the academic community to address them. This was followed by a synthesis of AAM's benefits and challenges.

The last segment introduced some prominent eVTOL projects and vertiports for test purposes, marking the first steps of bringing AAM to reality.

Chapter 3

3 Case of Study

3.1 Introduction

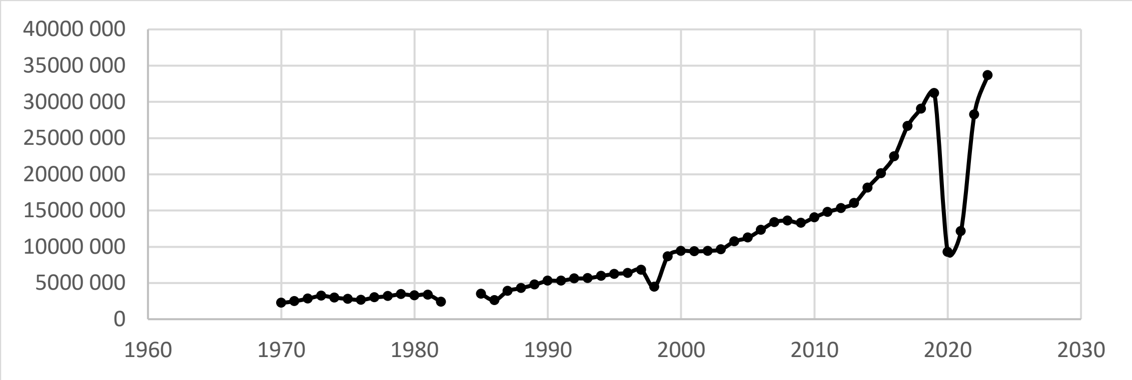
High hopes accompanied by economic potential have sparked the interest for AAM. Among the most advertised aspects of this promised future, reducing traffic jams, less pollution and noise and competitive pricing, only the second has been verified, while for the latter only the math behind the claim backs the prediction [47]. Whether to verify these claims or identify lacking aspects in need of innovation to achieve them, only by observing and refining a real vertiport network can the end goal be reached.

While eVTOL development is largely publicised, even if with results not being divulged, an equally critical AAM component, vertiports, see much less attention. Many companies do research vertiports, as is the case with Skyports [48], having projects partnered with various eVTOL companies (Joby Aviation, Volocopter and Wisk), yet a stark difference can be seen in the investments for these components. Many singular vertiports, under the role of test beds, have been announced for research purposes, a subject elaborated in a previous subchapter (2.4.2), yet a vertiport embedded in the urban environment has not been built.

Identifying a necessity that is not easily addressed by established means, as is the case of this work, may just start the first vertiport project in Portugal. Reason why, the potential of AAM to support the new reality for Portugal's capital airport is being studied by developing and simulating a vertiport associated with Humberto Delgado Airport.

3.2 Context on Humberto Delgado Airport

Humberto Delgado Airport, also known as Lisbon's Airport or Portela's Airport, is the biggest Portuguese airport in terms of passenger movements, operating under the ICAO code LPPT. Opened to the public in 1942, it initially operated two runways of which only one remains as such, sustaining the meteoric increase of 2.2 million passengers in 1970 to 33.6 million in 2023 (Graph 1).



Graph 1 - Passenger movements at Humberto Delgado Airport. Source:[49]

Reaching the limits to the number of movements possible by the single runway, not further optimisable, leads to the realisation the airport would be unable to sustain the continuously growing demand while being unable to expand runway capacity due to the unavailability of free land. Knowing of the impossibility of expansion, talks of a new airport have surged multiple times over the last decades, always ending in silence as it was not seen as a priority. Yet, in 2024, a decision was finally made by the government to follow the conclusions of an independent technical commission, declaring the intention to construct a new airport in Alcochete named after Luis de Camões. The intention is to gradually decrease operations in Humberto Delgado as they increase in Luis de Camões, eventually becoming the only operating airport [50]. This choice came with various challenges such as increasing the transport capability between both sides of the Tejo river. A direct connection between airports is of interest to allow cooperative operations during the transitional phase, representing an opportunity for the introduction of AAM, in line with the general interest demonstrated in the Independent Technical Commission's report [24].

3.3 Reference eVTOL

Due to the variety of companies developing eVTOL aircraft, these vehicles present a multitude of capabilities to be considered. Therefore, selecting the eVTOL to reference in the next steps requires the establishment of criteria by which to judge the various projects' suitability for the case of study, resulting in the elaboration of Table 2.

Table 2 - eVTOL choice criteria. Source: Own elaboration.

Criteria	Considerations	Restrictions
Vehicle category	Catered for commercial passenger transport	Passenger oriented
Pilot	Autonomous operations not yet allowed by authorities	On board pilot
Range	Enough to connect both airports	At least 30 km (direct route)
Payload Capacity	At least one passenger in addition to the pilot	Seating capacity for at least 2
Certification	According to EASA	As close to certification as possible
Energy Resupply	Significant impact on turnaround time and vertiport footprint	Preference for battery swapping

Following the defined criteria, two aircraft stood out: Volocopter's VoloCity [51] and Lilium's Lilium Jet [52]. The throughput of both aircraft is attributed to different philosophies. VoloCity's strength lies in flying more trips, rooted in the smaller ground time, as the turnaround is based on battery swapping (about 5 min). In turn, its weakness is the number of passengers, limited to one until fully autonomous operations, when it would double. On the other hand, Lilium Jet aims to transport more passengers at a time, up to 6 depending on the configuration, allowing for a compromise in ground time with significant charge times (typical charging session of 45 min).

The decision was made to consider VoloCity (Figure 4) as a reference for this study, as per its published design specifications [51]. The energy resupply method's impact on ground time and infrastructure footprint is the key factor behind this choice. Energy resupply by battery swapping contributes to minimising the vertiport's footprint by reducing turnaround times [6], a significant restriction in already developed zones, such as around Humberto Delgado Airport. The expected range is slightly above the required, leaving a safety margin. Volocopter has made extensive efforts in the direction of certification and pilot training, establishing a good track record that is expected to continue.

Figure 4 – VoloCity. Source:[51]

3.4 Public Survey

3.4.1 Introduction

To produce a vertiport layout, especially during the initial stage of AAM, before the public gets accustomed to relevant operations, prioritising measures to address predicted sources of friction is of utmost importance. Despite being subject to relevant changes with the actual experience of being affected by AAM operations, current views yet to experience a full-scale implementation rely on the ever-evolving image of AAM. It was for that reason that some relevant variables like cost were, at most, mentioned while not providing reference values.

An English translation of the survey questions can be found at A.1 Survey Questions, as the original was conducted in Portuguese in accordance with the chosen location for the vertiport.

3.4.2 Overview

A survey was conducted to understand the public view on vertiport operations, following six blocks. The first introduced the study being conducted and the survey's theme. The second pertained to knowledge of AAM, with a brief overview for those yet to hear of the matter. The third made questions to be answered from the point of view of an air taxi service user, under various relevant assumptions such as the realisation of checks by authorities and yet to be developed laws. The questions of this segment presented reasons in favour and against the use of the service, asking for the importance / relevance (on a scale of 1 to 5) they represent on the decision to use and oppose the use of the service. A question pertaining to sources of discomfort was also presented under the same scale.

The fourth block sought answers from the point of view of a resident in the area of operations. The first question inquired how much they would agree, from totally disagree (1) to totally agree (5), with the conversion / construction of a vertiport in various possible spaces like existing heliports or transport hubs. The following questions presented reasons to support and oppose the construction of a vertiport near their residence under a checkbox format.

The last blocks, demography and conclusion, seek to validate the representativity of the collected answers and present the chance of expressing suggestions or thoughts on AAM respectively.

As the questions were reliant on presented options, at various points of the survey optional open answer questions were presented for the expression of any point of view outside the ones listed on the questions.

3.4.3 Results

The values presented result from 203 validated answers that were filtered by various checks, leading to a confidence level of 95% and a margin of error of 6.88%.

It is well known that humans' biggest fear is the unknown, which is why the public's understanding of AAM and its component of air taxis is relevant. The first question addresses this point, inquiring about the level of knowledge, with the resulting answers being 21.7% unaware, 60.1% superficial knowledge and 18.2% advanced knowledge.

The second question wanted to clarify the disposition to use the service, using the scale "very improbable" (1) to "very probable" (5). This resulted in an overall average of 3.4, slightly above neutral (3). Answers in the improbable segment (1 and 2) represented 25.6% of the answers, 24.6% were neutral (3) and 49.8% were in the probable segment (4 and 5).

Analysing the previous questions together, the answers either neutral or positive in terms of willingness to try show the importance of being informed at a time before trust is established. Of those characterised as unaware, 43% were on the positive side of the scale of disposition to try (4 and 5). A percentage that grew with the knowledge of AAM, with 47% and 67% for superficial knowledge and advanced knowledge respectively, demonstrating the positive relation between being informed and willingness to try.

As with any other decision, when considering the option of using the service both reasons in favour and against are pondered, resulting in a conclusion. Under the objective of promoting air taxis in the context of AAM, understanding these reasons is paramount. On a scale of "not pondered" (1) to "decisive" (5), of the pre-selected reasons in favour, reducing transport times / avoiding traffic jams had the highest average of 4.0. It reached such an average due to the 108 responses on the decisive (5) level, more than the others combined. A downward trend was observed as the age group increased, for reference the age group of 18-29 presented an average of 4.37 while for >65 it was 3.69, which is to say the importance of reducing transport times decreased with the increase in age. On the other hand, symbol of social status saw the lowest average, with a value of 1.64, resulting from 130 answers of the lowest level (1), more than the rest combined, which included only 4 answers of the highest level (5). The other presented reasons had similar results.

On average, more safety was 3.19, reduced environmental impact was 3.03, recreative reasons / experience of flying in itself was 2.96 and novelty of the experience was 3.07. Recreative reasons / experience of flying did show a decreasing average with the increase in age, being more meaningful for users of age 18-29, averaging 3.6. A similar case is present for novelty of the experience, reaching an average of 3.7 for the same age group.

As for reasons against using the service, fear of flying / heights had the lowest average of 2.0. Even if the majority are not affected by such worries, of the 34 who answered either 4 or 5, only 10 showed improbable disposition to try representing a significant will to overcome such fears for the benefits brought. On the other hand, cost was the most concerning representing an average of 4.0. Due to the differences between helicopters and eVTOLs, this segment of air travel is expected to become significantly cheaper and, therefore, accessible to a larger share of the population even if still on the pricier side, at least in the short term. Incapacity of the service to cover the totality of the trip had an average of 3.0, the highest value besides cost. Measures such as ensuring ample methods of access and egress, like existing public transport alternatives, are therefore confirmed as of high importance and partnerships with companies capable of covering the rest of the trip become more enticing, something UBER has shown interest in [2]. Security concerns also had a relatively high average of 2.7, unexpected as the survey was not specifically distributed among a public exposed to general security concerns like terrorism or sabotage. A possible explanation for this result may be the rise of such incidents in Europe, with an increased presence on the news. Another factor is the lack of clarification on possible mandatory security measures and respective validation of effectiveness. Lastly, the general feeling of insecurity had an average of 2.8, which was expected due to the lack of implementations and the confidence gained only by exposure and a proven track record.

The last question of the user block aimed to clarify sources of discomfort during the use of the service, as the enjoyment of the trip contributes to demand. The answers were under a scale of “insignificant” (1) to “extremely meaningful” (5). With the highest average, significant winds, averaging 3.6, was to be expected. With an established position as a source of concern for passengers in any aircraft, the lack of relevant data by eVTOL manufacturers may have magnified the already present opinion. An open answer understandably expanded this concern to include all weather conditions. The second highest was proximity to other aircraft (during flight) with 3.22. This relatively high position is due to a lack of real experience, being difficult to establish even a reference value as it depends not just on eVTOL capabilities but also ATM advancements. This last one is expected to rely mainly on automation through AI, even if vehicle monitoring relying on the same means can be a source of confidence to users, as suggested in an open answer. The same reasons apply to proximity with buildings, averaging slightly lower at 2.9. The elevated rate of climb / descent, averaging 2.6, is a bigger concern for an air taxi under AAM than to helicopter operations. With the increased proximity of eVTOL with other objects, be it other aircraft or buildings, higher rates may be required for certain vertiport placements. With a concerning average of 2.6, overflight of water is relevant for vertiports operating in water platforms. Following these results, water platforms was the second least agreed option of the next question. While by no means of critical importance for vertiport placement and design, customer discomfort may discourage locations near bodies of water and routes that implicate overflight of water aiming to diminish the impact of operations in the community. It is, however, worth noting that those more concerned (47 answers of 4 or 5) with overflight of water majorly valued smaller transport times (37 answers of 4 or 5), opening the option of tolerating water overflight. Also related to vertiport placement, significant height disparity between the pad and ground level had an average of 2.3, explained by the established image of heliports on top of tall buildings. Of the presented reasons for discomfort, the one with the lowest average was boarding procedures in open pad with 2.1, possibly explained by being the standard for helicopter operations, even if a significant safety concern for larger scale ports expected of AAM.

Starting the block about a resident's point of view, a question was presented regarding possible generic locations for conversion / addition of vertiports, under the scale of "totally disagree" (1) to "totally agree" (5). All presented options had neutral to positive results, none being negatively seen. The safer option, pre-existent heliport was the most agreed upon, with an average of 4.25, result of an absolute majority 169 answers on the positive segment of the scale (4 and 5). Once again familiarity with helicopter operations and a proven history of safe operations should have played a role and may be a good representation for small-scale vertiports, even if not applicable for larger implementations. The second most voted option was transport hub (ex: railway station, airport), averaging 4.15, explained by the value such locations have to address the last mile problem, mentioned on the overview that preceded the questions. The location that followed was point of interest (ex: shopping mall), with 3.57, popular for the desirability. It is, for that same reason, that the more popular means of access get often saturated during peak times such as after work hours or at the weekend, increasing the desirability of a transportation alternative. Parking lots averaged 3.47, providing means of access and egress by road vehicles and the commodity to park said vehicles, facilitating use for arrival and departure to the vertiport. The structural capabilities and open sky nature of many top floors make an attractive case for conversion, even if specific studies and validation are needed. As the second to last, water platforms averaged 3.18. This relatively bad score can be seen as a result of the discomfort with over water operations, even if perfectly safe for heliports, as is the case with the downtown Manhattan heliport located on a pier. The least agreed option was rooftop of generic building, with an average of 3.15. This option would be required when seeking coverage of an area not applicable to previously mentioned alternatives, as in many large residential neighbourhoods. Covering the most out of the trip with an air taxi is of benefit, hence the importance of implementing vertiports as close as possible to the starting and end points of said trip, being the most common starting point the user's house, especially for daily commutes. That would naturally imply increased exposure to undesirable factors, as mentioned in one of the following questions. The lack of other suitability traits and conflicting views should be in the base of this result.

Of the reasons presented in favour of supporting the implementation of a vertiport near the respondent's home, 58.6% intend to use the services it brings, a value in line with the positivism shown on the question of disposition to use the service. Followed by increase in value of location (as the house owner), present in 46.3% of responses, achieving this relevance for economic reasons and an increase in real estate investments all around Europe. Standing both in favour and against AAM, an increase in frequency of associated transports (ex: bus) was a reason favoured by 37.9% of responses. While not particularly high, this percentage represents the pondering between benefits brought to users who favour public transport and the absolute majority that use a personal vehicle and would see no benefit due to the lack of intention to use them. The expected increase in people flow is accompanied by an economic opportunity for adjacent businesses, something seen in good eyes by 25.6% of respondents. Standing against common belief, 21.2% of respondents see aircraft operating in the area as a positive rather than negative, which is to say, not visual pollution as it is normally classified. Despite the variety of reasons presented, there were still 33 responses to which none applied.

The last question pertained to reasons to oppose the implementation of a vertiport. Following the human nature of limiting their own exposure to undesirable factors the most selected reason, by 74.9% of answers, was exposition to factors like noise or visual pollution, reaching maximum levels around vertiports where eVTOL concentrate. What followed was flights that disturb the comfort and tranquillity by being too close, selected in 67.5% of responses, explained by the same reason. As the third highest, with 54.7% of responses, was feeling of insecurity due to the risk of accidents. Just as many previous results, this percentage reflects a lack of confidence derived from a lack of safety records, studies related to safety and validation of standards yet to be imposed by the authorities. A lack of defined emergency procedures can be added to the list, being of concern for both those on the ground and in the eVTOL, expressed in multiple open answers. Standing against the increase in commercial activity, almost double the answers (46.8%) considered the increase in people's flow as negative. Naturally, with more people comes more noise and less tranquillity, going against the environment desired for a residential area. While still present in 41.9% of answers, the percentage of respondents showing concerns for local fauna can be said to be lower than expected given the ever-increasing environmental concerns. As the opposite of intention of use of the service, the option that got the highest percentage of answers in the previous question, non-intention to use the service was second to last with only 18.2%. Once again, 15 respondents did not see themselves reflected in any of the presented reasons.

Much of the basis of this study represents the expected future for air taxi operations, even if indeed from an optimist point of view. Many relevant factors, rightfully mentioned in the open answer fields, were either not approached or mentioned in a vague way as proper conditions for satisfactory predictions have yet to be met. Further enquiries are expected as steps are taken towards AAM implementations, reflecting more data and the development of factors that are still uncertain.

The significance cost represented was reinforced by 4 mentions, alongside disbelief respondents would integrate the user group of this service, an understandable concern as the increase in affordability of air taxis in the context of AAM is still to be validated. The answers also expressed many concerns also valid for electric cars, such as the capability of the electric grid to handle the increase in energy usage, the danger batteries represent in emergency situations such as fires, an autonomous future reliant on vulnerable communication networks, among others. Even the actual benefit to the environment may not be as solid as believed, beyond the benefits brought by not relying on combustion engines, the environmental damage of lithium extraction, lack of application of proper disposal methods and relatively high replacement rate of batteries stand against the publicised green nature of these vehicles.

3.4.4 Results in Context

The public enquiry was made without the Humberto Delgado Airport in mind, allowing it to be of reference to many more cases. For that reason, only applicable aspects will be commented in this section.

Many of the answers reflected concerns overlapping with helicopter operations, namely high winds and other meteorological phenomena, high rates of climb / descent, noise and the overflight of water. While already developed, the urban environment around the airport does not present any significantly high buildings, organised in such a way to originate phenomena like the canyon effect or turbulence. Additional studies will need to be conducted by professionals at the specific location chosen for the vertiport to account with the urban landscape. Still, the general area is judged not to affect the natural weather. Significant tall objects are also not observed, meaning high rates of climb / descent are not required for obstacle avoidance, even if eventually put in place to minimise the noise impact on the surroundings. Even if scarce, measurements of eVTOL noise have been conducted, as is the case of Joby's aircraft. According to NASA, Joby Aviation managed to develop an eVTOL that does not go above 65 dBA during take-off, when measured from 100 m (ground distance) [53]. Of course, this single case cannot be generalised to all eVTOL but does bring confidence that Volocopter also managed to minimise operational noise, a common goal of all developers. Additionally, being close to an airport, many constructions applied noise isolation measures, further diminishing noise perception when not on the streets. As such, even if concentrated on the vertiports, noise concerns are seen as properly minimised.

The direct route being considered does overfly water for a significant portion of the trip. An analysis of the answers showed that those more concerned with this aspect also mostly valued the time savings, compared with other means of transport. For the pretended route these aspects oppose each other. A detour to avoid water would increase the distance by a third, beyond the considered eVTOL range, having a similar impact on travel time. Unable to obtain a solution optimised for both aspects, trip time was given priority as it was the most important reason for choosing an air taxi.

Comfort with boarding operations in an open pad was expressed by respondents, reason why auxiliary buildings to individual gates may be waivered during layout design, being seen as optional. Also contributing to passenger comfort, ample means of access / egress are present, with a metro station right by terminal 1, various bus stops and multiple car parks.

With most pertinent concerns seen as properly addressed or minimised, a vertiport associated with Humberto Delgado Airport is considered to represent a suitable first implementation.

3.5 Vertiport Requirements

The idea of AAM and related studies predates the release of associated documentation by aviation authorities. Said works largely saw heliport requirement as a suitable proxy for eventual AAM vertiport layouts, presenting valuable contributions (as is the case of: [6], [13], [36], [38]), yet the point was reached where the uncertainties from using a proxy held back research.

As interest grew in AAM, aviation authorities found themselves in a conundrum. An understanding of eVTOLs and their operations was needed for the development of related legislation, yet data on the multitude of factors influencing the safety of operations could only be obtained by already functioning vertiports, going back to the need of legislation for their construction and closing the circle. As such, authorities worldwide published guidelines for vertiport design, pending case by case approval to get the ball rolling. Examples of said documents include the American FAA's version [27], European EASA's version [7] and Australian CASA's version [54]. The temporary nature of the references provided by these documents is openly declared, with revisions expected as data is collected from the implementations they make possible. As of the time of writing this work they are the most recent documentation on the matter, reason why, with Portugal being a member of the European Union, EASA's "Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category" [7] will be used for this work.

3.5.1 EASA Prototype Technical Specifications

While some components can be designed based on the eVTOL's geometry, most have their minimum dimensions expressed as a function of the diameter of the smallest circle capable of encompassing the aircraft, designated as D. In general the many components of a vertiport layout are to be designed in accordance with all eVTOL models they are to serve, which is to say, in accordance with the biggest D from among the expected eVTOL models. Additionally, operational choices may lead to either more strict or relaxed designs.

3.5.1.1 Touch-down and Lift-off

Just like for helicopters, when performing a take-off or touch-down, eVTOLs are to do so at a pad, capacitated to provide all necessary safety conditions. This element consists of three areas: TLOF, Final Approach and Take-off (FATO) and Safety Area (SA). All of these elements expand upon the other in accordance with the presented order, sharing the same circular, square or rectangular shape.

The TLOF represents the surface designed to bear the strengths experienced during the relevant operations, where the aircraft's undercarriage is supposed to touch the ground. The reference dimension for this component is 0.83D, increased to 1D should the vertiport be elevated. Expanding outwards is the FATO, with a length dimensioned in accordance with the rejected take-off distance or 1.5D, whichever is the biggest. The width follows similar criteria, with a minimum dimension expressed by either the rejected take-off distance or 1.5D, whichever is the biggest. The FATO provides an area free of obstacles for use on the final stage of approach or initial take-off. The final element is the SA, an obstacle-free zone in place to compensate for any manoeuvring errors during challenging conditions. The SA expands outwards from the FATO by either 3 m or 0.25D, considering the biggest among them. An important aspect of the SA is that it is not required to be solid, only free of obstacles. A representation of the last two components can be found in Figure 5.

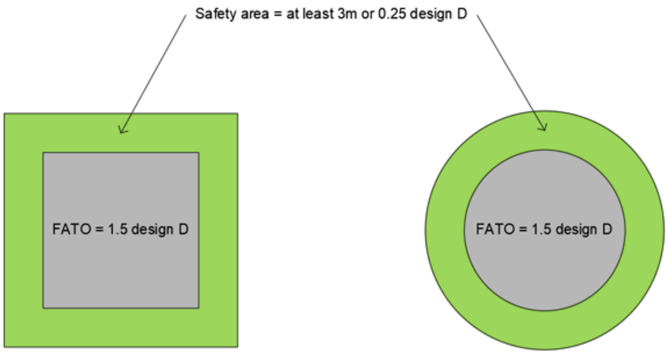


Figure 5 - FATO and associated SA. Source: [7]

Separation between active FATOs is an essential factor in vertiport design, being in place to allow simultaneous operations, however, lacking relevant data, a suggestion of a criteria for its determination was not made. EASA expects a safety analysis to be conducted to determine this design criteria considering downwash, operational performance and a requirement of non-overlapping flight paths. To facilitate this analysis, it was noted a separation of 60 m between FATOs is a prominent reference for heliports, considering MTOW inferior to 3 175 kg, establishing a good starting point.

3.5.1.2 Obstacle Environment

The subject of the obstacle environment was approached in EASA's document, which established the criteria for obstacle-free surfaces and volumes. They were, however, highly dependent on aircraft performance, based on which a category among the three presented was to be chosen, indicating minimum characteristics for the slope design. Not having access to such data, this work can only consider the stricter of these categories, a

4.5% slope, with its origin at the edge of the FATO's SA. The approach or take-off climb surface does not need to be straight, with the option of being curved often required to avoid high obstacles. Should the surface be curved, the performance and handling of the eVTOL are to be considered, avoiding undue passenger discomfort and undue noise in overpopulated areas.

Vertiports are expected to have at least two approach or take-off and climb surfaces, with a recommended separation of 135°, possibly more, under the goal of a usability factor of 95%. However, these criteria are sometimes not possible to achieve, which is why the separation may be reduced or even the number of approach and take-off and climb surfaces reduced to one under a favourable safety assessment.

3.5.1.3 Taxi Route

A taxiway intends to allow surface movement, be it self-propelled or by external equipment, of the aircraft, designed to accommodate the undercarriage width (UCW) of all aircraft it intends to serve. Its width should coincide with at least double the UCW or what is assessed as the dimension judged as sufficient to provide containment of the undercarriage for the most critical use cases, including taxi deviations.

Encompassing and expanding from the taxiway is the taxi route, intending to provide an obstacle free zone for safe taxiing, having a width of 1.5 times the aircraft width (equal to D for VoloCity) if designed for ground taxiing, or of 2 times the aircraft width if it permits air taxiing. A ground taxi route needs to be associated to a taxiway while an air taxi route does not, unless the possibility of both is desired.

3.5.1.4 Stand

The role of stands is to provide a proper environment for aircraft parking and servicing. If the loading and unloading of passengers or cargo is desired, a stand may be designated as a gate.

The stand's design needs to consider the aircraft it is to serve and its capabilities, such as turning (not in hover) or push-back, to implement the necessary safety distances for relevant operational procedures. Depending on the required procedures, EASA permits a smaller footprint in the form of a geometry based design, while a D based design option is still offered.

For a D based design, the minimum dimension is a circle with diameter 1.2D, associated to a PA. Said PA should expand outwards by 0.4D or another dimension in accordance with turning data from the aircraft flight manual (AFM), if turning is intended, or the necessary to achieve the width of the taxi route, should taxi-through be desired. This option is also compelling in case the stand coincides with a TLOF.

In both cases PAs do not need to be solid and can overlap as long as only one of the adjacent stands is active, while the other may contain static objects.

Geometry based stands restrict taxiing to the ground version and do not allow turning yet may present a space saving alternative to a D based design. Corresponding PA dimensions are tabled at page 39 from [7].

3.5.1.5 Separation Between FATO and Aerodrome Elements

For simultaneous operations between a FATO and an active aerodrome's runway or taxiway, a certain separation needs to be ensured to allow safe operations in both, free from mutual interference. Values for said separation are present in a table on page 45 from [7], ranging from 60 m to 250 m dependent on the maximum aircraft mass between the ones operated at all elements.

3.5.2 Initial Considerations

Designing a vertiport layout starts with understanding the physical dimensions and operational capabilities of the aircraft served by this infrastructure, alongside desired operational options, such as simultaneous use of adjacent gates. All of these impact the dimensioning and relative position of the various vertiport elements, as well as their numbers.

3.5.2.1 Vertiport Element Dimensions

The chosen reference for the eVTOL presents a D value of 11.3 m [51], that when inputted into the relations expressed previously, result in the dimension of the various vertiport elements presented in Table 3. As the eVTOL geometry was already circular, D based design was considered when applicable.

Table 3 - Vertiport elements dimensions for D=11.3m. Source: Own elaboration.

Component		**Relation (based on:[7])**	**Characteristic Dimension [m]**
Pad	TLOF	$1D\ (*)$	11.30
	FATO	$1.5D$	16.95
	SA	$FATO\ +\ 2(Biggest\ among\ 3m\ or\ 0.25D)$	22.95
Stand	Stand	$1.2D$	13.56
	PA	$Stand\ +\ 2 \times 0.4D$	22.60
Taxi Route	Width	$1.5 \times Aircraft\ Width\ (**)$	16.95
(*)	For an elevated vertiport (most strict case)		
(**)	Aircraft width equals D in this case (circular geometry)		
Note:	All elements have the outer diameter as the characteristic dimension, except for the taxi route, where it is its width		

3.5.2.2 Gates to TLOF Ratio

An important metric to consider during the layout design is the optimal gates to TLOF ratio, to better use the available space. While this ratio will be confirmed after simulating the layout, an initial reference is of value. A work by Parker D. Vascik and R. John Hansman [6] simulated multiple vertiport topologies under various operational times, in order to understand the correlations that influence throughput and the conditions that maximise it. Based on the results of the simulations, they then developed Equation 1, which represented the number of gates required to maximise the throughput of a TLOF as a function of turnaround time, take-off and landing times and taxi time. This relation is applicable when taxi to the TLOF is not done at the same time as take-off or landing operations, with the reason behind the choice of this relation rather than another that does, elaborated upon on the Vertiport Model chapter.

$$Gates\ Required = Ceiling\left(\frac{Turnaround\ Time}{max(Arrival\ Time, Departure\ Time) + Taxi\ Time}\right) + 1$$

Equation 1 - Optimal Gate to TLOF Ratio. Source: [6]

Both for use in the equation above and, predictively, for the simulation of the vertiport, the need for reference times was made obvious. As per Equation 1, the times required correspond to the operational segments of arrival, departure, turnaround and taxi.

For an aircraft with both passengers and cargo, turnaround can be said to be comprised of disembarking passengers, cargo and baggage handling, refuelling (in this case energy resupply), catering and cleaning services, maintenance checks and finally, boarding [55]. Depending on the operations some of the previous components may not apply. Should there only be hand baggage, cargo and baggage handling would either not be present or largely reduced, should the service provider not provide catering it would not need to be restocked, just as cleaning times, highly depend on the user's behaviour, may not even be required on every trip. Therefore, the turnaround time is more suitably depicted by a range of possible times rather than a singular one. Given the energy resupply method by battery change, such a component has no significant variations in time while being basically mandatory, providing a suitable lower bound, resulting in 5 min being considered as per the VoloCity's design specifications [51]. On the other hand, establishing the upper bound is a lot harder. To the many other components of turnaround time, previously listed, a significant variation is present, adding to the uncertainty of simultaneous realisation of some turnaround components and delays by the passengers themselves. Even if there is a history of helicopters acting as air taxis, the higher pace of operations aimed by eVTOLs prevents a comparison. To achieve the upper bound an additional 5 min are considered, taking into account all possible tasks to be carried out at the same time as the batteries change are done so, leaving these additional minutes for the required safety checks (ex: walk around) and possible delays, resulting in a considered maximum of 10 min.

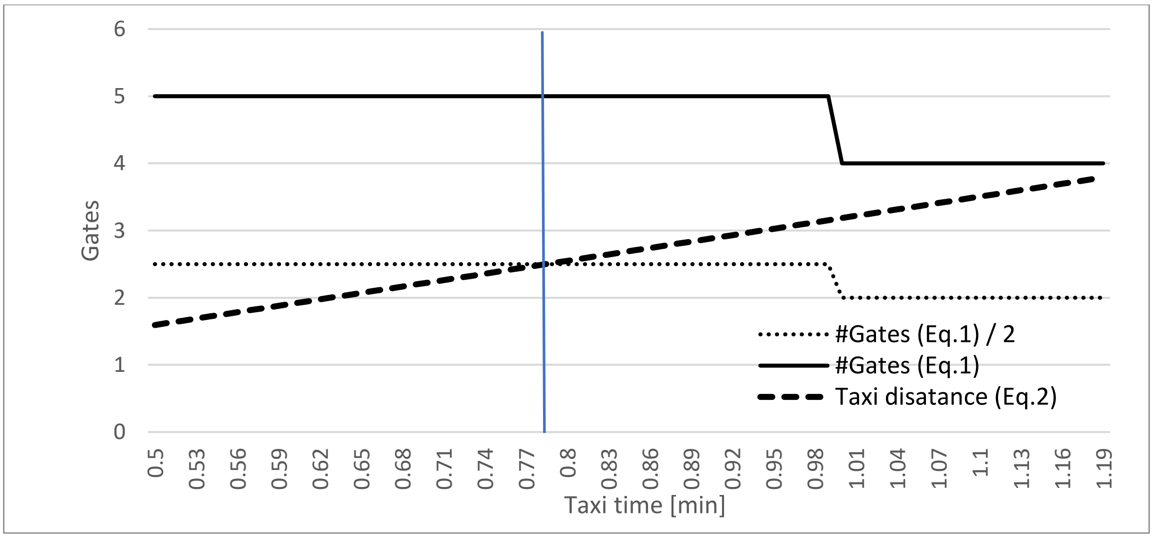
For the arrival and departure times a distance – speed method was initially considered, with the speed passible of parallelism with helicopters and the slope design details described on EASA Prototype Technical Specifications [7]. The problem lies with this last one, as while it is acceptable to consider the strictest out of the three possible slope design categories for obstacle analysis, the same cannot be said for determining the length of the slope. The decision of what category to consider, factoring the eVTOL capabilities, vertiport surroundings and the aircraft operator, cannot be emulated by this work. With lengths of the obstacle limitation surfaces ranging from 1 075 m (category B) to 3 386 m (category A), and a lack of reference of at which point of the slope approach / departure of the following aircraft may safely commence, a base for establishing the distance to consider is not present. As an alternative, an analysis of the test flights published by Volocopter, such as [56], was conducted, resulting in 1:30 min as a reference value for take-off. This time starts the moment the aircraft is in position for take-off, with the pilot having some time for the last in cockpit checks followed by motor startup and initial climb, stopping when the VoloCity is considered a safe distance away for TLOF use to be allowed by another aircraft. Considering the same criteria for when to start and end the counting of time, an equal time was obtained for the landing segment.

The last time pending a reference is the taxi time, once more better represented by a speed – distance relation, later applied on a case by case for the simulation (Survey Questions), yet not applicable for the current stage as vertiport elements disposition highly impacts the averaged taxied distance. Considering the many possible design philosophies for the layout like linear and pier [6] or perimeter and central [57] a bias for symmetry can be observed, being easier to implement and operate infrastructures with this characteristic. For that reason, to obtain this gates to TLOF reference ratio, it is considered the average taxi time corresponds to a length of about half the total number of gates (with non overlapping PAs). To apply this methodology, the required information shifts to the taxi speed rather than taxi time. Seeking such a value and considering the limited space available for the vertiport, even if by conversion of already present buildings, hover taxi is not seen as justifiable for the distances predicted to be required, outside other concerns like disturbance of other gates and personnel, the reason why the sought value corresponds to ground taxi speed. Once again, helicopters represent the most credible source of information, with subject matter interviews made by Zelinski [57] pointing out the ground taxi speed of helicopters as about 2.7 mph ($\sim 1.2\ m/s$). With this value, taxi distance in gates can be obtained as a function of taxi time, as per Equation 2.

$$Taxi\ distance_{gates} = \frac{Taxi\ speed\ \times Taxi\ time}{Gate\ length} = \frac{1.2 \times Taxi\ time_{seconds}}{22.6}$$

Equation 2 - Average taxi distance in Gates. Source: Own elaboration.

The number of gates required to maximise utilisation of a TLOF was thereafter obtained by interpretation of Graph 2, which plots Equation 1, its half and Equation 2 as a function of average taxi time. The average between the upper and lower bound was considered for the turnaround time, corresponding to 7.5 min.



Graph 2 – Gates per TLOF in function of average taxi speed. Source: Own elaboration.

Considering our criteria of initially fixing the average taxi time as enough to taxi by half the corresponding gates, such time can then be fixed as about 0.79 min. Lastly, having all variables of Equation 1 “fixed”, the reference ratio of 5 gates per TLOF can be obtained.

3.6 Vertiport Recommendation

At its most simple division, designing a vertiport requires two major choices: the location for the vertiport and the layout to implement on said location. Both are interdependent and need to be made considering the other, even if the location needs to be fixed before the layout design can begin. Such is the case, as the connection between the two is mainly derived from the surrounding environment and geometry / dimensions of the project area. Therefore, the next sub-chapter ponders over the location to consider while using criteria containing future layout concerns and previously obtained references, later further elaborated.

3.6.1 Location Choice

3.6.1.1 Choice Criteria

As part of the decision over where to consider the vertiport, the requirements / preferences based on which to judge possible locations had to be established, those being grouped by their nature as area, surroundings and accessibility.

The area group encompasses the plot’s area, geometry and suitability for construction / conversion. In terms of area, a minimum value was established for initial selection, in accordance with the Vertiport Element Dimensions and reference gates to TLOF ratio of 5, resulting in 2419 m² (1 FATO + 5 gates, all with the corresponding PAs), a value that remains as a reference as taxiways and arrangement of elements do mean the real value is significantly bigger. Non mandatory extras, but of great benefit to operations, also take additional space as is the case of stands and dedicated logistics space. Additionally, the geometry of the plot should be as conducive as possible to accommodate the intended vertiport elements under logical arrangements for operations. Suitability for construction / conversion can represent characteristics such as clean terrain, already levelled and public ownership.

The surroundings category evaluates the exposure of the surroundings to unfavourable factors (noise and downwash) and suitability to establish flight paths by evaluating the obstacle environment. Measurements by NASA on Joby Aviation’s eVTOL verified levels of 65dBA, an acceptable noise level, at a ground distance of 100 m during one of the most noise intensive operational segments, the take-off [53]. Being a value related to another eVTOL than the one referenced in this work, conclusions cannot be taken, but it does substantiate confidence on a target separation of around 100 m. Additionally, low altitude overflight of certain public areas, such as sidewalks and roads is to be avoided at all costs, as anything but a faint exposure of the public to downwash can invalidate the project. As per the CAA, many eVTOL projects have significantly higher disk loading than an equivalent weight helicopter, representing a much higher (in some cases up to four times) downwash and respective outwash, as disk loading is a primary factor behind this phenomenon [58]. Finally, obstacle conditions for approach and take-off and climb surfaces need to be in place, resulting in an obstacle environment analysis. For said analysis, a dataset provided by Centro de Informação Urbana de Lisboa (CIUL) [59], containing geolocation information of buildings, respective height and altitude of the terrain they stand on was used.

Accessibility refers to the ease of access / egress to / from the vertiport, of high relevance because of the last mile problem, as confirmed by the Public Survey. Other means of public transport will be assessed favourably if the respective stations are close to the location or in the presence of parking in case of personal vehicles.

3.6.1.2 Candidate Ponderation

Based on the previously defined criteria, an analysis of the area surrounding terminal 1, using satellite imagery and an on-site visit, revealed three locations, represented below (Figure 6), suitable for detailed consideration: Parking 6 (rooftop) (P6), Parking 3 (P3) and Parking 8 (P8).

Figure 6 - Vertiport location candidates. Source: Own elaboration.

3.6.1.2.1 Area

All candidates satisfy the reference area, with P6 having around 6 770 m^2, P3 having around 17 416 m^2, and P8 having around 30 720 m2. This is more than enough to accommodate suitably connecting taxiways and support infrastructure, maybe even partially remaining as parking for the passengers' vehicles.

Differences between candidates start appearing when looking at the suitability of the geometry. P6, located on a mostly rectangular shaped rooftop provides no bottleneck for the arrangement of the vertiport elements with a foreseeable high rate of space utilisation, even if presenting the least spare space. Mitigating this aspect, SAs and PAs do not need to be solid, permitting more lax minimum width requirements for each section. Despite not having a squarish shape, P3 still manages to compare to P6 just with its northern section, the problem being utilising the southern section, having a connection with limited width (for an eVTOL), but enough for support infrastructure, even if somewhat out of the way from the main block. Lastly, P8 presents the most challenging geometry, with the northern segment wide enough for a gate and taxiway but all other segments too irregular in shape and / or far from the main (northern) block to allow smooth operations.

Lastly, regarding suitability for conversion, P6 and P3 stand on roughly equal ground. P6 is mostly flat, with only the connections to the lower floor needing attention, while P3 represents an already flattened terrain to the point of being uneven with the surroundings. On the other hand, P8 is significantly uneven, with the northern segment being on a slight incline exacerbated as it goes around the small hill in the other segments, needing the most work of the considered candidates.

3.6.1.2.2 Surroundings

In terms of downwash exposition from operating aircraft to the surrounding public paths (sidewalks and roads), none of the options is without faults. In this case, P3 and P8 stand on equal ground, either at or close to the same level as the public paths going right by their respective outlines, significant downwash speeds are to be expected, presenting a source for pushback by the community. That said, despite the increasing availability of data related to eVTOL operations, downwash data remains elusive to the public domain, making a proper judgement on this matter highly dependent on appropriate measurements. Still, CAA’s study [58] does indicate this matter is much more of a concern to eVTOLs than it is for helicopters, leading to a more cautious approach. On the other hand, while also overflying public paths close to TLOF operations, the initial height of the rooftop of P6 does provide a significant mitigating factor to the subject of downwash, even if it still requires further study when possible.

Another make or break factor, confirmed by the Public Survey Results, is noise. The same logic process applies to downwash and similarly applies to noise, except for how these phenomena propagate. In general, the presupposed fact that more distancing is preferable to diminish public exposure remains, leading to similar conclusions. Both P3 and P8 are expected to be disadvantaged in relation to this factor on account of their proximity to the public. Once again, a small advantage that by no means solves this issue can be considered for P6, from being on the second floor. Additionally, should the FATO be positioned on the western limit of P6, a distance of about 90 m can be achieved to the closest building, not reaching the reference of 100 m. However, that value was obtained for an open field, not considering the walls that exist in this scenario. Specific studies are once again required to judge this matter properly.

Lastly, the surrounding airspace must be assessed, checking for obstacles to possible flight paths. Regarding limitation surfaces, EASA [7] contemplates slopes ranging from 4.5% to 12.5% originating from the edge of the FATO's SA or clearway when applicable (take-off climb surface). While this last case is of interest by considering an initial height above the FATO, because it is not applicable to the approach, such extra elevation will not be considered forward. The slopes vary both in length and climb ratio yet share the goal of reaching a height of 152 m above the FATO. The obstacle environment will be analysed using a dataset provided by CIUL [59], containing the terrain's altitude and the height of the building itself, the sum of which results in the altitude of the building's roof. Unfortunately, the dataset did not include the parkings being studied, which is why their data had to be either obtained from other sources or estimated in relation to a known point. For P3 and P8, the terrain altitude that coincides with an associated vertiport was obtained using Google Earth. As for P6, needing to take the building into account, the difference in height to a neighbouring building (Meliá Hotel) was obtained considering photographic proportions from an on-site visit. The difference can then be subtracted from the roof's altitude of the Meliá Hotel (present on CIUL's dataset) to reach the altitude of P6's rooftop. The obtained data is presented in Table 4.

Table 4 - Altitude information of the vertiport location candidates. Source: Own elaboration.

Location	FATO's altitude [m]
P6	85.99
P3	86.94
P8	89.87

On the images below, referenced on the next paragraphs, the candidate locations are shown as orange. The elements of the dataset are displayed purple with those who surpass the respective absolute height coloured yellow.

Considering P6, there were 1 743 data points among the dataset, presented in Figure 7, with an absolute height above 85.99 m. The number of such buildings in the immediate surroundings of P6 leaves few options for possible flight paths, either towards the northeast (NE) or south (S). Observing Figure 7, it can be concluded flight paths are possible yet require a curved section after which a clear expanse free of obstacles can be seen in the direction of the Tejo river, and beyond to the new airport.

For P3, there were 1 657 data points with an absolute height above 86.94 m, presented in Figure 8. It faces a situation extremely similar to P6, even if not needing a curved flight path, having the possibility of going straight east with only a few obstacles in the immediate surroundings.

Standing the highest, P8 also has the least identified obstacles, with 1437 data points with an absolute height above 89.87 m, shown in Figure 9. A flight path is possible towards the northeast (NE) direction, needing a slight curvature through the biggest opening between obstacles out of the candidates, after which there are no obstacles to note.

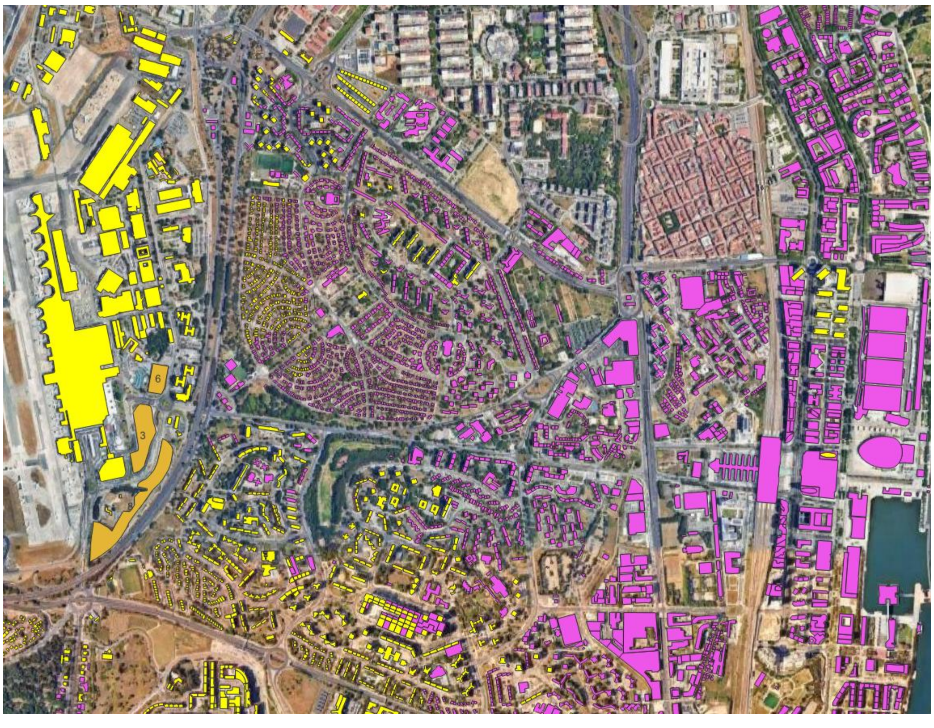


Figure 7 - Buildings that breach 85.99 m. Source: Own elaboration.

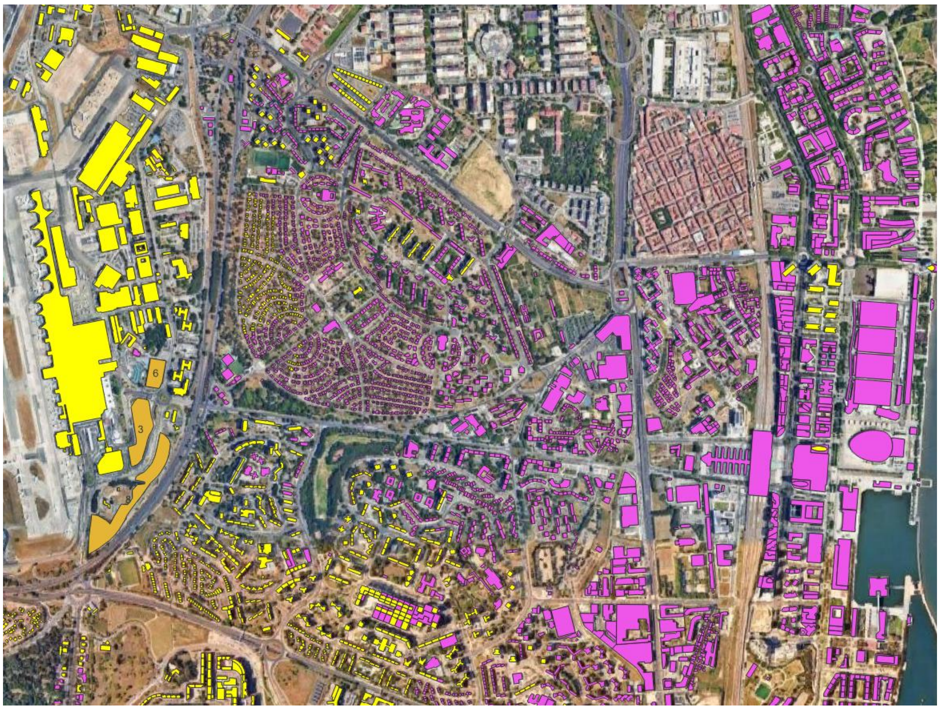


Figure 8 - Buildings that breach 86.94 m. Source: Own elaboration.

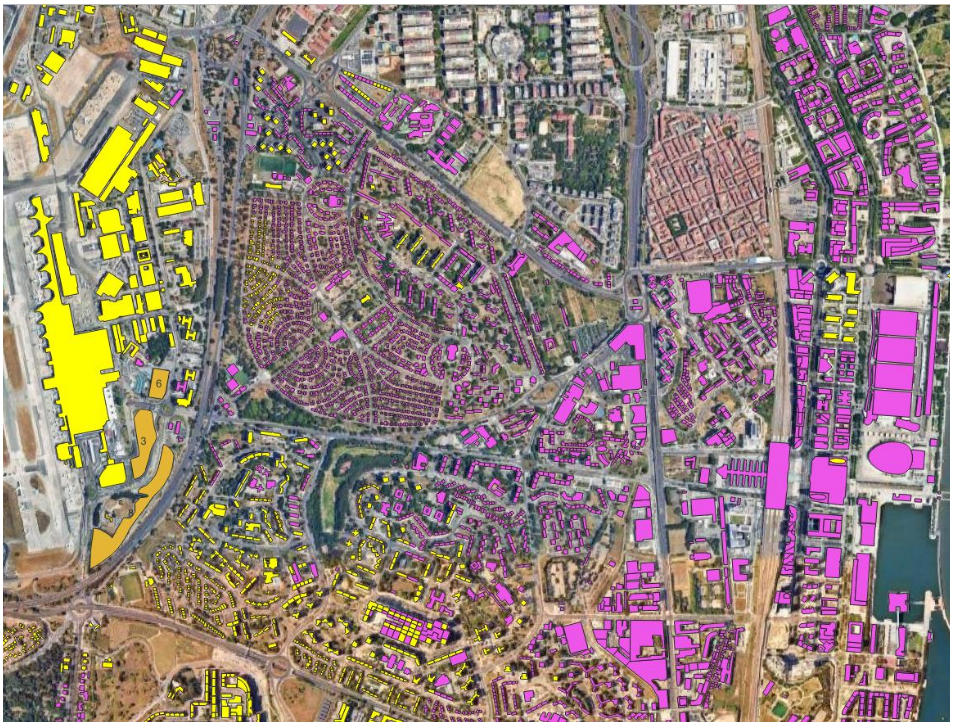


Figure 9 - Buildings that breach 89.87 m. Source: Own elaboration.

3.6.1.2.3 Accessibility

All options are within walking distance of the airport terminal 1, the main transport hub the vertiport is expected to serve. Parking 3 stands closest, with two exits but a crosswalk away from the terminal, which is the option with the best accessibility. Slightly further are P6 and P8, with P6 only needing an additional small walk, around the same as P8 by the northern exit (inclusively going through P3). P8 also has a southern exit, requiring a perfectly walkable distance, even if the furthest of the ones so far touched upon.

Standing close to Lisbon's airport main terminal, stops for both main public transport networks, bus and metro, are already present close by, making the vertiport attractive for travellers going beyond the airport. That said, it is important to note that should a vertiport be implemented, bus stops and routes could easily be added / changed to support this new infrastructure, while the same does not happen for the metro. Metro accessibility considerations are equivalent to the access to terminal 1, as the metro exit was specifically built to serve the terminal.

The main bus stops are shown in Figure 10. One stop is associated with P6 and another to P3 while also being close enough to serve P6. Two stops stand closer to the airport terminal, P8 can use these stops but is significantly further from them than the other alternatives.

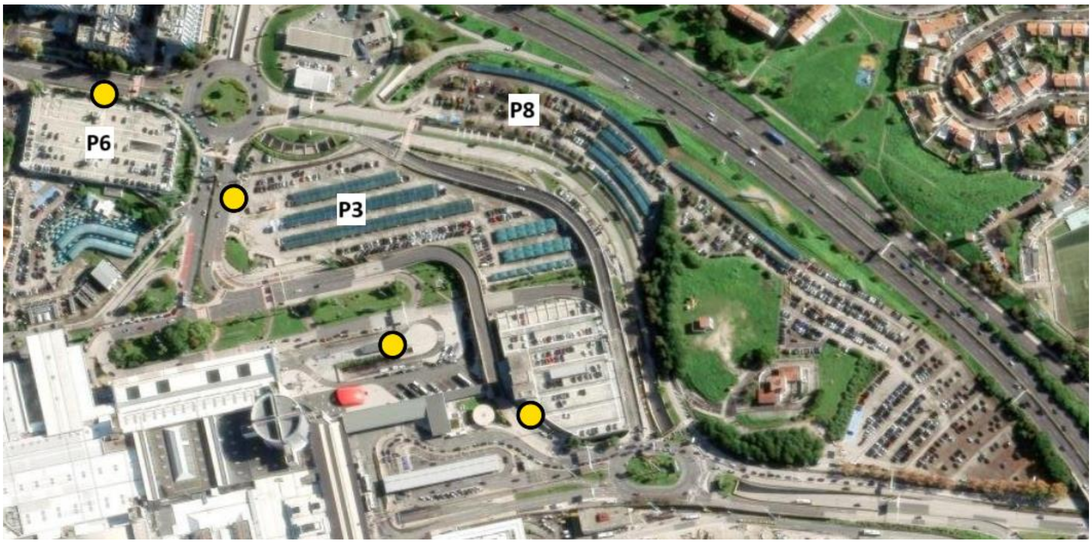


Figure 10 - Bus stops. A mark may combine both directions. Source: [60]

Lastly, parking for a personal vehicle could also be provided on site at P6 and P8, with P6 still having the ground floor available and P8 having a large area unfit for the vertiport but already serving as parking. As for P3, maintaining the current parking spots is not viable should a vertiport be implemented there, being unable to provide separation and protection from the air operations. That said, standing right by the other parkings, they would remain a viable option for customers seeking to use the vertiport.

3.6.1.3 Chosen Location

Seeking an appropriate first implementation, the decision was made to consider P6 for the rest of this work. The weight attributed to each category was largely based on the importance for a successful implementation, resulting in the considerations made on the impact on the public being highly valued. Should the vertiport not be in line with the people, it would not succeed. Being the best on such considerations, alongside a balanced performance on the remaining ones, P6 was judged as having the biggest chance of success amongst the studied locations for an initial vertiport implementation.

3.6.2 Layout

Considerations beyond the characteristics of the various elements already presented at Vertiport Element Dimensions, have to be made in order to design the vertiport layout. As the considered energy resupply method is battery swapping, time spent on turnaround is relatively low, making simultaneous use of adjacent gates / stands a valuable operational option under the trade-off of non-overlapping PAs. Additionally, while said PAs do not need to be solid, in consideration of the public below and the lack of need for the respective space, the components not overlapping with P6's roof were minimised. The flight path directed north was not the one considered in order to minimise the overflight of buildings while maximising the distance from them during approach and departure operations. As a result, the TLOF was aligned with the SW corner, a decision made to mitigate the effect of the closest buildings / obstacles, located north (Bengazil palace), east (hotels) and west (airport) of P6. The SE corner was also left empty due to the chosen flight path.

The gates were then arranged closest to the TLOF, minimising taxi times. In addition to the five gates, part of the remaining space was used for three additional stands. Aircraft seeking to land will not be paired with aircraft departing, making a buffer indispensable for dealing with this imbalance. In addition, they can play the role of backup gates, introducing a welcome redundancy.

During the Public Survey, open pad boarding was seen as acceptable by respondents, allowing the remaining space to be used for other supporting elements, of which a proper space for battery storage and recharging is mandatory. While not required as per current guidance material, security checks can tranquillise the public, being an option worthy of further thought. Should space on the rooftop not be sufficient, implementing these spaces on a part of the lower floor is also acceptable.

As a result of the considerations described above, the layout displayed in Figure 11 was achieved.

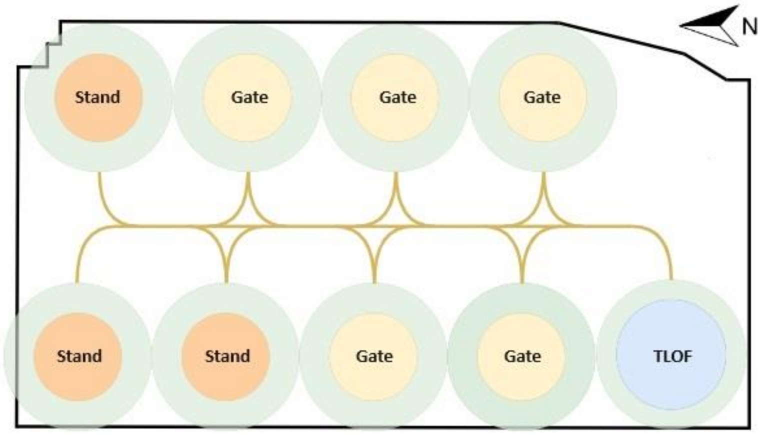


Figure 11 - Recommended layout. Source: Own elaboration.

3.7 Vertiport Simulation

Many assumptions and references were used to achieve the proposed layout, be it to validate them, obtain a more certain throughput value and understand the limiting factors, a simulation of this layout is of value.

Being unable to properly model the variability of operational time segments, the reference values obtained for these are mainly singular, resulting in the reference data being specifically suitable for DES. In DES, operations are modelled based on sequential events, mostly reduced to time delays [61]. The chosen software, Anylogic [40], goes beyond DES and also provides entity and resource management capabilities employing agent-based modelling (ABS) integrated into the simulation, avoiding the use of multiple softwares catered for each method and combining the best of both options [61].

Other abilities valued for this use case include the capability of inputting the layout, increasing realism for the simulation of the taxi segment by distance-speed time determination and the possibility of specifying non singular times (ex: uniform time distribution from 5 to 10 min), namely for depicting the impact of passenger delays on the turnaround time.

3.7.1 Vertiport Model

3.7.1.1 Model Elaboration

The elaboration of the model started by identifying the event sequence for the eVTOL, from the arrival at the vertiport to the departure, alongside the resource requirements to proceed at each stage. The simplest chain of events, consistent among air operations, consists of: landing / arrival, taxi to the gate, turnaround, taxi to pad and take-off / departure [38]. The relation between the previous elements can be visualised in Figure 12, which also shows components related to staging stands, even if outside the elaborated model.

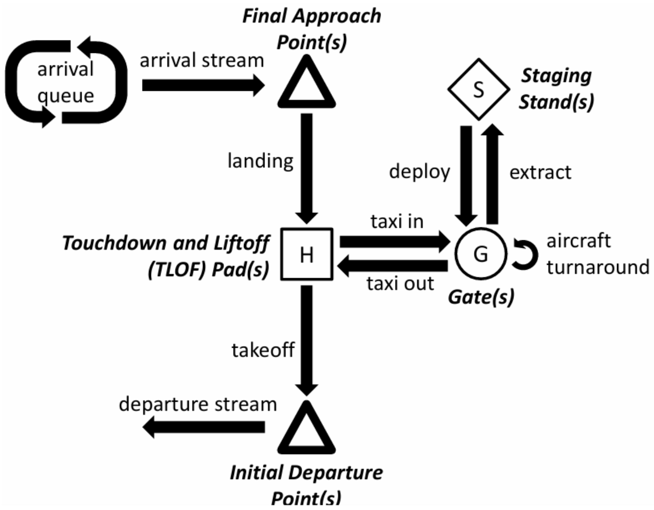


Figure 12 - Vertiport concept of operations. Source: [6]

As each step cannot be taken without ensuring the necessary resources (treated as Anylogic agents), such dependencies were also identified. For example, approach and landing cannot start without an available TLOF and gate, as the normal functioning of the vertiport would be compromised otherwise. Complementarily, for resources to be available to the following aircraft they need to be released when no longer necessary, just as the TLOF is no longer necessary when taxying to the gate, even if the gate remains required. As a result, the following list of events and intermediate resource management steps was elaborated, containing some simulation specific events:

- Source of eVTOLs – Creation of the eVTOL agent and its introduction to the model;
    - Simultaneous seizing of a TLOF and gate – Preparation for landing.
- Landing – Time delay representing approach and landing;
- Touch-down – Initiation of the positional layer of the simulation, assigning the eVTOL position as the TLOF;
    - Release of the TLOF;
- Taxi to gate – Time delay of duration determined by assigned TLOF to assigned Gate distance and stipulated taxi speed (1.2 m/s);

- Turnaround – Time delay between 5 min and 10 min as per a uniform distribution;
    - Seizing of a TLOF – Preparation for departure;
    - Release of the Gate – Only after all requirements for taxi to pad are guaranteed;
- Taxi to TLOF - Time delay of duration determined by Assigned Gate to Assigned TLOF distance and stipulated taxi speed (1.2 m/s);
- Take-off - Time delay representing take-off;
    - Release of the TLOF;
- Sink of eVTOLs – Deletion of the eVTOL agent, marking the end of the simulation path.

3.7.1.2 Model Considerations

There are many differences between aircraft seeking to land / take-off on a vertiport and the ones seeking to do so on a heliport or airport, preventing their use as proxies for the depiction of arrival scheduling and processing of operational requests [13]. In the absence of a proper model for the arrival and departure streams, on the basis of resource utilisation scheduling, both arriving and departing aircraft compete for the TLOF, leading to a deadlock. To prevent this from happening, arriving aircraft were required to seize both the TLOF and gate simultaneously, not one at a time, and should all gates be in use, departing aircraft were given priority in seizing the TLOF.

As any depiction of the arrival queue would be mostly baseless, the simulation considers it saturated, studying the most demanding scenario when the biggest throughput is expected. Therefore, the results are indicative of the maximum capacity for this layout. Lacking the necessary information and arrival demand variations, the decision process on when to extract or deploy an eVTOL from the staging stands could not be modelled, which is why, while present, staging stands fall outside the simulation. Being considered to play a role of normalisation for unbalanced arrivals and departures, fulcral to the operation of the vertiport under realistic conditions, stands have a marginal impact on throughput values [6], making the presented results still representative of real operations. Another operational decision not implemented on this model was the pre-staging of aircraft near the TLOF in case of successive take-offs, once again lacking the necessary data to identify the moments it would be of benefit and model its use.

3.7.2 Simulation Results

Various simulations were conducted to assess the proposed layout's performance and verify the optimal gates to TLOF ratio at its base. Sufficient simulation time was allowed for the measured metrics to stabilise before the respective values were noted down.

Variations in the inputted variables were not made, being inputted the values sought and justified during the calculation of the Gates to TLOF Ratio. What changed between simulations was the number of active gates, in such a way the ones active were also the closest to the TLOF, achieving numbers above 5 by considering stands as gates. The results are shown below in Table 5.

Table 5 - Simulation results. Source: Own elaboration.

Active Gates	Aircraft served [hourly]	Movements [hourly]	Wait to depart [min]	TLOF utilisation	Gates utilisation
3	14.157	28.314	0.91	0.86	0.83
4	16.109	32.218	2.93	1.00	0.85
5	15.966	31.932	6.73	1.00	0.88
6	15.607	31.214	10.83	1.00	0.90

The table contains data related to the maximum number of aircraft the proposed layout can serve, the corresponding number of movements (take-offs and landings) and utilisation of the resources (TLOF and gates), a metric that represents the average part of the resource pool associated to an eVTOL, different from time spent being used. The last metric, “wait to depart", represents the simulation bottleneck, where aircraft that had finished the turnaround were waiting for TLOF availability to depart.

Analysing the results, maximum throughput was achieved for the simulation with only 4 gates, slightly beating the configuration with 5 gates. As going either higher than 5 gates or lower than 4 negatively impacted the throughput, the only cases being compared are for 4 and 5 gates. For both cases, the TLOF utilisation was of 1, meaning they were limited by that component, reason why the use of one more gate resulted in a longer waiting time to depart (after turnaround), from 2.93 min (4 gates) to 6.73 min (5 gates), without any meaningful variations of the other metrics. The results of the work by Parker D. Vascik and R. John Hansman [6], behind Equation 1, can be defended based on intangible benefits. While the extra stands can serve as gates should the need arise, having a properly equipped gate from the get-go brings a more preferred type of redundancy and operational margin for error. Further optimisations are also still possible, namely in resource attribution, a component where sub-optimal results were noted during simulations. It is for these reasons the proposed layout remains with 5 gates.

The configuration, recommended and presented in Figure 11, operating eVTOL of the discussed characteristics, could serve about 15.966 aircraft per hour, representing an astonishing 31.932 movements per hour. Currently, before fully autonomous operations, each aircraft can only take one passenger, meaning the number of aircraft served is equal to the number of passengers served.

3.8 Conclusion

Starting by exposing the context around the theoretical development of this vertiport, the characteristics of the eVTOL to consider were chosen per the identified needs. Shedding some additional light on the vertiport's context, a public survey was conducted to better understand the more important points to consider, both to improve the user experience and limit the discomfort of non-users within the operational area.

Before decisions on the location and respective layout could be made, the closest document to eventual regulations was analysed, with the more relevant points summarised. Based on these, calculations were made by applying the mentioned criteria to the eVTOL's characteristics. Additionally, an important ratio for the vertiport's layout design was obtained during a step where the secrecy still encompassing both vertiport and eVTOL development was largely felt.

Based partially on the information obtained so far, the criteria for the choice of location were laid out and used to evaluate the candidate locations. A decision was then made, with public impact having the most weight. Fulfilling the most possible prerequisites, the layout design process was started, with the decisions and respective considerations properly explained.

Having achieved a layout, the basis for its evaluation and validation lies in the operational performance. To obtain such data and confirm the assumptions behind the layout design, a model of the operations was developed and used to simulate the recommended layout, with the results analysed.

As such, the process for a vertiport implementation was carried out within current limitations on data availability, with the layout's performance validated. The evaluation of the vertiport in the context of Lisbon's future will be carried out in the next chapter.

Chapter 4

4 Result Analysis

4.1 Introduction

The main goal of this chapter is to assess the potential of the proposed vertiport implementation to connect the current and future airports associated with the city of Lisbon.

To do so, not only will the adequacy of the throughput be assessed by calculating the percentage of Airport Humberto Delgado's passengers the vertiport can accommodate, but also how this solution compares against other more conventional transport options, were they chosen to connect Humberto Delgado to Luis de Camões.

4.2 Public Survey

Some key takeouts from the survey are:

- Of the respondents, 21.7% were completely unaware of UAM, 60.1% had superficial knowledge and 18.2% had advanced knowledge;
- A significant percentage of the public (49.8%) showed a positive stand on trying an air taxi service based on eVTOLs;
- A positive relation was observed between knowledge of AAM and willingness to use the service in study;
- The biggest benefits driving prospective users are time savings, increased safety (based on aeronautical standards) and novelty of the experience;
- The more relevant reasons keeping people from being users are the expected cost, the inability to serve the full customer's trip and a feeling of insecurity;
- The top 3 vertiport placement locations, in terms of favour by the public, are existing heliports, major focuses of people (combination of transport hub and point of interest) and parking lots;
- Homeowners valued the proximity to the service (as potential users), the valorisation of their property and the associated increase in the availability of other means of transport;
- On the other hand, noise and visual pollution, disturbance of comfort by close flights and insecurity over possible accidents proved to be the biggest points sustaining opposition to a vertiport implementation.

The conducted survey showed results largely in line with other similar endeavours by other authors ([9], [23]). With them as a basis and the verified relations, it can be concluded that there is a lack of public relations efforts by eVTOL companies in Portugal. Two presented contrasts need to be mediated to achieve long-term success: the number of respondents willing to try an eVTOL air taxi with concerns as a user of cost and the benefits brought to the areas around vertiports with the degradation of quality of life bared by the residents. The first is relevant to foster recurring customers rather than one-time users, the foundation of economically stable operations. The latter influences the acceptance of the locals, balancing financial gain at the cost of quality of life not all are willing to take. Both cases stem from the combination of two factors: the general secrecy involving commercial UAM development and a lack of effort to spread information, allowing pessimistic views to guide public opinion and actions.

Humans are not logical, and no amount of scenario prediction gives the users the required level of trust in an autopilot for them to partake in a fully automated large scale operation. As such, the requirement for the presence of a human capable of breaking the programmed rules on standby behind the commands remains. This means that more than logic and ample preparation, a long-standing mental barrier needs to be broken to reach the intended operations under autopilot.

Logically, AAM's aim of launching a fully autonomous system should be perfectly reasonable for the general public because if it reaches the point of being openly available, it would have done so after complying with the daunting safety standards of aviation. Such standards would be even stricter than those in place with an on-board pilot. An understanding of all these fail-safes and controls behind aviation is one of the reasons why those with more information on AAM proved more willing to use the service when the opportunity presents itself, overcoming the intrinsic scepticism regarding the safety of eVTOLs, a factor with significant presence among respondents.

4.3 Recommended Vertiport

4.3.1 Throughput

As an infrastructure directly associated with and aimed at serving passengers of the Humberto Delgado Airport, an understanding of how many of the airport passengers the vertiport can process is an important metric to assess its capability to fulfil the intended purpose.

Consulting data published by Portugal's National Statistics Institute (INE) [62], during the peak tourism month of the summer (August, 2024), Lisbon's airport handled

3 387 994 passengers (disembarking + embarking). Such a number equates to an average of 109 290 daily passengers.

One of the conditions on the basis of the EASA guidance material [7], used to design the vertiport being analysed, is the limitation of operations to VFR conditions. As such, operating hours for the vertiport can be seen as equivalent to daylight hours, being considered the value of 13.613 H, an average for such data of August 2024 (based on data from [63]), when weather events impeding operations are very uncommon.

Based on the simulation the vertiport proved capable of handling 15.966 aircraft per hour, considering both a landing and take-off for each, representing one instance of disembarking and embarking. For the yet autonomous operations, with an on board pilot, the vertiport can therefore process 15.966 arriving passengers, plus another 15.966 departing passengers, resulting in a combined 31.932 processed passengers per hour. Considering the 13.613 H of operation per day, the vertiport is therefore projected to be able to serve 434.72 passengers per day during August. Lack of data related to how the eVTOLs handle adverse weather conditions and the unpredictability of the weather during more adverse months prevented a meaningful analysis of the whole year.

For the considered month, when operational conditions for the vertiport are more favourable and the airport presents a greater number of potential clients, the vertiport appears capable of absorbing 0.398% of the airport's daily traffic, which is expected to rise to 0.796% with fully autonomous operations. While this value may initially seem insufficient, when considered in light of the limited percentage of passengers seeking to commute from one airport to the other and not opting for other transport alternatives, the vertiport appears poised to handle the target demographic.

4.3.2 Other Considerations

The obtained solution is, however, highly variable depending on future factors and uncertainties. While the straight-line distance from the vertiport to the new airport's location is about 30 km, some deviations are plausible to be required depending on the airspace restrictions derived from Airport Luís de Camões' new runway. With an intended max airspeed of 110 km/h [51] and a cruise speed closer to 90 km/h [64], the intended trip should take around 20 minutes each way, not counting the landing and take-off.

The aircraft fleet can, therefore, be bigger than the storage of the vertiport can handle, creating the need for additional stands outside operating hours. With a location for such a use not addressed in this work, it represents an open problem. As seen by Humberto Delgado's case, the immediate surroundings of airports are highly sought after, making the surroundings of Luís de Camões' vertiport an unpopular candidate, especially for the expansive terrain needed, even if the area remains undeveloped.

Should UAM in Lisbon expand beyond the shuttle between airports use case, as studied in this work, the expansion of capacity in Humberto Delgado's area is a complex subject. In addition to the proposed vertiport, the other studied locations can accommodate vertiports of their own should they prove capable of overcoming their respective hurdles, as P6 would already be at its limit, resulting in a fragmented system with many associated complications. The biggest problem would be the saturation of the airspace, with the proximity of the locations standing against highly frequent landing or take-off operations in a relatively small area, funnelling aircraft into the same favoured flight path. The most promising expansion lies on the terrains currently used by Humberto Delgado Airport, which would naturally only be usable after the transition of airport activities to Luís de Camões Airport, presenting the most desirable blank slate for vertiport construction.

4.4 Other Means of Transportation

The more usual ground-based transports have the benefit of operating independently of weather and visibility conditions, allowing for 24 hour operations if required. However, they do so at the cost of other fragilities and obstacles, in addition to overall higher travel times.

One of the most used navigation services, Google Maps [65], estimates travel times from 35 to 55 min depending on the time of day (values for a Friday, Figure 13), not considering expected improvements to the road network, yet to be built, but also increased traffic congestion normal around landmarks. Current infrastructure already covers most of the path required, allowing for a fast implementation, but proves insufficient for already present needs due to the Tejo River crossing requirement, precisely the bottleneck behind the 20 min trip time variation along the day.

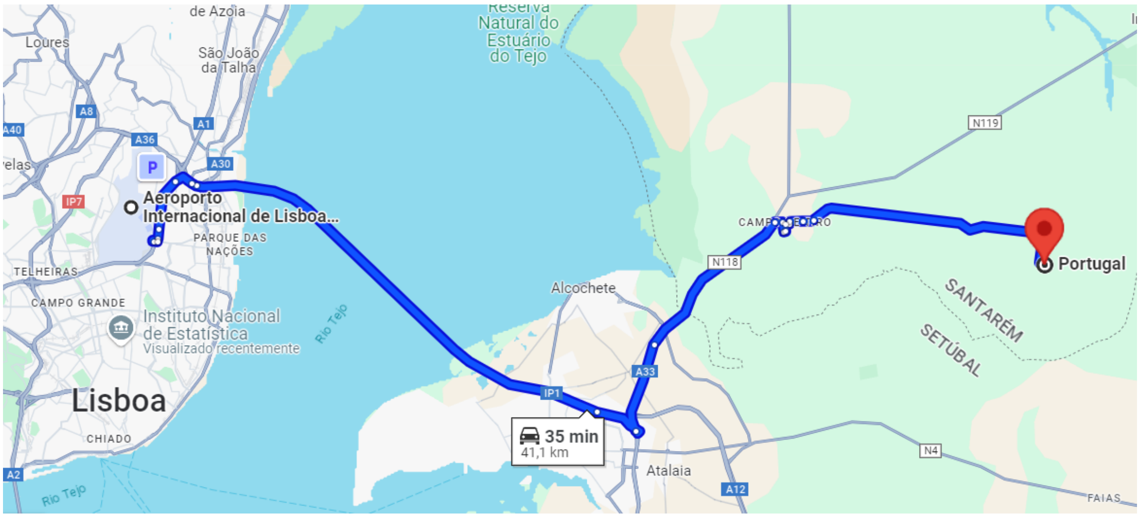


Figure 13 - Current road connection from Humberto Delgado Airport to intended Luís de Camões Airport location. Source: [65]

During VFR conductive hours, travel by eVTOL can provide ride time savings of 15 to 35 minutes, alongside extra comfort and enjoyment of the trip, representing a great choice for the individual passenger. However, to those seeking to travel in a group or to whom a lower fare is worth the sacrifices, a bus shuttle or even personal car presents a difficult proposition to beat. Besides allowing group travel, the general throughput of these solutions highly outperforms what the recommended vertiport can achieve, especially for the bus scenario.

The throughput values obtained for the vertiport consider the turnaround component, with a similar estimate not being done for the road vehicles. Yet even despite the associated error of not considering the turnaround, a normal taxi allows for 4 passengers to be transported, taking around 55 min at the worst case, with ratios even more against eVTOL if a bus is considered. That said, initial eVTOL users were always expected to emphasise the aspects where eVTOLs excel, namely speed and privacy until more passenger capacity and lower fares are achieved.

Backed by the long-established crown of more efficient transportation for high numbers of passengers, rail based solutions have much potential. There is, however, a significant flaw in the time and cost needed for implementation. The current rail network (Figure 14) presents no node close to the intended new airport location, making the required expansion efforts beyond significant and many years in the future. Even if the benefits may triumph against the significant upfront investment, just as the time required for the implementation, Luís de Camões also requires significant time to begin operations on a scale that generates demand justifying such transport means.

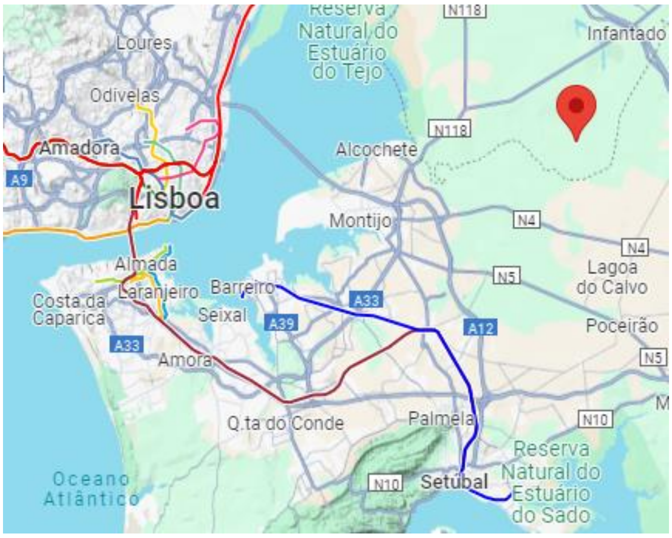


Figure 14 - Lisbon's Metropolitan Area rail network. Source: [65]

Joining the goal of a high-speed rail network connecting Lisbon and Madrid, a third bridge crossing the Tejo river is to be built [66]. Said bridge was already announced to contain both a road and train track component. In the end, for both cases, the construction of transport infrastructure like this one can significantly improve the efficacy of the transport methods by reinforcing the Tejo river crossing. On the other hand, eVTOLs' strength lies partially precisely in not being limited to a pre-built road / track and the immediate availability of the path it takes.

Another different requirement lies on the vehicle operators, be it in number, qualifications and remuneration. Comparing eVTOLs to road alternatives, in the case of cars, at most the driver needs a category B driver's license already common for personal use, foregoing specialised training. A more uncommon category D is required to upgrade the vehicle to a bus. There are drivers already with a D license looking to work, but even if the driving lessons and examinations need to be bored by the employer, the cost of doing so remains but a fraction of the pilot's license for the eVTOL that also comes with periodic revalidation training and examinations to be maintained. Trains also require specialised drivers, but the reduced number required to transport the same quantity of passengers once again makes the economics pend against eVTOLs. Lastly, applicable to both comparations, all staff related to the operations of aerial vehicles, in line with the more specialised and harder to transfer experience, seek higher compensation for their work.

4.5 Conclusion

The current chapter aimed at confronting the presented solution based on AAM, which uses a vertiport at Humberto Delgado Airport, with more conventional options for this particular scenario.

To achieve this, the main conclusions from the public survey were presented and discussed, aiming to emphasise the barriers identified by individuals in the way of a successful AAM implementation.

The adequacy of the recommended vertiport was then analysed in light of the expectations for an initial implementation, reliance on many yet undefined external factors and possible capabilities expansion, assuming AAM success.

Lastly, a comparison was made between AAM and the other more conventional transport options, touching on trip time, throughput, implementation time, and operator qualifications.

With the previous angles in mind, it can be concluded a vertiport associated with Humberto Delgado Airport is a suitable solution for the initial demand, while faltering upon either an increase of demand (possible in case of branching beyond the airport shuttle use) or completion of the infrastructure projects, aimed at making ground alternatives more compelling (third crossing over the Tejo river, train / underground line expansions). While improvements to AAM can be achieved during the many years such projects take to complete, it comes at a cost of the differentiation factor of quicker implementation time. As such, use of AAM in this case becomes hard to sell, having long term relevance dependent on uncertain improvements.

Chapter 5

5 Conclusion

5.1 Dissertation Synthesis

With technological advancements, efforts have been underway to make personal aerial transport a sensible option for regional / urban settings. Focusing on a new vehicle category, eVTOLs, designed with the present in mind, a future with shorter transport times and fewer traffic congestions, while fuelled by a green energy source, is sought.

After years of AAM development, this work aimed to assess whether a vertiport implementation would be aligned with the future of Lisbon's metropolitan area by going through 4 defined steps (Object and Objectives) to develop a vertiport. Despite the many limitations fought against, all objectives were achieved:

1. Identify public concerns, both as possible users and elements of the community surrounding the ground infrastructure;
2. Assess possible areas for a vertiport implementation, determining the most suitable location;
3. Development of an associated vertiport layout in accordance with design guidelines and public impact;
4. Assess the recommended layout under the context of the case of study.

After an introduction to AAM, the vehicles and infrastructure it is based on and what it seeks to improve, in chapter 2 (State of the Art), the preparations for (objectives 1 and 2) and actual vertiport design (objective 3) were carried out on chapter 3 (Case of Study).

Chapter 3 starts with a contextualisation of Humberto Delgado Airport's present and announced future, explaining the relevance of this endeavour. Of the many eVTOL projects, a model to reference is then chosen in preparation for objective 3. Directly addressing objective 1, a public survey was conducted and analysed, allowing for important conclusions to be considered in the following steps towards objectives 2 and 3, exploring both the point of view of users and of those around a vertiport implementation. Finishing the groundwork for objectives 2 and 3 the requirements present on current EASA guidance material are analysed and applied to the referenced eVTOL, alongside other initial considerations, seeking an optimal utilisation of the vertiport infrastructure. It was then possible to proceed with the location choice from amongst the identified candidates while pondering both design requirements and the mitigation of identified public concerns, ending with the selection of Parking 6 and achieving objective 2. Layout design could then commence, always with mitigating public concerns, resilience, operational requirements and EASA documentation in mind. Achieving a suitable layout for the chosen location, objective 3 can be seen as achieved. In preparation for objective 4, a simulation model is then developed and implemented to the recommended layout, resulting in the data required to judge it.

Having an idea of what performance to expect from a vertiport, chapter 4 (Result Analysis) directly addresses objective 4, revisiting the survey results, expressing the recommended vertiport's performance in light of Humberto Delgado Airport and how it faces against tried and true, ground based alternatives. To do so, transport times, throughput, implementation time and operator qualifications are considered. A conclusion spanning both the present and future prospects is then reached.

Chapter 5 (Conclusion) closes the dissertation by reviewing what was done and achieved, the restrictions found during the development of this work and opportunities for future research.

5.2 Limitations

Despite having achieved all proposed objectives, at various stages of this work the limitations imposed by a lack of real-world data can be felt, leading some aspects to either not be touched or developed only superficially. More than the secrecy derived from security concerns, the high competitiveness of the eVTOL market results on the companies reinforcing information control, with even the glimpses derived from publicity not divulging much information.

Despite the jump into practice already being felt as necessary, the current more conceptual stage remains, with information availability expected to increase after the transition. Encouraging such a move is part of the motivation behind this work.

The many eVTOL projects are exactly that, a promise for the future. Without the basis to seriously consider more eVTOL options, deriving a "worst case" D value around which to design the vertiport, making it less restrictive and more future proof, was not seen as justified for this work. Backing this point, after the development of chapter 3 (Case of Study), the company behind one of the projects considered during this work, Lilium, unfortunately filed for insolvency [67]. On the other hand, companies more secure in funding see less of a need to disclose information until the completion of their eVTOL projects.

Lacking a history of real-world operations, many points of view pertaining to subjects such as safety, piloting (manual, from a distance and autonomous) and the economy of a vertiport project, could not be exposed to respondents. As a result, the public survey became highly dependent on the individual respondent's preconceived image. Such an image is, however, not always based on facts, more often than not developed from either scepticism or the idealism around the fulfilment of the performance aimed at by developers. Both cases are not a safe representation of reality.

Adding to the limitations on the considerations while designing the vertiport, obtaining a realistic performance value for this infrastructure was not possible as there is no current basis for modulating customer demand and associated aircraft movements. As a result, a saturated queue had to be considered and dependent simulation of other components, the stands, had to be forsaken.

However, all the previous limitations are normal at the current stage of AAM development. Surpassing them is only possible with further advances and maintained interest in this concept, a trend favoured precisely by going around them and attempting to foresee what we stand to gain. Then, we can backtrack and redo the journey with greater detail, perfecting the process.

5.3 Recommendations for Future Research

As discussed in the previous subchapter, the process of projecting a vertiport still needs many improvements, which are derived from a deeper understanding of the steps taken in this work.

A study dedicated to unveiling the effects of eVTOL on the public, once again covering the point of view of those flying in them and those around operations, would greatly contribute to this subject. Besides a more detailed approach to the matter, understanding the effects of actual exposure to operations on public perception can point out the more urgent improvements required to either the aircraft or the associated infrastructure.

The great variety of eVTOL projects, under varied design philosophies, makes choosing a certain model a challenge in itself. A work comparing various metrics for models covering the many propulsion configurations and energy resupply options can become a great base for an initial selection of models worth individual analysis, under the context of the intended use case.

Following data collected on the various test flights and vertiport test beds, mentioned previously in subchapter 2.4.2 (Vertiports), a proposal for vertiport element dimensioning is of interest, based on actual operational data and possibly even dependent on certain eVTOL characteristics such as the propulsion configuration. Based on the same source, a perfected vertiport model would provide substantial confidence to vertiport proposals, increasing the chances of these becoming reality. Adding to the previous research topic, demand modelling / estimation is in itself worthy of specific research, having an impact not just on vertiport modelling but also on the associated economics.

Lastly, addressing the primary concern expressed by potential future users, as highlighted by the public survey conducted on this work, research related to the economics of AAM is still lacking, having yet to reach the stage of estimating user costs. To achieve such a value, a breakdown of both the economics of a fleet operator and a vertiport operator is inherently of interest.

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Appendix

A.1 Survey Questions

A.1.1 Introduction

Advanced Air Mobility – Air Taxi

Mudar de conta

Não partilhado

Technological evolutions allow for a future with the long dreamed of air taxis to be glimpsed upon in the horizon. To bring this concept to the light of day it is necessary to understand the perception and attitude of the public in relation to the changes in the cities and people, necessary to an implementation.

Even if Advanced Air Mobility covers both the transport of goods and passengers, this enquiry has as a goal understanding the various factors related only to the second case – passenger transport. More specifically, two points of view are to be studied, as a user and as a resident on the area of operations.

Answers are strictly confidential, and the resulting data will be used only for statistical results. In case of doubts, the author can be reached through the email: tiago.nave@ubi.pt

Souce: Lilium

A.1.2 Knowledge of the Concept

Knowledge of the Concept

What is Advanced Air Mobility (AAM)? It is a new vision for day to day transport, of both people and goods, now expanded to the air space!

Do cars already fly? Not being exactly a car, eVTOL vehicles are quite close to a "flying car", being more like a quiet electric helicopter. Their potential lies in the capability to land and take off vertically, necessary for use in the urban environment, while only producing noise comparable to a truck traversing a city.

What is a vertiport? Just like helicopters, even if capacitated to land / take off in any space with the necessary dimensions and load capacity, they are not necessarily legally authorised to do so. A dedicated space for such operations, maintenance and recharging is necessary for eVTOLs, being named vertiport.

A trip containing air taxis is, therefore, comprised of 3 segments: land transport to a vertiport, air transport to a second vertiport and finally land transport to the final destination.

Why Advanced Air Mobility rather than a normal car? The current momentum of this concept is due precisely to limitations felt mainly in road transport, especially in major population centres. Thanks to eVTOL vehicles it is possible to overfly traffic jams, on a more direct straight-line trajectory, under velocities comparable to the practised in motorways, releasing user's time and being potentially crucial in certain applications.

Source: Volocopter

What was your previous knowledge of the implementation of air taxis? *

- ◯ Total lack of knowledge
- ◯ Superficial knowledge / Little knowledge
- ◯ Advanced knowledge

A.1.3 Point of View of a User

Point of View of a User

The following questions should be answered from the point of view of a **USER**. The following points are also to be presumed:

- The aircraft is under total control by a trained pilot, also on board.
- The safety level is, at least, equal to the one of a car.
- Legislation was meticulously developed and validated.
- Authorities carried out all necessary inspections.

Questions are presented following previously selected options, about which an associated importance level may be requested. To express options outside the ones given, an open answer space is present at the end of the page.

Source: Mckinsey

What is your disposition to use an air taxi service? *

	1	2	3	4	5	
Very improbable	○	○	○	○	○	Very probable

How important would the following reasons be in your decision to **use** an air taxi? *

An importance of 1 can be considered “not pondered”, while 5 would be “decisive”.

	1	2	3	4	5
Reduce transportation time / Avoid traffic jams	○	○	○	○	○
Increased safety	○	○	○	○	○
Reduced environmental impact	○	○	○	○	○
Recreative reasons / Experience of flying in itself	○	○	○	○	○
Novelty of the experience	○	○	○	○	○
Status symbol	○	○	○	○	○

How important would the following reasons be in your decision to **oppose the use of air taxis?** *

An importance of 1 can be considered “not pondered”, while 5 would be “decisive”.

	1	2	3	4	5
Fear of flying / heights	○	○	○	○	○
Security worries (terrorism or sabotage)	○	○	○	○	○
Incapacity by the service of covering the totality of the trip (initial and final land component)	○	○	○	○	○
Cost	○	○	○	○	○
General feeling of insecurity	○	○	○	○	○

How significant are the following possible sources of stress / discomfort during the use of the service? *

A meaningfulness of 1 can be considered equivalent to "insignificant", while 5 would be "extremely significant".

	1	2	3	4	5
Proximity with buildings	○	○	○	○	○
Proximity with other aircraft (mid-flight)	○	○	○	○	○
Desnível significativo entre o local de aterragem / descolagem e o solo (ex: no telhado de um edifício)	○	○	○	○	○
Boarding procedures in open tarmac	○	○	○	○	○
Significant winds	○	○	○	○	○
Overflight of water	○	○	○	○	○
Elevated rates of climb / descent	○	○	○	○	○

In case a point of view of relevance was not present in the previous options it can be pointed out here.

Fill identifying the question, option and possible significance level if applicable.

A sua resposta

A.1.4 Point of View of a Resident

Point of View of a Resident

The following questions are to be answered from the point of view of a **resident** in the area of operations.

Questions are presented following previously selected options, about which an associated importance level may be requested. To express options outside the ones given, an open answer space is present at the end of the page.

Source: Lilium

Options for conversion or construction of vertiports are pointed out below. Which leaves you less apprehensive? *

	Totally disagree	Disagree	Indifferent	Agree	Totally agree
• Pre-existent heliport	○	○	○	○	○
Transport hub (ex: train station, airport)	○	○	○	○	○
Point of interest (ex: shopping centre)	○	○	○	○	○
Rooftop of generic building	○	○	○	○	○
Car parking lot	○	○	○	○	○
Water platforms	○	○	○	○	○

Which positive points would lead you to **support** the construction of a vertiport near your home?

- ☐ Intention to use the service
- ☐ Valorisation of the zone (as the owner)
- ☐ Expected increase in commercial activity
- ☐ Appreciation of the aircraft operations in the zone
- ☐ Increase in the frequency of associated transport means (ex: bus)
- ☐ (none of the above)

Which negative points would lead you to **oppose** the construction of a vertiport near your home?

- [ ] Lack of intention to use the service
- [ ] Exposition to factors like noise and visual pollution
- [ ] Increased concentration of people associated with the service
- [ ] Feeling of insecurity due to the risk of accidents
- [ ] Possibility of flights too close for comfort and tranquillity
- [ ] Negative impact on local fauna
- [ ] (none of the above)

In case a point of view of relevance was not present in the previous options it can be pointed out here.

Fill identifying the question, option and possible significance level if applicable.

A sua resposta

A.2 Paper Submitted to ICEUBI2024

Application of eVTOL aircraft in Advanced Air Mobility: Vertiport in Humberto Delgado Airport

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Abstract

Recent technological evolutions permitted the expansion of urban transport to a new dimension, in the airspace, originating the Advanced Air Mobility. The aim of this work is to understand the potential of a vertiport associated with Humberto Delgado Airport. Many challenges remain in order to implement a route, travelled by new eVTOL vehicles, in an industry that cannot compromise in strictness and safety. Prototype technical specifications have been released, but their transitional nature, alongside a lack of improvements to ATC and the many operational uncertainties bring doubt to the representativity of the models used so far. Seeking to minimise the impact of the previously mentioned factors, the steps for implementing a vertiport were taken while considering appropriate specifications, the impact on the public and obstacle environment of the airspace. Achieving a recommended layout, a model was developed aiming to predict its performance, possible bottlenecks and validate previous predictions. The many sources of uncertainty were pointed out alongside ponderations made in every decision. Results show that the lack of validation of claimed eVTOL capabilities, translated in rigorous EASA vertiport specifications, leads to few options for a vertiport associated with the airport. The achieved theoretical implementation is foreseen to be capable of serving only 0.74% of the hourly airport passenger traffic. Perhaps acceptable for an implementation seeking validation and public approval,

expansion of operations would only be possible with more relaxed requirements by authorities. Further research, targeted to the identified challenges is required to perfect this process, alongside issues not mentioned by this work such as the integration with the airport and approval by authorities beyond EASA.