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URBAN AIR MOBILITY: MODELLING THE FUTURE TRANSPORT SYSTEM

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ABSTRACT

The design of effective transport systems with suitable level of services is considered a key factor for meeting the requirements of our society. Many solutions have been tested to improve freight and passenger mobility services, and in the last decades they have been significantly supported by new high-tech solutions. Among these, the advances in the aviation field, particularly the development of electric flying vehicles – like Unmanned Aerial Vehicles (UAV) and electric vertical take-off and landing (eVTOL) vehicles – have suggested possible actions for setting Urban Air Mobility (UAM) services. UAM solutions would provide services for passengers, goods and emergencies and, particularly in large cities, could provide faster trips than ground ones.

Initial studies emphasized the potential of UAM solutions for reducing urban congestion, trip times, CO_2 and noise emissions – these latter depending on the electric engine technology. However, further analyses have showed that although ground mobility could benefit from integrated UAM services, however these latter not necessarily would produce such expected positive effects.

In any case, Air Cargo, Air Surveillance, Medical delivery, and, mainly for passenger transport, Air Taxi, Intercity flight and Airport Shuttle are among the expected aerial service opportunities. It is also expected that early UAM operations will be performed at Very Low-Level airspace as 0-500 m Above Ground Level.

As the aerial service would be realized in urbanized areas, to ensure safe and efficient operations it is necessary to redefine concepts for flight management in low controlled/uncontrolled airspace, which will support the implementation of transport networks using the third (vertical) dimension for allowing urban flights. Recently, several studies have focused on the development of urban aerial transport networks that will complement the existing urban ground transport networks. As an example, NASA has presented a Concept of Operations (ConOps) for managing Unmanned Aerial System (UAS) flight, by identifying the UAS Traffic Management (UTM) system, while in Europe the SESAR Joint Undertaking (SJU) is developing U-space concepts.

In the above perspective, the purpose of this research is to both explore the main features of urban aerial mobility and test a UAM aerial network model, which could be integrated in a multimodal transport system where ground and aerial mobility services are provided.

Analyses on transport systems generally focus on two sub-systems: (i) the transport demand sub-system, i.e., the mobility features and requirements, and (ii) the transport supply sub-system, i.e., the service and facilities enabling mobility. Then, the UAM transport system analysis has involved both the future UAM transport demand and the supply systems. As for the latter, an aerial network model, also tested on a small case study, has been proposed in this research.

In the first research step, the UAM demand has been investigated. Particularly, the demand features for an Airport Shuttle (AS) service have been explored by a suitable survey, which combines Revealed and Stated Preference methodologies. Apart from some statistical analyses, collected data have been used also to calibrate some discrete mode choice models in order to identify relevant features that would affect UAM demand levels.

In the second research step, the focus has been on the transport supply model for UAM services, by focusing on both the ground access points to UAM services (the so-called *vertiports*) and the aerial network model. Vertiport design and placement models and methods proposed in the literature have been analysed to explore capacity issues that could influence future UAM service implementation. In addition, the analyses have also focused on number and location of vertiports that would affect the transport demand. Furthermore, a suitable three-dimensional urban aerial network (3D-UAN) model that could support fast aerial connections between Origin/Destination (O/D) pairs has been proposed. The model intends to complement and improve dynamic corridor patterns – i.e., airspace volumes designated for flight using procedures whereby the size and time of applicability may differ according to air traffic needs – integrated with a multi-layer airspace structure. The feasibility of the proposed network model has been verified by implementing some tests. More in details, some flying vehicles supporting an AS service have been simulated on the aerial network, which has been specified in terms of both topological features and link transport costs. These preliminary results have showed that the proposed 3D-UAN model could be suitable for supporting UAM services. Particularly, the dynamic features of the network model fit well the flexibility requirements – linked to airspace restrictions and the heterogenous environment where the services will be introduced – of UAM systems. In addition, indirect CO_2 emissions linked to aerial vehicles (such as operational, disposal phase charges) have been computed to estimate potential environmental impacts based on the proposed UAN model.

Finally, in the last research step a digital twin model applied to an existing urban context – the city of Bologna, in Northern Italy – has been implemented in combination with the 3D-UAN model, by testing the overall UAM supply framework explored in this thesis.

To summarize, the UAM concept is fascinating several stakeholders and policy makers all over the world, and some preliminary experiments are in progress, which involves several societal and technological research fields. As for transport engineering, the UAM system framework proposed in this thesis paves the way for further research on air-ground multimodality in urban areas, which requires further analyses in terms of both ground and aerial transport supply and demand.

CONTENTS

ACRONIMYS

- 3D-UAN: Three-dimensional Urban Air Network
- AAM: Advanced Air Mobility
- AGL: Above Ground Level
- AS: Airport Shuttle
- ATC: Air Traffic Control
- ATM: Air Traffic Management
- AtoA: Affinity to Automation
- AV: Automated Vehicles
- BVLOS: Beyond Visual Line of Sight
- CA: Car Availability
- CAVs: Connected Autonomous Vehicles
- CNG: Compressed Natural Gas
- DAA: Detection and Avoidance
- DDC: Dynamic Delegated Corridor
- DEP: Distributed Electric Propulsion
- DTM: Digital Terrain Model
- EASA: European Aviation Safety Agency
- eVTOL: electric Vertical Take-Off and Landing
- FAA: Federal Aviation Administration
- FANET: Flying Ad-Hoc Networks
- FATO: Final Approach and Take-Off area
- FCFS: First-Come-First-Served
- FF: Frequent Flyer
- FV: Flying Vehicle
- GDP: Gross Domestic Product
- GIS: Geographic Information Systems
- HLP: Hub Location Problem
- IATA: International Air Transport Association
- ICAO: International Civil Aviation Organization
- ICT: Information and Communication Technology
- IP: Integer Programming
- ISPRA: Italian Institute for Environmental Protection and Research

- LPG: Liquefied Petroleum Gas
- MC: Monetary Cost
- MCTS: Monte Carlo Tree Search
- MD: Maximum Dimension
- MEC: Multi-access Edge Computing
- ML: Mixed Logit
- MMDP: Multi-Agent Message-Passing Decentralized
- MNL: Multinomial Logit
- O-D: Origin-Destination
- P: Privacy
- PC: Private Car
- POI: Points of Interest
- PT: Public Transport
- RP: Revealed Preference
- RP-C: RP Mode Choice
- RSS: Residual Sum of the Squares
- SJU: SESAR Joint Undertaking
- SP: Stated Preference
- TCL: Technical Capability Levels
- TLOF: Touchdown and Lift-Off area
- TR: Travel Reason
- TTS: Tip-to-Tip Span
- TTT: Total Travel Time
- UAM: Urban Air Mobility
- UAS: Unmanned Aerial System
- UAV: Unmanned Aerial Vehicles
- UTM: Unmanned Aircraft System Traffic Management
- V2I: Vehicle-to-Infrastructure
- V2V: Vehicle-to-Vehicle
- V2X: Vehicle-to-Everything
- VFR: Visual Flight Rules
- VLL: Very Low Level
- VLOS: Visual Line of Sight
- VOT: Value of Time

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CHAPTER 1 – INTRODUCTION ON UAM SYSTEMS

1. INTRODUCTION ON UAM SYSTEMS

The last decades have been characterized by a wide industrial development and an exponential growth of world population. It has been reported that the global population reached 8.0 billion in 2022, with an increment by almost 2 billion persons in the next 30 years (United Nations, 2022), which has both induced the further expansion of cities and raised mobility and infrastructure problems. Requirements of faster and high-performance transport services represents key aspects that transport systems are asked to satisfy. Technological advancements in telecommunications, electric and electronic fields have been used to improve the transport sector too, in order to optimize travel and waiting times, reduce congestion and fuel consumption (Rose et al. 2015). At the same time, advancements in the aviation industry – such as Distributed Electric Propulsion (DEP) – have helped designing new aircraft with improved aerodynamic performances and reduced energy consumption, emissions, noise, landing distance, and manoeuvrability.

The Urban Air Mobility (UAM) concept – or more generally Advanced Air Mobility (AAM) – provides a disruptive innovation not only to aviation but also to mobility systems and urban planning. It is expected to provide faster trips than ground ones, lower environmental emissions compared to traditional aviation, and enhanced connectivity to reshape urban living.

This dissertation contributes to the research and developments in the field of UAM systems and services, in order to understand to what extent they might integrate with the other existing transport systems.

1.1. Urban Air Mobility: overview on some main key elements

Urban Air Mobility is a recently proposed passenger and goods air mobility system that would involve "*safe and efficient air traffic operations in a metropolitan area for manned aircraft and unmanned aircraft systems*" (Thipphavong et al., 2018). UAM might be considered a realization of the more general Advanced Air Mobility, which includes many applications and functionalities – like mapping, traffic monitoring, infrastructure inspection, medical emergency (Sutheerakul et al., 2017; Besada et al, 2018; Hassanalian et al., 2017; Chappelle et al., 2018) – with the aim of making mobility safer and reliable – e.g., by reducing waiting and travel times (Volocopter, 2021), or extending intermodal transport well beyond high-density urban centres or surrounding areas (Andritsos et al., 2022).

Hereafter only the term UAM will be used, and it will identify the aerial transport system addressed to realize fast services for moving passengers and goods in urban areas.

Several factors affect the successful implementation of an operational and efficient UAM system. First of all, the ongoing progresses in electric and communication technologies paves the way to the UAM vision, driven by advanced aircraft development such as Unmanned Aerial Vehicles (UAV) and electric Vertical Take-off and Landing (eVTOL), which will operate specially in the Low Airspace. Compared to traditional airplanes and helicopters, these Flying Vehicles (FVs) are characterized by electric engines, and they are monitored by fast, closed-loop electronic controllers and sensors (Pavel, 2022). Mainly these aircraft are equipped with components that involve autonomous or remotely piloted flights, including the command, control and communications systems (Gupta et al., 2013) to cooperate each other and with ground control centre (Zhang et al., 2020). It is assumed that novel aircraft procedures will imply a Very Low Flight Level, i.e., a maximum altitude of 500 ft Above Ground Level (AGL). In this regard, a key challenge is the identification of appropriate regulations that would allow ruling procedures and flight management in uncontrolled low airspace, ensuring aviation safety standards. In this context, two centralized systems have been established: the Unmanned Aircraft System Traffic Management (UTM) in USA and the U-Space Concept in Europe to promote the development of smart, automated, interoperable traffic management solutions, by achieving high level of integration (Prevot et al., 2016; SESAR Joint Undertaking, 2017). Other early approaches aim to integrate and manage air traffic in low airspace by developing virtual multi-level structures or corridors (as air volume), where route management is directly realized by autonomous aircraft with onboard technologies, such as sense-and-avoid and high-precision localization systems for low-level (Yand and Wei, 2020; Dulchinos et al., 2022). The route guidance would be supported by algorithms (Sathyaraj et al., 2008; Zhang et al. 2020), also involving contingency management procedures and cooperative route planning (Krishnakumar et al., 2017).

The related regulations are currently being defined by the European Aviation Safety Agency (EASA) and the US Federal Aviation Administration (FAA). Particularly on airworthiness, a Special Condition to approve small VTOL aircraft operations have been published by EASA in July 2019 (EASA, 2019), then improved in 2020 with the Light Unmanned Aircraft Systems operating in medium risk situations (EASA, 2020), and in 2021 with the Guidelines on the design verification of UAV operating in the specific category (EASA, 2021). Then, the Agency has prepared a U-Space/UTM regulatory package (Regulation (EU) 2021/664, 2021/665 & 2021/666), which has started to be applied in early 2023, to assist the safe airspace integration of UAV operations in urban environment. Nevertheless, the UAM traffic management system is still under development and a proper structure that allows the efficient services performance has not yet been identified.

Besides, the take-off and landing operations of UAM vehicles require ground infrastructure, the so-called *vertiports* (Fadhil, 2018). The core issues related to ground infrastructure are placement and layout design. The current approaches to identify the suitable layouts and locations are based on existing models for heliport design “AC 150/5390-2C: Heliport Design” (FAA, 2012). Accordingly, the preliminary options for vertiports layout include linear, satellite, and pier topologies (Vascik and Hansman, 2019). To minimize impacts within the already dense metropolitan area, some strategic vertiport locations were identified on the rooftops, barges over water, inside highway cloverleafs, and on top of existing ground-transport infrastructures (Vascik and Hansman, 2017).

Some methodological approaches have been specified to determine suitable vertiport locations, such as the GIS approach (Fadhil, 2018; Delgado Gonzalez, 2020), the K-Means algorithm (Jeong et al., 2021) and the Hub-location problem approach (Chen et al., 2021; Rath and Chow, 2021). However, due to the novelty of UAM systems and its technological features, there are few publications on vertiport location and design and on the consequent effects on its capacity (Straubinger et al., 2020).

Finally, the successful introduction of UAM transport systems involves public acceptance and potential demand. Currently, the main users’ concerns are associated to safety, privacy, noise and environmental pollution (EASA, 2021), while some studies suggest that UAM could bring several benefits to society such as reduction of travel time, creation of new jobs and reduction of local environmental emissions (Holden and Goel, 2016; Porsche Consulting, 2018; EASA, 2021). Data collection for UAM demand estimation is a significant challenge due to the lack of historical data. However, the increasing market interest for UAM applications has driven researchers, to analyse the potential demand – both in terms of freight volume displaced and passengers willing to use these services – by using Stated Preference surveys (Brunelli et al. 2023; Al Haddad et al., 2020; Ahmed et al. 2021 Rifan et al., 2023; Gunady et al. 2022).

To summarize, UAM solutions require hypotheses, models and methods to identify the key elements that would allow the above factors are identified as the fundamentals to planning and integrating UAM services into existing ground and aerial transport systems (Figure 1.1.).

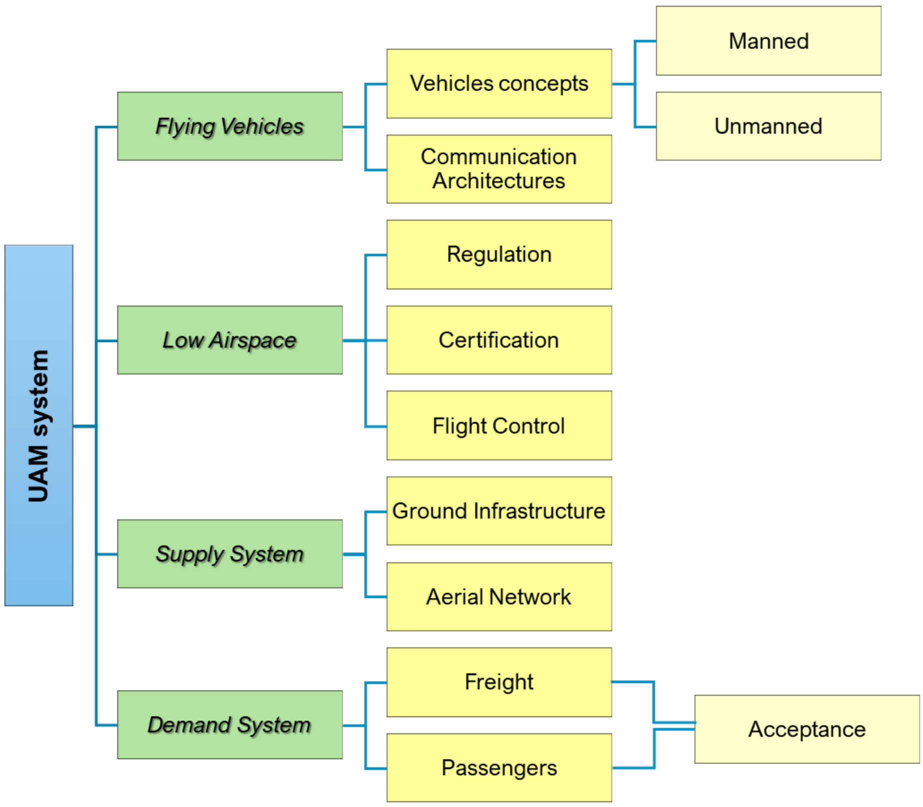

Figure 1.1. – Urban Air Mobility system elements.

1.2. Objectives and contribution

As well-known, a transport system is defined as the set of two sub-systems – transport demand and transport supply – where "transport demand" may be defined as the number of trips made by travellers or goods between different points of interest in a given area, and "transport supply" is represented by infrastructures and services (in addition to regulations) producing travel opportunities to satisfy the mobility needs (Cascetta, 2001).

Starting from the above concept of transport system, the aim of this research is to explore some aspects of the newly defined Urban Air Mobility system, both in terms of "demand" and "supply", by considering the key factors that characterizes it.

More in detail, this doctoral research aims to:

1. Identify the possible aerial operations in metropolitan contexts and the low airspace constraints, as well as to introduce the technologies involved to manage them.
2. Explore the future UAM passenger demand, in order to understand the main travellers' requirements.
3. Analyse issues related to the design of ground infrastructures (*vertiports*) that would ensure accessibility to UAM services.

4. Provide an aerial supply model by setting a 3D network structure including fundamental topological elements and link cost functions coherent with FV trips, which are thought to involve advanced connectivity and autonomous flight technologies, such as Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication architectures.
5. Estimate, preliminary, the aerial network model performances by simulating a UAM use case service and evaluating the FVs flow on the network.
6. Evaluate potential vertiport locations in real scenario, by considering a digital twin approach where both the 3D network model and the vertiport requirements are included.

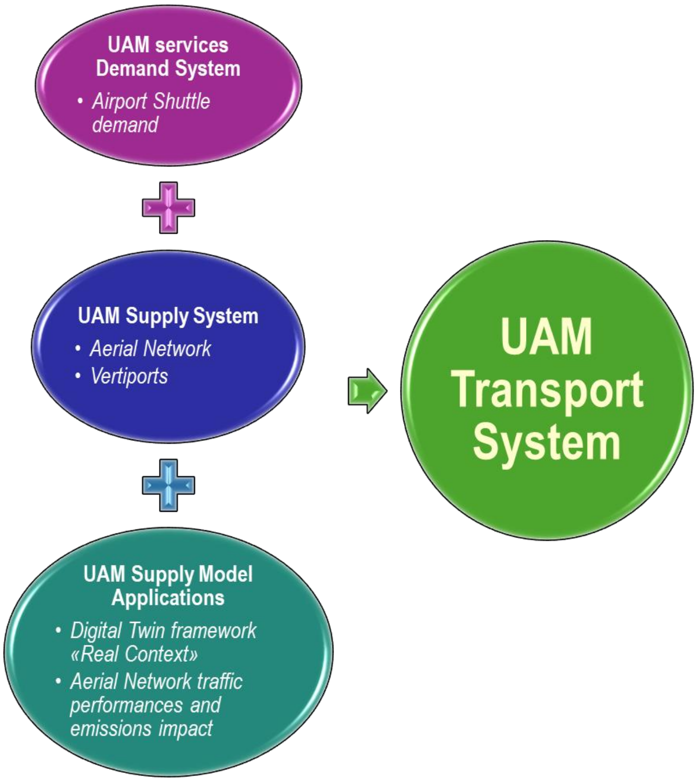

Figure 1.2. – Key aspects analysed in the thesis.

In the first phase, the research project explores the current features of low airspace management – where it is assumed that UAM operations will take place – and the innovative FVs characteristics which mainly influence the system procedures. The analysis of the current approaches used to regulate air traffic at low altitude, which integrates advanced communication systems, was necessary in order to outline the constraints that the urban air transport network should include for safe and integrated services with traditional aviation. Similarly, the exploration of FV technical specifications – as the Flying Ad-Hoc Networks (FANET) – which use radio transceivers to provide connectivity and communication between aircraft and the ground infrastructures (Schalk, 2017), and the "see-and-avoid" devices to ensure unmanned flights (Chand et al. 2017), have contributed to set the major hypotheses to create a dynamic transport supply system consistent with these characteristics.

In the second phase, the transport demand sub-system has been preliminary explored. To realize effective UAM services it is crucial to pinpoint users' travel behaviours and needs, mostly because this new transport mode introduces a disruption with respect to one or more elements of well-known existing ground systems. The demand analysis has been addressed to understand people willingness to use FVs, by identifying the most relevant factors that influence users' mode choice for an UAM service, in particular connecting city centre and airports by means of eVTOL. To this aim, a Stated Preference (SP) together with a Revealed Preference (RP) survey (Kroes and Sheldon, 1988) has been realized and some discrete choice models have been calibrated in order to analyse user's preferences towards one or more relevant factors associated to both current used ground transport modes and the novel aerial service. Investigating the future transport demand allows conceiving an adequate aerial service (e.g., from vertiport placement in suitable catchment areas to vertiport capacity and FV trip scheduling) that can meet travellers' needs and expectations.

In the third phase, the UAM supply model has been discussed, by considering the ground facilities and the aerial ones. Indeed, the aerial transport supply model is closely related to a suitable planning of ground infrastructures (vertiports), as well to determine the assumptions on the network capacity levels. Therefore, a general analysis has been carried out on both 1) the emerging vertiport layouts presented in the literature, to assess the expected number of movements that could be operated at the Origin/Destination (O/D) points of the emergent networks, and 2) the urban and suburban location methodologies, to guarantee places with suitable obstacle clearance for air traffic management.

Then, an Urban Air Network (UAN) model, which includes the third (vertical) dimension (3D-UAN), is proposed to satisfy the basic principle of linking O/D points as in standard ground transport networks. In fact, UANs should be designed to guarantee effective connections between Points of Interest (POI), reduced travel times and safe flight paths. An early method to set a 3D-UAN was based on a multilayer airspace model for UAV (Samir et al., 2019). Lascara et. al (2019) presented a framework that includes Dynamic Delegated Corridors (DDCs), which are dynamic airspace volumes as Airways, designated for flight procedures in order to facilitate separations among FVs and traditional aircraft.

The proposed 3D-UAN tested in this research consists of multiple 2D-graphs, for different layers, which allow transfers in low airspace at predetermined flight heights in order to fly in safety conditions by avoiding potential obstacles and providing suitable vertical FV separations.

It includes *fixed nodes*, *transition nodes* and *dynamic links*. Nodes are connected through *dynamic links,* which also connect Layers vertically. Fixed nodes are set out at the ground access and egress points – e.g., vertiports for departure and arrival – interconnected with current ground systems. Moreover, the proposed model includes an *ad-hoc* link cost function that ensures the shortest travel paths as well as suitable FV separations on dynamic links. Still, the presented cost function regulates the waiting time at vertiports to prevent aircraft collisions along the aerial network and is intended to support collision avoidance sensors installed on FVs. Then, a simulation model has been set to test the effectiveness of the proposed 3D-UAN model, particularly to verify UAM services and the optimization of travel times and routes between specific origin and destination pairs. Since the lack of experimental data due to the novelty of the UAM system concept, the test has been realized by simulating the features of a scheduled UAM service.
Moreover, a digital twin framework has been used to test the supply transport system, which includes a UAM service, in a real context (city of Bologna, Northen Italy). By means of GIS software and territorial open-data, the digital twin of the city has been built and used to identify the proper vertiport locations by also combining the 3D-UAN model proposed in this thesis. Some FV urban operations have been simulated, and the air traffic flow and travel times on the network have been estimated.

The results achieved in this dissertation intends to provide a substantial contribution to the development of Urban Air Mobility transport services:

- First, the investigation on the demand expectations for UAM passengers' services, also compared with the current users' transport mode choices, helps outlining the profile of future users and their willingness to use UAM services. Some factors influencing mode choices have emerged, which allow providing stakeholders and policy makers with some suggestions based on user's preferences and features.
- The analysis of vertiport current design and placement methods can encourage the definition of suitable concepts for integrating these infrastructures into current urban and suburban environments.
- Finally, the innovative three-dimensional air network model (3D-UAN) provides a methodological framework that could be effectively implemented to manage and regulate urban air traffic in low airspace, especially due to its dynamic properties. Indeed, the dynamic characteristics of the proposed network model suits the technological features of FVs that will operate on it. The tested model and the obtained

results might help certifying Agencies (as EASA, FAA) to establish the adequate regulations to integrate UAM systems and promote a multimodal mobility with ground and airside components.

1.3. Thesis outline and dissemination

The dissertation is structured as follows.

In Chapter 2, the background relating to UAM system development is outlined. In particular, the main components of the FVs, the main transport services and the state of the art related to the management of low airspace are described. In Chapter 3 the potential demand level for UAM Airport Shuttle services is examined. The methodological approach and data collected by an ad-hoc survey are discussed and employed to analyse the willingness to use such service. Moreover, the survey results are used to calibrate some discrete choice models and to estimate the preliminary factors affecting passenger choices. In Chapter 4, the access points to UAM services, i.e. vertiports, are introduced and explored by reviewing the main features of ground infrastructure layout, capacity and location requirements. Then, Chapter 5 reviews some preliminary aerial networks structures and presents a three-dimensional Urban Air Network (3D-UAN) model in combination with a suitable link cost function, in order to allow UAM operations and air traffic flow management in the near future. The characterization of the supply model is described, by specifying the structure of the aerial network and explaining the implications of the adopted cost function, particularly to ensure FV separation on aerial links. In Chapter 6 some 3D-UAN model applications are presented. Furthermore, a 3D-UAN experimental scenario is described, and the model performances and results are discussed.
Finally, the overall achievements related to the UAM transport system development have been discussed and summarized in Chapter 7.

The thesis is based on the following publications, which have been produced during the three-year PhD period:

- Chapter 2 based on: Ditta, C.C. and Postorino, M.N., 2022. New Challenges for Urban Air Mobility Systems: Aerial Cooperative Vehicles. In *Intelligent Distributed Computing XIV* (pp. 135-145). Cham: Springer International Publishing.
- Chapter 3 based on: Brunelli, M., Ditta, C.C. and Postorino, M.N., 2023. SP surveys to estimate Airport Shuttle demand in an Urban Air Mobility context. *Transport Policy*, 141, pp.129-139.

Adamidis, F., Ditta, C.C., Wu, H., Postorino, M.N., Antoniou, C., 2023. Urban Air Mobility for Airport Access: Mode Choice Preferences and Pricing Considerations. *Submitted to Transportation Research Part A*

- Chapter 4 based on: Brunelli, M., Ditta, C.C. and Postorino, M.N., 2023. New infrastructures for Urban Air Mobility systems: A systematic review on vertiport location and capacity. *Journal of Air Transport Management*, 112, p.102460.

- Chapter 5 based on: Ditta, C.C. and Postorino, M.N., 2023. Three-Dimensional Urban Air Networks for Future Urban Air Transport Systems. *Sustainability* 15, no. 18: 13551.

  Ditta, C.C., Postorino, M.N., 2023. A 3D Urban Aerial Network for New Mobility Solutions. In: *Intelligent Distributed Computing XV* (pp. 277-286). IDC 2022. Studies in Computational Intelligence, vol 1089. Springer, Cham.

- Chapter 6 based on: Ditta, C.C. and Postorino, M.N., 2023. Three-Dimensional Urban Air Networks for Future Urban Air Transport Systems. *Sustainability* 15, no. 18: 13551.

  Brunelli, M., Ditta, C.C. and Postorino, M.N., 2022. A Framework to Develop Urban Aerial Networks by Using a Digital Twin Approach. *Drones*, 6(12), p.387.

CHAPTER 2 – BACKGROUND AND STATE OF THE ART

This section is built upon the conference paper on book series:

- *Ditta, C.C., Postorino, M.N., 2022. New Challenges for Urban Air Mobility Systems: Aerial Cooperative Vehicles. In: Camacho, D., Rosaci, D., Sarné, G.M.L., Versaci, M. (eds) Intelligent Distributed Computing XIV. IDC 2021. Studies in Computational Intelligence, vol 1026. (pp. 135-145). Springer, Cham.*

The paper focuses on the background related to cooperative features of UAM flying vehicles and on the preliminary requirements to manage the low airspace.

2. BACKGROUND AND STATE OF THE ART

2.1. Urban Air Mobility system background

The Urban Air Mobility (UAM) vision has its origins in early 1910s, when several inventors built and delivered various concepts of "flying car", as the Autoplane concept by Glenn Curtiss around 1917 (Mitchell and House, 2001), even though none achieved the commercial availability. Later between the 1950s and 1980s, several operators began providing early UAM services using helicopters in USA cities, although high fuel costs and safety vulnerability made the services spread hard (Cohen et al., 2021). Then, the recent development of advanced and innovative aircraft, remotely piloted or fully autonomous (Fan et al., 2020), laid the foundations for a new mobility system, which quickly involved the interest of the markets.

The Urban Air Mobility (UAM) concept concerns an emergent mobility system, which would create fast, safe, and integrated transport services by using both the third spatial dimension and "intelligent" technologies. The aim is to improve and change significantly intra and interurban mobility.

UAM systems are thought mainly to transport both passengers and freights by advanced and autonomous flying vehicles in low uncontrolled airspace. Besides, it would involve emergency operations such as medical aid (Cohen and Shaheen, 2021) and transport of organs, blood, or medical devices (Ackerman and Koziol, 2019; Claesson et al., 2016), particularly beneficial for rural and remote areas. Improvement in power electronics, electric propulsion, sensors, data analytics, as well as large cost reduction in producing hardware components, gave the opportunities for novel aircraft generation (Straubinger et al., 2020) known in the literature as small Unmanned Air System (sUAS), Unmanned Air Vehicles (UAV), electric Vertical Take-Off and Landing (eVTOL), or simply "drones" depending on applications – i.e., passenger transport, freight delivery, data collection – and prototypes – i.e., manned and unmanned. As for passengers, UAM services would be realized by electrical Vertical Take Off and Landing aircraft (eVTOL), which are expected to be cheaper and quieter than current helicopters (Porsche Consulting, 2018). Presently, there are several eVTOL prototypes under development with different properties – e.g., speed, range and number of seats (Bacchini and Cestino, 2019) – which will be detailed in the following sections. For simplicity in this dissertation, UAM aircraft will be generically called Flying Vehicles (FVs).

Particularly, the expected flying parameters for UAM passenger services would be an average cruise speed of 170 km/h; range of 95 km + reserve range of almost 10 km; operation altitude of 150 m (or 500 ft) AGL (Holden and Goel, 2016; Bacchini and Cestino, 2019). The FVs features – mainly high precision on-board sensors, such as radars, Detection and Avoidance (DAA), controlling battery systems and vehicle stabilization – will decrease dependency on pilot skills, while keeping high levels of inflight safety. Also, high-performance wireless communication links will transfer and receive data through different frequency band (WLAN, LTE, 5G), and will ensure reliable Vehicle-to-Vehicle (V2V) and Vehicle-to-Everything (V2X) communications (Santa and Gómez-Skarmeta, 2008). Thanks to the combined use of FVs and advanced telecommunication technologies, it is expected that the UAM concept will provide direct paths, quick connections and point-to-point links without necessity, or limiting usage, of roads or ground infrastructures (Hill, et al., 2020), by optimizing the urban and extra-urban connection capability.

Implementing the overall UAM system, alongside with FV technological progresses, requires evaluating and solving some key issues. Firstly, an appropriate low airspace control structure is essential to carry out flight missions, and currently it has not been fully implemented. It is assumed that UAM procedures will be performed mainly in uncontrolled airspace – Class G according to ICAO airspace classification (ICAO, 2001) – not involving ground-based centres as Air Traffic Control (ATC). However, FVs could operate in controlled airspace in some specific circumstances, as hot spots overflight (i.e., airports no-fly-zone). Despite the existence of the Air Traffic Management (ATM) system for traditional aviation, which provides worth basis for the development of a similar system in the lower space, there are technical and management issues to be solved to integrate the UAM system into the current ones, due to the heterogeneous characteristics of the urban airspace environment. Indeed, the flight management in low airspace which has to ensure safety conditions for on-board users and surrounding environment, relies both on air traffic regulation models and on FVs capabilities to communicate each other and with the control centre. To achieve these purposes UTM and U-space are considered a fundamental enabler. UTM is a traffic management system for uncontrolled operations, which identify services and responsibilities, data exchange protocols, software functions, infrastructure, and performance requirements for enabling the FVs operations into low uncontrolled airspace. Similarly, U-space services aim to provide automated and sustainable traffic management solutions to the safe integration of FVs in all classes of European airspace in the long term, starting in the low airspace (Raju et al., 2018; Barrado et al., 2020). The development of these service providers will enable many application cases, of which the passenger services will be the most challenging. Two different Concepts of Operation (ConOps) have been defined for passenger transport: an on-demand and a scheduled

UAM service. The on-demand UAM service will match in real-time passenger demand and FVs. UAM flights will be booked in short term to reach any destination in the UAM system; the flight paths and landing slots are not available in advance, but they rely on demand (Hansman and Vascik, 2018). Then, the scheduled service is specified by predefined flight plans based primarily on the demand requirements (Asmer et al., 2021). In this regard, the demand system analysis is essential, in order to explore the use cases that best meet society and context. Since this type of service is not yet operational at the moment, the transport demand examination is achieved by means of survey and statistical methods (Profillidis and Botzoris, 2018). In the following, the UAM demand analysis will be explored more in detail.

In order to introduce a multimodal and integrated transport system, ATM systems in low airspace must be supported by structured transport supply model (similar to ground transport supply system), which includes both an aerial network and ground access points. Indeed, to allow novel aerial transport systems accessibility, it is necessary to set up some elements (or infrastructures) interconnecting the landside and airside. Particularly, the infrastructures that will host eVTOLs operations are named *vertiports* and will have to be embodied into the current complex and heterogeneous urban environments. A vertiport is a type of airport or heliport that guarantee FV land and take-off vertically, and to execute operations including passenger disembarking and embarking, pre and post flight checks, FV battery charging/swapping and maintenance (Taylor et al., 2020). This infrastructure design and location currently constitutes a significant challenge for the suitable implementation of UAM services. Vertiport design – in terms of landing pads and parking stands – and placement are strictly related to vertiport layout, and consequently depend on its capacity, which in turn depends mainly on land occupancy (Holden and Goel, 2016; EASA, 2021; Goyal et. al, 2019). Several recent studies in these fields are contributing to identify design methods and the opportune planning of urban transport systems, where transport sub-systems – both ground and aerial – cooperate due to vertiport introduction (Preis et. al, 2021; Schweiger and Preis, 2022; Brunelli et al., 2023).

Finally, ground transport systems are simulated by using the *transport supply* model – i.e., network models – determined by graphs including nodes and links, and cost functions associated to each network link (Magnanti and Golden, 1978); similarly, UAM transport systems require structured supply models. Due to the innovative nature of these systems, the literature on models designed explicitly for UAM services is rather poor, wherefore in the following sections a new model will be presented, which is intended to meet UAM operation requirements and travellers' expectations in terms of performances, by guaranteeing the principles of time and cost optimization. Actually, a limited number of studies concerning a framework to develop aspects such as the organization and safety of this emerging transport system have been proposed.

To summarize (Figure 2.1.), the development of UAM systems requires setting 1) regulations of low airspace in which FVs are moving, together with the main flight management and control criteria; 2) the cooperative and automated FVs properties coherent with the previous aspects; 3) suitable design and location of ground infrastructure (i.e., vertiports) which allows FVs land and take-off procedures and transport demand access/egress to the aerial system; 4) a model as an aerial network – crossed by FVs – which link origin/destination points and ensure shortest and safest paths.

Figure 2.1.– Relationships between Low Airspace, UAM Flying Vehicles and UAM Transport Networks.

In the following sections, the FVs features, the Low Airspace management and the main UAM services and use cases will be analysed.

2.2. Flying vehicles for UAM operations

2.2.1. Flying vehicles prototype and features

Design and development of suitable FVs is essential for the successful implementation of an UAM transport system. In the last few years, the interest of global industries and researchers for UAV – or FV in general – has grown significantly, bringing these new aircraft into the public domain for commercial and industrial applications. FV development comes out to a promising and valuable opportunity for prospective aviation industry and manufacturers and the aviation. Also, the advancements in electric propulsion systems, high-storage batteries, wireless communication and modern control techniques have brought up new opportunities for autonomous transport and aerial mobility (Ducard and Allenspach, 2021). In this section, particularly, the main features of FV prototypes that will allow passenger transport and good delivery are examined in order to evaluate how they could affect the development of UAM transport systems.

Currently, the most relevant studies on FV design are addressed to provide aircraft that can satisfy an on-demand service, by improving metropolitan and countryside mobility by faster and effective operations. Firstly, two main FV categories have been identified: (i) short take-off and landing (STOL), which needs short runways to reach the speed suitable for take-off, as fixed wing aircraft, and (ii) vertical take-off and landing (VTOL), which requires reduced areas for taking-off and landing, more suitable in urban environments, by employing the same propulsion system for hover such as helicopters and multirotor platforms (Liu et al., 2017). Their employment will depend on the use cases required, since each type has different advantages over the other.

Several companies are developing FVs prototypes, such as Kitty Hawk (US), Lilium (Germany), Volocopter (Germany), Joby Aviation (US), E-Hang (China), as well as traditional aircraft producer like Airbus (Netherlands), Boeing (US), Bell (US), Embraer (Brazil), and Uber (US). Particularly, Uber was a pioneer at conceiving the new concept of mobility. The "Uber Elevate" project outlines the preliminary aerial ride sharing service, by purposing rapid and reliable transport by means of eVTOL (i.e., VTOL aircraft equipped with electric engine) (UBER Elevate, 2018). Indeed, it is assumed that FVs concepts for UAM operations are characterized by Distributed Electric Propulsion (DEP) and autonomous technologies (Holden and Goel, 2016; Shamiyeh et al., 2018); accordingly, the aviation industry has particularly focused efforts and economic investments on eVTOLs prototypes production. Thus, the DEP technology is defined by mixture of distributed propulsion and electric propulsion, by assuring zero vehicle emission, quieter flight and high propulsive efficiency, reducing effort and complexity of VTOL aircraft to a controllable level (Penttinen et al., 2019). Then, autonomous systems, through high precision onboard sensors, such as radar and detection and DAA, improve the control battery systems, vehicle stabilization and inflight safety (Alvarez et al., 2019). Still, the autonomous flight relieves risks correlated to human factors, as the misfortune reduction due to pilot involvement.

Therefore, the Vertical Flight Society classified eVTOLs in different configurations[1] (Figure 2.2.): *rotary-wings, fixed-wings and lift + Cruise*.

[1] http://evtol.news/classifications

Figure 2.2. – Example of eVTOLs configurations for UAM operations.

The *rotary-wings* aircraft are multirotor that have large disk actuator surface to ensure an excellent hover power. Nevertheless, they are limited in cruise speed, less efficiency in cruise flight and a smaller range compared to other eVTOLs. This design might be the best solution in highly urbanized contexts. The enclosed fans provide safety advantages during ground handling, but their small cross-section produces a high downwash velocity that involves high noise emissions (Bacchini and Cestino, 2019; Straubinger et al., 2020).

The *fixed-wings* models have a wing for a powerful cruise and employ the same propulsion system for both hover and cruise. They guarantee high cruise speed and improve the achievable ranges, although they provide limited performances in hover power.

Particularly, different prototype configurations (rotary-wings or fixed wings) can affect climbing time to reach the suitable altitude and the transition distances to switch flight mode – i.e., vertical or horizontal flight – by influencing the overall flight efficiency and the consistency with specific use case (Bacchini and Cestino, 2019; Straubinger et al., 2020).

The *lift + cruise* models perform smooth transitions between vertical and horizontal flight, due to their different powertrain for hover and cruise. Indeed, these prototypes are equipped by two set of engines: one for lift only and another for both lift and cruise. The cruise efficiency is ensured by a suited wing, like fixed wing eVTOLs, meanwhile hover and cruise procedures are allowed by using two different propulsion systems (Thipphavong et al., 2018; Bacchini and Cestino, 2019; Straubinger et al., 2020). The main technical and performances features of each category are summarised in Table 2.1., specifically based on VoloCity rotary wings developed by Volocopter, Lilium Jet fixed wing by Lilium GmbH and Cora lift + cruise by Wisk Aero prototypes.

Table 2.1. – eVTOLs specifications for rotary-wings, fixed wings and lift + cruise prototypes.

	Rotary wings	**Fixed wing**	**Lift + Cruise**
Powerplant	Batteries	Batteries	Batteries
Propeller Configuration	18 rotors	36 electric vectored thrust fans (DEVT)	• VTOL flight: 12 propellers • Forward flight: 1 pusher propeller
Cruise speed	110km/h	250 km/h	180 km/h
Range	35 km	250 km	100 km
Dimensions	11.3m x 9.5m	13.9 m x 8.5 m	11 m x 6,4 m
Max. payload	200 kg	200 kg	181 kg
Capacity	2 passengers with luggage	6 passengers	2 passengers
Autonomy Level	Semi-autonomous	Piloted	Autonomous

Source : https://www.volocopter.com/solutions/volocity/
https://lilium.com/jet
https://www.boeingfutureofflight.com/wisk

By considering the features highlighted above, the short-range missions are best performed by rotary-wings aircraft because they have better hover performances, while fixed wings and lift + cruise models are more appropriate to operate in long-range missions.

Then, the FV size depends on wingspan, engines volumes and payload capacity in terms of passengers on board. Actually, the seat capacity, provided by different eVTOL prototypes, ranges from 1 to 6 passengers (Ugwueze et al., 2023).

Finally, the discussed FV prototypes are enabled to reach appropriate altitude based on minimum safe altitude requirements. In particular, FAA sets the height above 152 m (500 ft) AGL as satisfactory (obstacles free airspace) and practical to avoid energy wasting in a climb procedure (Patterson et al., 2018). Furthermore, the rotary wings models are designed to cruise at 2000 m (6.562 ft), and fixed wings and lift + cruise can reach 3000 m (10.000 ft).

2.2.2. Cooperative and automated flying vehicles

FV features that mainly made pioneering the introduced aerial transport systems are the novel communication architectures and the autonomous (or unmanned) flight. Particularly, they will require an advanced Information and Communication Technology (ICT) infrastructure to guarantee effective coordination and control of operations, and V2V and V2I communications. The automation and connection characteristics will increase the interoperability in order to manage the flow of information related to passengers' demand, freight distribution, and emergency situations. The real time data transmission will allow FV identification, lateral flight speed, location and times. Indeed, by using control algorithms, actuators and integrated software, the FVs could detect and perceive the environment, analyse detected information, communicate, plan and take decisions independently. Researchers have assumed that the communication scheme would have two architecture network approaches, according to the aircraft level of automation and the support needed by operators: the cellular networks and *ad-hoc* networks (Schalk, 2017). The cellular networks (e.g. LTE, 5G) depend on access points, as base station, by which FVs will be connected through dedicated communication links. The *ad-hoc* networks, already used for V2V communications, do not rely on connections to base stations and they are also suitable for communication application in FVs, e.g. Flying Ad-Hoc Networks (FANET) (Chriki et al., 2019). In *ad-hoc* networks, FVs can communicate each other through direct links. If a receiving FV is out of the communication range of the sending one, other FVs within the range can act as relays and forward the transmission over multiple "hops" (Schalk, 2017).

This architecture will support UTM systems and the development of cooperative multi-FVs systems, by encouraging FVs independency. Indeed, FV-to-FV connections allow coordinating actions, identifying a framework where the FVs could handle data information about traffic and environment conditions, and make routing decisions by using airways in Low Airspace. In fact, the active information exchange and the anti-collision sensors (DAA) placed in each aerial vehicle will allow FVs to control autonomously their operations and use the available low airspace capacity. Recent studies proposed Multi-Group and Multi-Layer FV Networks, based on *ad-hoc* architecture network to FVs communication. The Multi-Group FVs Network would consider a backbone network of FVs (i.e., high capacity connectivity infrastructure) connected to the ground station, which also will create connections with other FVs. Intra-group communications will occur within the FVs *ad hoc* network, while inter-group communications will be achieved through respective backbone FVs and the ground station. The ground station will allow FVs to receive information and guideline by UTM/U-space. This FV-to-FV architecture is suitable for a scenario that involves many FVs with different flight or communication features. Thus, it could be an efficient solution in UAM networks, which will be a heterogeneous and complex environment where different flights will be involved. The Multi-Layer FV Network (Figure 2.3) would be described by a lower layer where individual groups realize a FV *ad hoc* network, and an upper-layer FV *ad hoc* network composed of all FVs' backbone network connected to the ground station. In this network, information exchanged between any two FV groups does not need to be routed through the ground station. The ground station computation load would be reduced as only data from backbone FV will be processed. The multi-layer FV *ad hoc* network architecture is important for implementing the one-to-many FV operation mode (Li et al., 2013). In order to reach satisfactory cooperation among FVs in these connected systems, the software features will be crucial for achieving a suitable management of the data flow and for elaborating them in order to ensure safety during flight and approach phases.

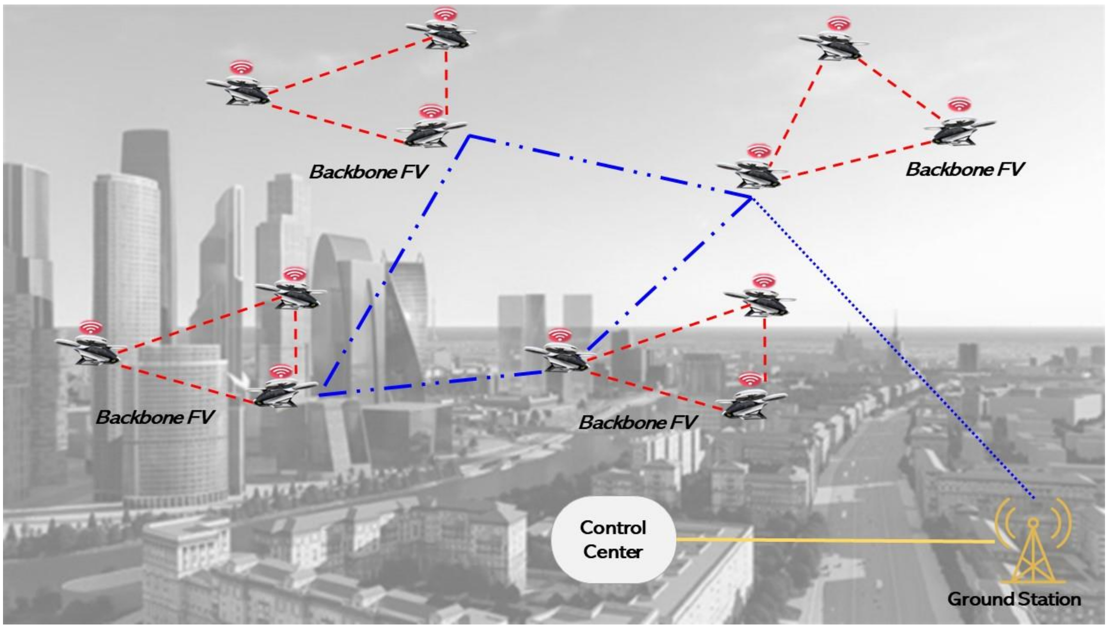

Figure 2.3. – Multi-Layer FVs communication network.

Due to their automated features in an integrated and safe UAM network, the multiple cooperative FVs might guarantee flight paths and vehicle separations. Yang and Wei (2020) presented a message-passing decentralized computational guidance algorithm, which realizes separation capability and runs on each cooperative FV. The model is formulated as a multi-agent MDP (MMDP), solved by the Monte Carlo Tree Search (MCTS) algorithm that can run on-board the vehicle. By using MMDP structures and by incorporating information (such as position, speed, destination) by wireless connections, FVs will decide immediately actions to reach the optimal state and separations from other FVs. The model would allow to 1) avoid potential *Loss of Separation* events among FVs in the same airspace level, and 2) guide FVs quickly toward their destinations. The problem would be solved in two dimensions because the aircraft are supposed to fly at the same altitude. In addition, airspace sectorization is proposed with the purpose of reducing the computation time. This framework would be suitable in free-flight conditions and would provide a potential solution for ensuring distributed separation by supporting safe, efficient, and scalable operations in high-density urban air scenarios (Yang and Wei, 2020).

2.3. Low Airspace Management for UAM

In order to develop an effective UAM system, it is necessary to set a suitable airspace infrastructure by allowing safe flight management and operations. Currently, it is assumed that early UAM systems will be manned and operated under Visual Flight Rules (VFR) at Very Low Level (VLL) airspace, i.e., 0-500 AGL. Therefore, by considering ICAO airspace classification – classes A to E controlled, in classes F & G operations are uncontrolled (figure 2.4.) – UAM flights might have origins and destinations in class E (under VFR) or class G airspace (ICAO Annex 11, 2001). However, UAM is expected to be developed in metropolitan areas to realize fast connections between city areas and airports or among close airports in the region; then, it is be expected that UAM flights will operate also in classes B, C and D (Thipphavong et al., 2018).

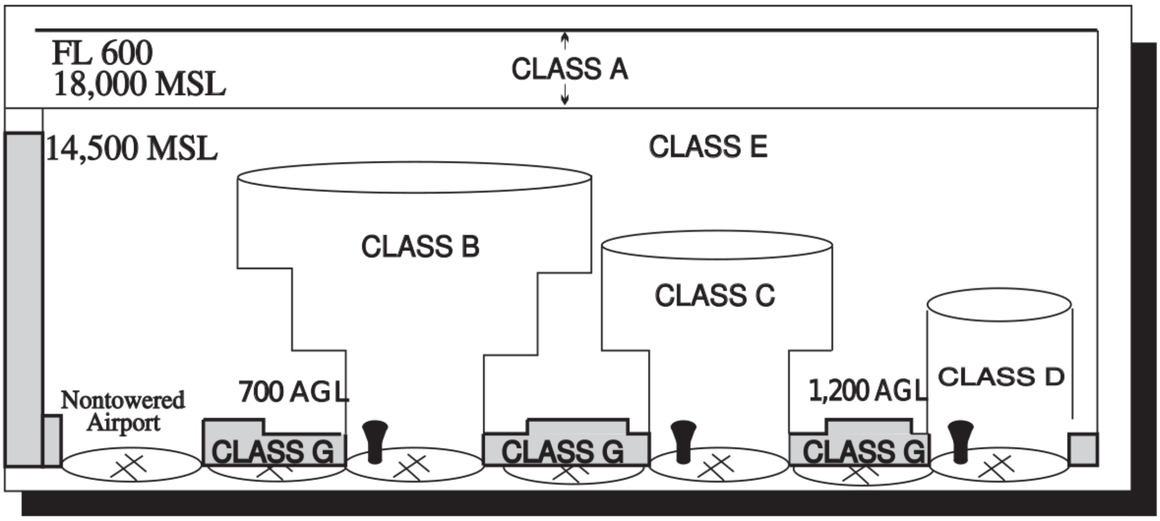

Figure 2.4. – ICAO airspace classification.

Source: http://www.faa.gov/air_traffic/publications/media/AIM.pdf

The development of automated FVs for civil applications drives researchers to identify an ATM framework to control flight activities. NASA has presented a Concept of Operations (ConOps) to set safe procedures and activities of Unmanned Aerial Systems (UAS) in the airspace infrastructure and then UAS Traffic Management (UTM) system have been identified. The aim of UTM is to ensure safe and efficient low-altitude airspace operations by providing services such as airspace dynamic configuration, dynamic geofencing, weather information, route planning, flight separation and congestion management (Kopardekar et. al, 2016). The UTM architecture (Figure 2.5.) is supported by UAS remote pilots, control centres, vehicles and airspace infrastructures, which are interconnected by three different communication methods: wide-area wireless, wireline, and V2V.

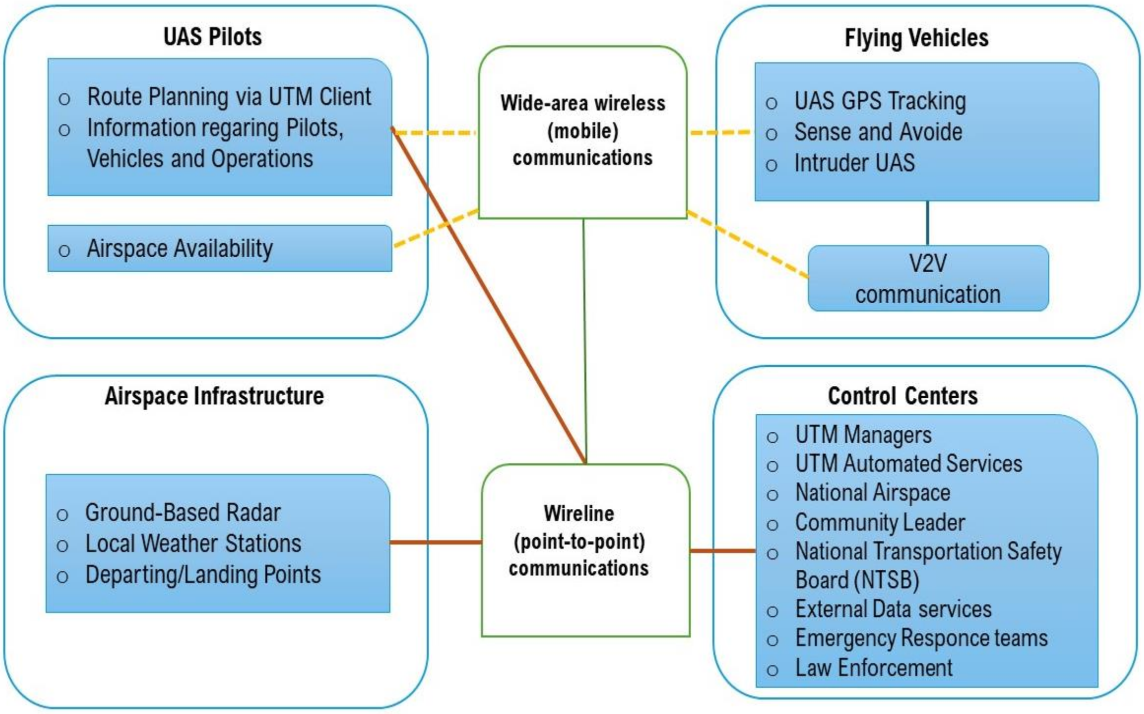

Figure 2.5. – The UTM Architecture.

The UTM architecture was initially designed for drones, but it is evolving to support aerial transport networks with fully autonomous FVs that will be able to manage their journey independently. Moreover, the UTM system concept would be described by several subsystems: UTM Client, UTM Services, UTM System Automated Services and UTM Manager. The UTM Clients – achieving relevant flight information by Ground-based radars, GPS and local weather stations – are web-based software applications that will permit remote pilots and controllers to access critical airspace data and to plan and review flight paths. UTM Services will allow pilots to submit flight plans, to view real-time FV location, and access relevant data to ensure safe operations. In addition, UTM Automated Services will prepare routes for autonomous vehicles and review pilot flight plans. UTM Managers oversee user and FV authorisation, off-nominal event management and quality assurance of UTM automated service. Finally, the UAS pilots are user authorized by UTM Manager to control UAS and program plan for autonomous flights (Jiang et al., 2016).

NASA defined an UTM platform characterized by four UTM Technical Capability Levels: TCL-1, TCL-2, TCL-3 and TCL-4 (Kopardekar et. al, 2016), which are expected to represent and regulate the complex airspace environment from rural to urban areas. Each increasing level includes and improves the applications and methods of the previous one. TCL-1 provides interactive planning and constraint management capabilities to manage multiple UAS operations in low risk rural areas within Visual Line of Sight (VLOS). Also, it employs a simple airspace notification system to de-conflict operations by introducing virtual geographic boundaries (so-called *geofences*) around low risk areas. TCL-2 supports Beyond Visual Line of Sight (BVLOS) operations, involving increased traffic density and flight level separation plans. It aims to develop procedure to maintain the BVLOS safety when several FVs share airspace. Contingency management will be automated for each FV. TCL-3 enables FV operations next to manned aircraft over moderately populated areas. It would improve in-flight de-confliction services, trajectory compliance monitoring, and automated contingency management involving multiple FVs. Then, TCL-4 will aim to manage operations involving simultaneously all autonomous and connected FVs in urban and high-density environment. Operations will include data collection, delivery and on-demand taxi use (Johnson, R.D., 2018). Some studies verified that TCL-4 could be employed for UAM operations, and the systems could be improved through the implementation of air services (Verma et al., 2020).

In Europe, a similar approach has been adopted by introducing the U- space, developed in 2017 by SESAR Joint Undertaking (SJU). The U-space involves specific procedures and services, identified to guarantee safe and secure drone activities in airspace through high-level digitalised and automated functions. Moreover, the U-space will support ATM, service providers and authorities to manage operations in all types of airspace (particularly VLL airspace). The U-space system consists of four levels (Table 2.2.) with raising automation and connection specifications, which require substantial improvement of data exchanges and interaction with the environment (SESAR, 2017).

Currently, resources are committed for developing and designing the most advanced U-space services (U3/U4), which will empower UAM activities in complex metropolitan areas. U-space systems should be responsible for providing a suitable airspace separation among manned and unmanned aircraft, controlling functionalities during weather events, and relevant hazards, avoiding unsafe conditions through appropriate operations (SESAR, 2020). Moreover, the CORUS-XUAM is a very large demonstration project which want to validate that U-space services could support integrated UAM flight operations, preventing effects on the activities conducted by ATM, in order to perform safely, securely and efficiently in a controlled and shared airspace. The demonstrations have set manned and unmanned procedures in dense conditions, including operations nearby airport and other critical infrastructures, to perform the services in VLL urban, sub-urban and inter-urban areas (SESAR, 2021).

Table 2.2. – U-space services.

U1 – *Foundation services*	**U2 – *Initial services***
▪ *E-registration* ▪ *E-identification* ▪ *Geo-fencing*	▪ *Management of Operation* ▪ *Flight Planning* ▪ *Flight Approval* ▪ *Tracking* ▪ *Airspace Dynamic Information* ▪ *Procedural Interfaces with ATC*
U3 – *Advanced services*	**U4 – *Full services***
▪ *Complex operations in dense areas* ▪ *Capacity Management* ▪ *Assistance for Conflict Detection* ▪ *Availability of automated "Detect and Avoid" (DAA) functions Operation in all environments*	▪ *Integrated Interfaces with Manned Aviation* ▪ *Full operational capability of U-space* ▪ *Very High Level of Automation Connectivity and Digitalisation*

UTM and U-space services will aim to bear and control FV flight plan procedures, also to guarantee that flights will be within an allowed geofence area. The service activities could be worsened by the latency and loss of packets due to LTE mobile network performances. To overcome this issue, the framework proposed in Bekkouche et al. (2018) is a high-level informatics architecture for a Multi-access Edge Computing (MEC), which would reduce the latency and increase the reliability of the communications between connected FVs and UTM services (Ali et al., 2021). The use of MEC in FVs traffic management and networks would reduce issues due to ineffective communication. The model consists of three components: 1) the cloud domain, which organises the management services; 2) the core and transport network, which ensure the communication traffic between MEC-hosted services and the cloud domain, and 3) the MEC nodes, which will host the FVs Flight Controller service. This service will monitor and control the routes of autonomous FVs, will collect information and instruction from cloud-hosted services, and consequently will calculate and adapt FVs flights (Bekkouche et al., 2018).

2.4. The UAM use cases and services

Service providers have to ensure the several aerial applications that were figured out for UAM systems. Indeed, a list of potential use cases has been drafted by NASA researchers

(Thipphavong et al., 2018): Air Taxi on–demand service, Air Cargo, Air Metro, Emergency operations, news gathering, traffic and weather monitoring. As for passenger transport, several types of air services have now been defined in the literature with different characteristics and specific requirements on the UAM system (Schuchardt et al., 2021; Crown Consulting Inc, 2018; Baur et al., 2018). Particularly, Air taxi and Mega-city service, Airport Shuttle (AS), and Intercity aerial services are expected to be leading the international market in the coming decades (Figure 2.6.).

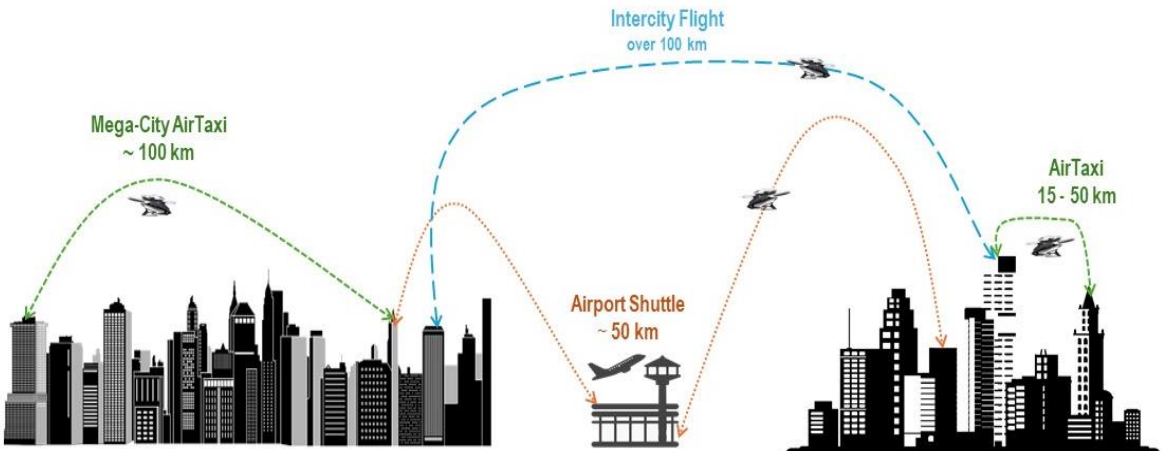

Figure 2.6. – Example of Urban Air Mobility use cases.

The Air Taxi service refers to an on-demand air transport system, proposing short-haul trips between O/D pairs within the urban area. In order to improve the inner-city traffic issues and provide to the dispersed demand within the city, an extensive network of landing sites (vertiports) has to be planned. The air taxi service has not a specific flight planning, but it strictly depends on demand requirements (Polaczyke et al., 2019). Due to short-haul trips (between 15 to 50 km), the rotary-wings FV configuration is considered suitable for this application, considering low cruise speeds between 80 to 100 km/h and lower energy consumption. It is assumed that Air Taxi will need a high number of routes leading to a complex air traffic management. Moreover, the urban environment is characterised by numerous high buildings that also present challenges to the ATM and the communication and navigation systems (Asmer et al., 2021). Further, noise issues could affect public acceptance.

The Mega-City use case is another application dealing with an on-demand Air Taxi service in an urban environment, where flight distances will be greater (e.g., mega-cities in Asia and North America). In this scenario distances of up to 100 km are assumed and an average cruise speeds of 150km/h. Thus, lift + cruise prototypes are more acceptable to ensure procedures, also because it is assumed that only one stopover without a recharge capability will be operate (Asmer et al., 2021).

The Airport Shuttle operations will provide scheduled flights between airports and strategical locations in metropolitan area or POI, as the city centre or central business districts (Straubinger et al., 2020; Cohen et al., 2021). It could be considered that the transport range would be the same as air taxi services, thus about 50 km, because the major routes between airports and city centres worldwide is below 30 kilometres. These flights will be performed by rotary-wings configuration at a speed of 100 to 150 km/h, also enabled to store luggage on board. As the AS will perform scheduled operations, the demand on these predefined routes is expected to be high (Cohen et al., 2021; Asmer et al., 2021).

Finally, the Inter-City use case provides scheduled services between cities, which will cover distances of more than 100 km and simplify direct access to POI in the cities served. Especially, this scenario could ensure fast long-distance connection attractive for commuters and business travellers (Akash et al., 2021). The suitable FV configuration can be the lift+cruise one, which cover higher distances and can achieve speed of between 100 and 180 km/h. Operation will occurs only between vertiports, thus the FVs can be recharged after each mission.

CHAPTER 3 – POTENTIAL UAM PASSENGER DEMAND

This section is built upon the journal article:

- *Brunelli, M., Ditta, C.C. and Postorino, M.N., 2023. SP surveys to estimate Airport Shuttle demand in an Urban Air Mobility context. Transport Policy, 141, pp.129-139.*

- *Adamidis, F., Ditta, C.C., Wu, H., Postorino, M.N., Antoniou, C., 2023. Urban Air Mobility for Airport Access: Mode Choice Preferences and Pricing Considerations. Submitted to Transportation Research Part A*

The papers focus on the future demand levels of UAM Airport Shuttle services to connect main airports and city centres.

3. POTENTIAL UAM PASSENGER DEMAND

3.1. UAM future demand levels: Airport Shuttle services

Planning effective UAM transport services (see section 2.4.) involves the analyses of the future demand levels which could be attracted and satisfied. This new aerial transport mode in urban contexts introduces a rupture with respect to one or more elements of well-known existing ground systems. Consequently, people's expectations, and especially their travel behaviours, are not known and have to be investigated by suitable methods.

Depending on the expected travel demand levels, UAM services would produce impacts on current ground transport systems. As highlighted by the European study on people's concerns towards these systems (EASA, 2021), safety and security are the main worrying factors for UAM services, as well as environmental pollution and noise together with privacy violation. In addition, the EASA analysis reports that people consider UAM medical aid and goods delivery applications more useful than passenger transport. In any case, as discussed in previous sections, there are several opportunities for implementing UAM passenger services as Air Taxi, Intercity flight and Airport Shuttle (AS) services (Goyal et al., 2018). Among these, AS services seem to be the ones with the higher number of advantages, e.g. low complexity in current system integration (Desai et al., 2021), and the first ones that would be implemented.

The potential of FV applications and usefulness of these UAM services lead many countries around the world to plan their development in the next years. In particular, the European Union is actively participating in the research and development of UAM systems in many fields – from medical aid to passenger transport (Agouridas et al., 2021). In the Italian context some important airports – such as Rome, Venice, and Bologna – declared their interest in developing AS services in the near future. In this perspective, the Italian National Authority for Civil Aviation (ENAC) published a roadmap for the implementation of UAM services, and particularly the first passenger services would be aerial connections between city centres and airports (2025 jubilee in Rome and 2026 winter Olympic Games, ENAC, 2022). This confidence in both UAM opportunities and operational implementation of aerial services is mainly encouraged by the high number of FVs prototypes (see section 2.2), which have different range, speed and seat capacity.

In the above perspective, the following sections focus on the analysis of passengers' willingness to use AS services by exploiting data collected by online surveys distributed in the EU area, with additional face-to-face data gathered at Bologna Airport (Northern Italy), which is an important large regional airport with many national and international air links. Starting from the information obtained by suitably planned Stated Preference (SP) surveys, some mode choice models have been calibrated in order to analyse the main key factors underlying travel demand for AS services. Particularly, three different Multinomial Logit (MNL) models have been calibrated and analysed to explore the influence of the different variables from the users' point of view, while a Mixed-Logit (ML) model has also been used to test sample heterogeneity.

3.2. Literature review

In recent years, transport service providers – such as Uber – have been engaged in developing Air Taxi services (Holden and Goel, 2016) attracted by the idea of "flying cars" and possible operational scenarios (Cohen et al., 2021; Postorino and Sarnè, 2020). However, Air Taxis services could be difficult to implement (Desai et al., 2021) while AS services seem promising even in the short/mid-term. In fact, AS services are intended to connect airports with surrounding regions and points of interest in metropolitan areas (Shaheen et al., 2018), thus ensuring a fast connection between the airport and its catchment area. Moreover, air transport demand, especially at regional airports, could increase due to the use of shared AS services (Roy et al., 2019).

In this perspective, several cities such as London, Munich, and Singapore (Cohen et al., 2021; Volocopter, 2022) have shown interest to test and develop UAM services. As an example, for the 2024 Olympic games, the city of Paris aims to launch an AS service which will connect Charles de Gaulle airport with the city centre[2]. Similarly, thanks to a partnership with a European eVTOL manufacture, cities such as Rome, Venice, and Bologna in Italy, would like to develop AS services in the short/mid-term[3].

A critical aspect about the implementation of AS services – and UAM systems in general – is the estimate of the travel demand level for them. Although the EASA report (EASA, 2021) focused on UAM system acceptance and expectations, however, it did not examine the potential passenger demand for AS services. Knowledge about the expected demand levels is important for the system design and to assess its performances, particularly they might have great importance for several stakeholders. For example, the (additional) demand level that can be gathered by AS services could expand the airport catchment area, which is one of the major

[2] https://presse.groupeadp.fr/pontoiseairfield-uamtests/?lang=en

[3] https://www.atlantia.com/en/w/-urban-blue-a-company-for-the-international-development-of-urban-air-mobility-uam-launched-today

interests of airport operators. Moreover, high demand levels could bring advantages to eVTOL manufactures and ground transport operators. In fact, the former could increase the market for their aircraft, whereas the latter could provide services to access or egress the vertiports (i.e., eVTOL stations acting also as passenger terminals for aerial services) in order to rise their revenues.

At a first attempt, simulation techniques have been used to understand the relationships between UAM demand levels and relevant variables. Particularly, some scenarios have been identified and simulated by using suitable software and variations of demand levels have been computed when some relevant elements change. For example, an increase in the number of vertiports seem to positively affect the number of passengers (Rimjha et al., 2021; Wu and Zhang, 2021), although the positive marginal effects become negligible as the number of vertiports exceed a given threshold. The influence of variables such as access/egress time to/from the vertiport, processing time at the vertiport, boarding time and trip monetary costs were also tested. The results obtained by the different simulations show that an increase of access, processing or boarding time causes, as expected, a significant decrease of demand levels (Balac et al., 2019; Pukhova et al., 2021; Rimjha et al., 2021; Wu and Zhang, 2021).

Some other studies in the literature aim to estimate UAM demand levels by using socio-economic variables at a significant aggregated level, which could greatly influence the results. An estimate of the expected 2042 UAM demand level for several metropolitan areas has been obtained by a gravity model with socio-economic explanatory variables such as Gross Domestic Product (GDP), population and ticket price (Becker et al., 2018). Further studies provided similar aggregated analyses for estimating the demand levels for AS services in different US cities such as Los Angeles, Atlanta and New York (Roy et al., 2020). Socio-economic variables have been also used by Goyal et al. (2021) – with several constraints such as willingness to pay, infrastructure capacity and noise restrictions – to simulate many UAM scenarios and estimate the corresponding demand levels. The results show that large population cities with limited urban areas (i.e., high-density areas), high GDP per capita and high air passenger demand are good candidates for adopting UAM services (Becker et al., 2018). On the other hand, the factors that negatively affect UAM demand levels are monetary costs, aircraft designed range and cruise speed (Roy et al., 2020; Mayakonda et al., 2020).

More detailed information on potential travel demand for UAM services and users' characteristics may be obtained by SP surveys. SP methods are useful to collect data for hypothetical alternatives and scenarios that have not been implemented yet. In addition to statistical analyses and figures, collected SP data can be used to calibrate discrete choice models to assess potential demand levels, as suggested by some reference books (see for example Cascetta, 2001). Moreover, SP surveys may help identifying users' satisfaction towards the used transport mode (Susilo and Cats, 2014) and the effects of some relevant variables (such as educational level or social environment) on people's choices (Grot et al., 2021; Jia and Chen, 2021). By adopting this method, important variables from the users' perspective can be identified (Krauss et al., 2022; Carrone et al., 2020; Rotaris et al., 2021). For example, in recent years SP surveys have been widely used to evaluate user's perception and demand levels for Automated Vehicles (AV) (Becker and Axhausen, 2017). Due to some similarities between UAM and AV scenarios, SP analyses for Air Taxi services (Fu et al., 2019) may use the results obtained in AV studies as a baseline (Gkartzonikas and Gkritza, 2019; Becker and Axhausen, 2017). Furthermore, SP analyses of UAM scenarios showed that variables such as trip safety, affinity to automation, ethical and data concerns could have an impact on the expected demand levels (Al Haddad et al., 2020). Moreover, some gender differences were highlighted by the results obtained in the Ingolstadt area (Southern Germany). In particular female respondents seem less interested in UAM services than their counterpart (Janotta et al., 2021) and have more concerns especially about safety and security. However, this result is not confirmed by other SP surveys (Fu et al., 2019; Keller et al., 2022).

As for connections, long distance ones are considered the most suitable for UAM services (Shaheen et al., 2018; Keller et al., 2022). In this perspective, Garrow et al. (2019) investigated that only people travelling at least 30 minutes and with an annual income higher than a defined limit ($75000) were interviewed and a mode choice model was calibrated, founding that the variables with the strongest impact on Air Taxi demand are access/egress times and eVTOL operation costs, further confirmed by other studies (Haan et al., 2021). However, although the study by Garrow et al. (2019) was intended to address supposed captive customers for UAM services, targeting upper income residents limits the results of the study and could lead to biased market estimates. Another SP research conducted in Czech Republic shows that when ground transport mode satisfaction is low, respondent's willingness to use UAM increases and vice versa. Finally, SP surveys allowed highlighting respondents' worries about UAM services in terms of privacy, safety noise and environmental pollution, which have been described by different studies (EASA, 2021; Al Haddad et al., 2020).

From the above overview, it emerges that most of the studies in the literature focuses on Air Taxis demand estimation and only a limited number aims to investigate the demand levels for AS services, although stakeholders and policy makers agree that AS services would be the first to be implemented. In this perspective, this dissertation focuses on the analyses of factors that would affect the possible future demand level for AS services by using data obtained by both Revealed Preference (RP) and SP surveys.

3.3. Methodological framework

3.3.1. Survey Design

In order to assess users' willingness for AS services, a survey has been designed, then implemented on Google Forms, and it has been distributed on several platforms (LinkedIn, academic websites and other social media). Particularly, the respondents have been contacted by using the social networks associated to the above platforms, which captured mainly Italian people. Then, data have been collected from April to June 2022. In addition, face-to-face interviews have been conducted in several terminal areas of Bologna Airport (Northern Italy) – i.e., lounge business, check-in and boarding gate areas. The survey was completely anonymous, complying with the EU General Data Protection Regulation (GDPR)[4], and it has been proposed to individuals with more than 18 years, without any social or gender discrimination.

By using Revealed Preference and Stated Preference "data fusion" techniques (Mark and Swait, 2004), current users' behaviour (RP data) and future users' plans (SP data) can be analysed. Particularly, the demand features of not-existing transport systems cannot be obtained by using only RP data but can be achieved by also using SP data (Kroes and Sheldon, 1988). Therefore, the questionnaire includes two main sections, RP and SP sections. It is worthwhile to note that SP methods are largely used for testing alternatives and/or scenarios not existing yet by designing the choice context – such as UAM services – rather than recording choices in a given context – as in the case of RP surveys. Meanwhile, some limitations of using SP data are the introduction of some distortions in the results (and in the calibrated models) due to the possible differences between stated and actual choice behaviour, which depend on both the SP survey technique and the way the surveys are designed. The first error cause cannot be removed, the second one can be avoided by designing and carefully executing the surveys. To limit the above distortions, due to user's lack of experience with UAM services, scenarios have been designed as simple as possible, the description of both the FV and the context has been provided and the number of factors and SP alternatives is as smaller as possible (Cascetta, 2001).

The RP section includes three different classes of questions (Table 3.1). First, nine questions address socio-economic features, and two questions explore user's experiences about sharing

[4] Official Journal of the European Union, 4.5.2016, L 119/1

mobility and driving assistance systems. In order to acquire reliable statistics, the average income has been inferred mainly from information on current employment, as respondents are often reluctant to provide a true indication of their income. Similarly, car availability has been deduced from the number of driving licences per family unit.

Table 3. 1. – Revealed Preference data information.

Data Categories	
Socio-economic Profile	▪ *Age* ▪ *Gender* ▪ *Educational level* ▪ *Occupation* ▪ *Number of cars owned* ▪ *Experience of sharing mobility and driving assistance*
Air travel and Airport Access Information	▪ *Air travel frequency* ▪ *Air travel reason* ▪ *Last air travel data (trip origin, origin airport)*
Last ground mode used to reach the Airport and its main characteristics (time, monetary cost)	▪ *Car* ▪ *Taxi* ▪ *Public Transport (Train, Bus)* ▪ *Car - Sharing*

The second class includes six questions, which focus on both air travel habits and characteristics of the last air trip. Finally, the third class collects data about the last chosen ground transport mode for reaching the origin airport. This class contains three to five questions – depending on the used transport mode – about travel time (such as time spent to access the bus stop/train station, time on board) and monetary costs (such as airport parking area costs, motorway fees, fuel consumption, bus/train/taxi fares) that characterize the transport mode used to reach the airport. In addition, for each ground transport mode respondents are asked to provide a satisfaction rate, from 1 to 5 (totally unsatisfied and totally satisfied respectively). Moreover, further specific questions have been asked for private car users, such as being the driver or a passenger.

The SP survey section starts with a brief description of the AS service characteristics by focusing on the features of the FV and on some key factors of the proposed service. Other information is provided such as the allowance to use smartphone or laptop on board, the number of boarding luggage and the presence of a pilot (manned service). To collect suitable SP data, the respondents are addressed to different fact sheets depending on the declared distance range travelled to reach the airport. Several related studies (Bacchini and Cestino, 2019; Hagag *et al.*,

2021) and eVTOL technical information provided by manufactures[5] were used to identify three distance ranges – 30, 60, 90 km – which are likely to be included in the airport catchment area (Rothfeld *et al.*, 2019). Furthermore, some fixed value variables are considered, i.e., the vertiport access time, the waiting time and the AS monetary cost per km (Table 3.2.). This latter has been used to compute the service fare based on the declared travelled distance. Only the due fare has been proposed to respondents.

Table 3.2 .– Fixed variables in SP scenario.

Main variables of the proposed AS service	
Travel distances ranges	30 km – 60 km – 90 km
Access time to vertiport	10 minutes
Waiting time at vertiport	10 minutes
AS trip monetary cost per km	2 €

The aforementioned values have been assumed in the perspective of a mid-term scenario (2030-2035), in the hypothesis that at that time there will be a suitable distribution of vertiports in the study area, easily accessible by ground transport. The egress time from the vertiport has not been considered because the destination vertiport has been considered placed next to the airport or embodied in the airport[6]. Also, access and egress time seem to significantly affect the total travel time (Balac et al., 2019; Lim and Hwang, 2019). However, in this SP experiment, which considers trips towards the airport, the assumption about negligibility of vertiport egress time at destination is coherent with recent orientations encouraging to start with AS services, in which the vertiport for accessing/egressing the air passenger terminal is included in the airport area, thus ensuring fast air-ground connections. As for vertiport waiting time – which consists of operational times such as security and boarding – it has been assumed by considering some UAM simulation results in the literature (Rothfeld *et al.*, 2021) in order to ensure an optimal level of service based on airport standards (IATA, 2019). Finally, the AS monetary cost per km has been defined based on several studies (Al Haddad *et al.*, 2020; Fu, *et al.*, 2019; Pukhova et al., 2021). It is worthwhile to note that the assumed monetary cost per km – which is equal for all the distance ranges – was derived from the literature by considering a mid-term scenario. Although it might be considered under-estimated for unshared services, however high-

[5] https://www.volocopter.com/wp-content/uploads/20220607_VoloCity_Specs.pdf

[6] This assumption is based on current trends and tests that have been planned and made in some cities, e.g. Rome, Italy, October 6 2022 (see also at: https://www.volocopter.com/newsroom/italys-first-vertiport-deployed-at-fiumicino-airport/), Paris, France, November 10, 2022 (see also at: https://skyports.net/vertiport-testbed-for-european-urban-air-mobility-testing-inaugurated-in-paris/).

automation levels – such in AS services – would confirm this preliminary cost estimate. In any case, cost reference values are still rather arbitrary, as the final cost will depend on several variables – which in turn need to be defined and estimated – and the operating environment as well as the business model adopted. SP methods offer the advantage to set cost values that will be considered by users as part of the alternative, thus reducing potential biases. Finally, it has been clearly described to respondents that the proposed AS service has the same safety standards as traditional aviation.

The SP alternatives are obtained by the combinations of two varying factors (running time and monetary cost). For each factor, two different levels were considered regarding eVTOL prototype features (Garrow *et al.*, 2021). Particularly, the estimated cruise speed (120 km/h or 200 km/h) has allowed identifying two sets of running times for the three different range distances. Similarly, seat capacity values (1 or 3 passengers per aircraft) have been used to compute appropriate fares related to unshared rides or rides shared with two other passengers, the latter being less expensive. The "full factorial design" obtained by combining levels and factors is showed in Table 3.3. for each considered travel range.

Table 3.3. – Full factorial design for the three distance ranges.

SCENARIO			***ALTERNATIVES***			
			1	**2**	**3**	**4**
30 km Scenario	*Factors*	*Monetary Cost (€)*	*60*	*60*	*20*	*20*
		Running Time (min)	*15*	*9*	*15*	*9*
60 km Scenario	*Factors*	*Monetary Cost (€)*	*120*	*120*	*40*	*40*
		Running Time (min)	*30*	*18*	*30*	*18*
90 km Scenario	*Factors*	*Monetary Cost (€)*	*180*	*180*	*60*	*60*
		Running Time (min)	*45*	*27*	*45*	*27*

Each respondent is assigned to the correspondent SP scenario (30, 60 or 90 km), depending on the distance travelled to reach the airport in his/her last air trip. Afterwards, the respondent has been asked to rank the available travel alternatives, i.e., the transport mode used to reach the airport and the four SP alternatives. As an example, the SP scenario for 90 km distance range is shown in Figure 3.1.

To identify users' declared preferences, respondents had to rate some variables based on the importance (from 1 to 5) they give to each variable (i.e., total travel time, waiting/service time, access/egress time, cost and privacy). Finally, to investigate respondent's perception about UAVs, they had to indicate if they would use an AS service operating with autonomous FVs, i.e., without pilot on board.

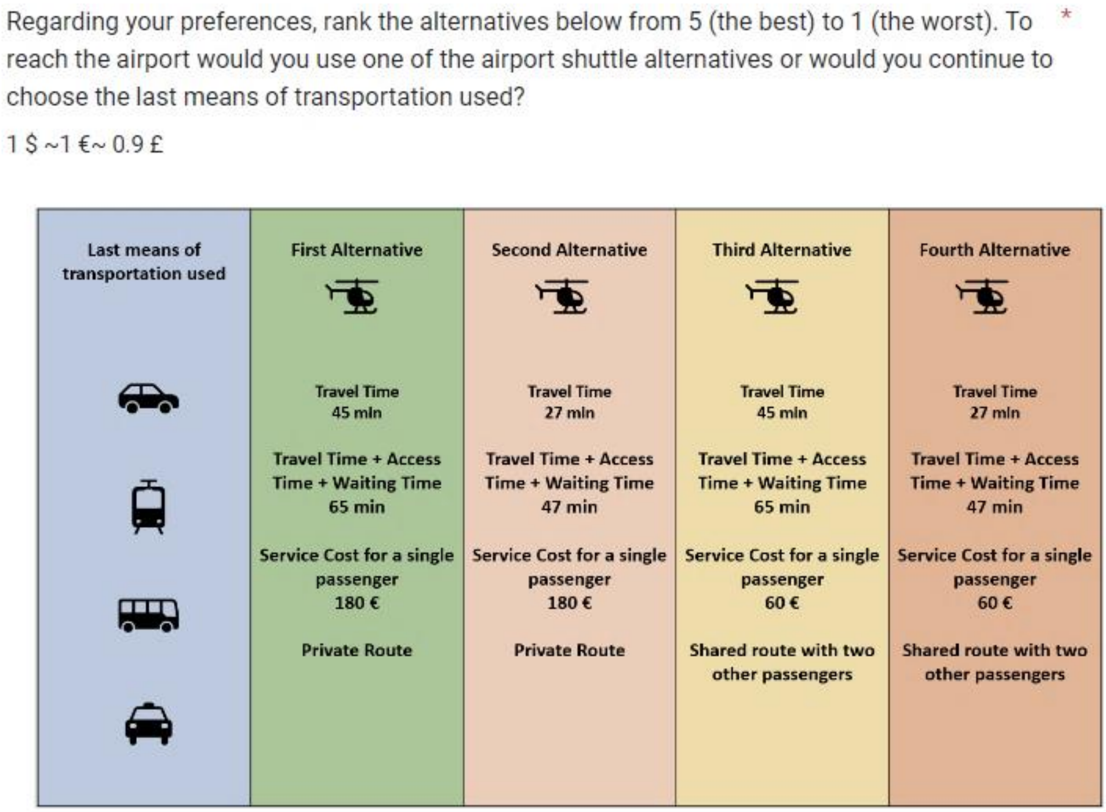

Figure 3.1. – Example of Stated Preference scenario for the 90 km distance range.

3.3.2. Discrete choice models

In order to estimate discrete mode choice models, the random utility theory has been applied. Particularly, the models have been estimated by introducing Multinomial Logit and Mixed Logit methods. The MNL average utility of each alternative *i* for an individual *n* is defined by the random utility model (Cascetta, 2001; Train, 2009):

$$U_{in} = V_{in} + \varepsilon_{in} \quad \text{with} \quad V_{in} = \beta_i^T x_{in} \qquad \text{(Eq. 3.1)}$$

where U_{in} is the utility associated with each alternative *i*; V_{in} is the systematic part of the utility; ε_{in} is the random utility component; β_i is a vector of the estimated parameters for alternative *i*; and x_{in} is a vector of the observable variables considered for each alternative *i*. The probability to choose the alternative *i* by individual *n* from a choice set C_n of alternatives is:

$$P(i|C_n) = \frac{e^{V_{in}}}{\sum_j e^{V_{jn}}}, \quad \forall j \in C_n \qquad \text{(Eq. 3.2)}$$

Furthermore, the ML models' specification provides for random taste variation and correlation in unobserved factors over the questions, and the probability is estimated through the following form (Train, 2009):

$$P(i|C_n) = \int \left(\frac{e^{\beta_i^T x_{in}}}{\sum_j e^{\beta_j^T x_{jn}}} \right) f(\beta) d(\beta) \qquad \text{(Eq. 3.3)}$$

where *f(β)* is the mixing distribution of the logit function. Particularly, in the following analysis the coefficients have been estimated by the lognormal distribution. The lognormal distribution allows theoretical consistency with the expected signs of the coefficients, although it could generate likelihood functions rather flat around the maximum, thus making convergence difficult to achieve, and could produce biased mean value or overestimated standard deviations due to its long tail (Hess and Polack, 200; Sillano and Ortúzar, 2005).

To obtain a steady estimate of the coefficients, several Monte Carlo simulations of 500 draws have been performed by different starting coefficient values, in order to obtain a convergent, stable solution.

Consequently, the general utility functions of the alternatives *i=1, 2…,j,* estimated through MNL and ML models, can be summarised as follows:

$$U_{i(MNL)} = \beta_{\text{Total Travel Time}_i} * \text{Total Travel Time}_i + \beta_{\text{Monetary Cost}_i} * \text{Monetary Cost}_i + \beta_{\text{RP-Choice}_i} * \text{RP} - \text{Choice factor}_i + \cdots + \beta_{\text{Age}_i} * \text{User age}_i \qquad \text{(Eq. 3.4)}$$

$$U_{i(ML)} = \text{Total Travel Time}_i * -e^{\left(\beta_{\text{Total Travel Time}_i} + \sigma_{\beta_{TTT}}\right)} + \text{Monetary Cost}_i * -e^{\left(\beta_{\text{Monerary Cost}_i} + \sigma_{\beta_{Mc}}\right)} * + \beta_{\text{RP-Choice}_i} * \text{RP} - \text{Choice factor}_i + \cdots + \beta_{\text{Age}_i} * \text{User age}_i \qquad \text{(Eq. 3.5)}$$

Where $\sigma_{\beta_{TTT}}$ and $\sigma_{\beta_{Mc}}$ are the standard deviations of total travel time and monetary cost factors. Finally, an important variable in transport mode choice models is the Value of Time (VOT), i.e., the amount of money a traveller is willing to spend to save a unit of time, estimated through the following equation (in €/hour):

$$\mathrm{VoT_i} = \frac{\beta_{\mathrm{Total\ Travel\ Time_i}}}{\beta_{\mathrm{Monetary\ Cost_i}}} \qquad \text{(Eq. 3.6)}$$

3.4. Data Analysis

The number of collected responses was 225, which is reduced to 197 because some invalid or biased observations were excluded. Regarding the information obtained by the RP survey, the sample is mainly composed by EU citizen with a little gender difference in the sample (only a little bit more male than female respondents). Furthermore, the majority of the respondents are in the age range 18 – 45 years, employees or students with, in general, a high education level. Occupations such as self-employed and manager positions are mainly declared by older respondents. Moreover, the most common air travel reason was “leisure” followed by “business” and “study”. However, the percentage of people that were travelling for business purposes is not negligible. Finally, it is important to note that the over-representation of some respondents’ categories in the sample (e.g., young respondents) could be caused by the on-line distribution method used to share the survey (social media or academic websites). To expand the amount of data and includes groups not “captured” by the on-line questionnaire, some face-to-face interviews were conducted at Bologna airport, which also reduces potential biases as on-line respondents might be categorised as “technology savvy”. Table 3.4. summarises the main sample features for all the collected data (online and face-to-face surveys), which refer to the population of the social networks of the considered platforms, and the average number of passengers for the average traffic day at Bologna airport. As expected, the most chosen transport mode used to reach the airport is the private car. In details, 60.8% of the respondents used the private car to reach the airport and, in particular, 43.2% used the private car as passenger and 17.6% as driver. Public transport (PT), taxi and train have been used by a limited number of travellers (16.6%, 11.6% and 11.1% respectively). Despite their low utilization rate, these two latter transport modes scored the highest respondent satisfaction levels as summarized in Figure 3.2., where satisfaction levels range from 1 (Totally Unsatisfied) to 5 (Totally Satisfied). On the contrary, it emerged that car drivers were less satisfied and even PT scored a higher satisfaction value. The difference in the satisfaction level between car drives and car passengers seems to affect users’ choice in the SP survey part. In fact, car drivers – who are the least satisfied – declared a higher willingness to use AS services compared to car passengers (60% and 49% respectively). This difference can be due to factors such as the lower perception of monetary costs and less stress associated with driving activities of car passengers compared to car drivers.

Table 3.4. – Survey sample features.

Characteristics		***Percentage***
Nationality	Italian	90.4%
	Other	9.6%
Age	18-25	33.2%
	26-35	38.7%
	36-45	13.1%
	46-55	10.1%
	56-65	4.5%
	>65	0.5%
Gender	Female	40.2%
	Male	58.8%
	Prefer not to answer	1%
Education	High school or lower	26.1%
	Bachelor's or Master's Degree	55.8%
	PhD or specialization course	18.1%
Occupation	Unemployed	0.5%
	Student	29.6%
	Employee	51.8%
	Self-employed	11.1%
	Manager	7%
Frequency	Annually	44.2%
	Biannually	19.1%
	Three-Monthly	18.6%
	Monthly	15.6%
	Weekly	2.5%
Travel Reason	Work	19.1%
	Study	7.5%
	Leisure	73.4%

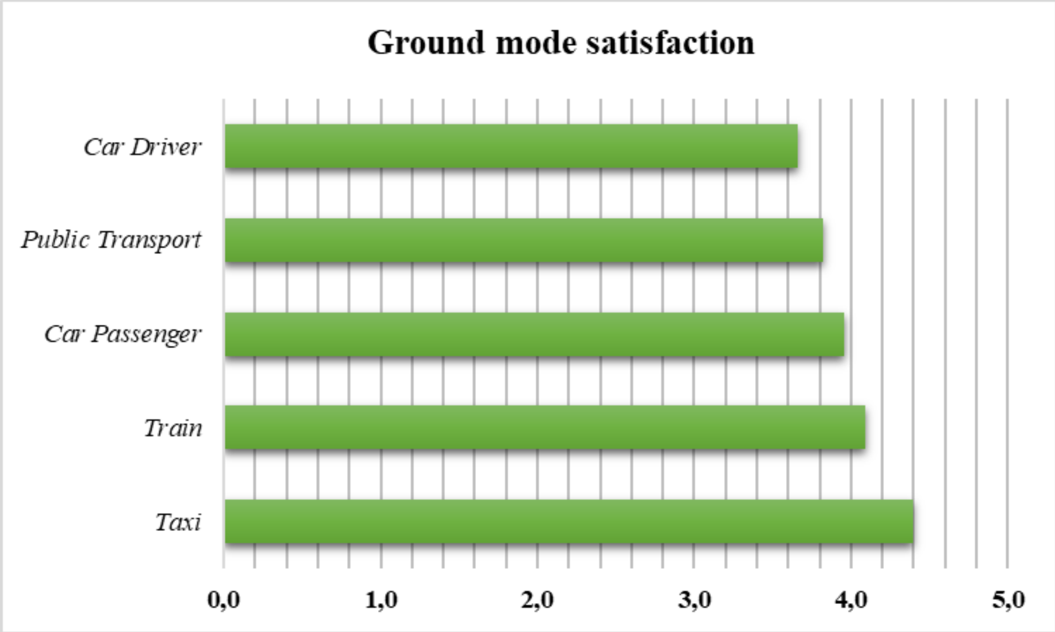

Figure 3.2. – Satisfaction of the different ground transport alternatives to access the origin airport.

Starting from the choices declared by the respondents in the SP module, several factors can be identified that support the introduction of AS services (Table 3.5.).

Table 3.5. – Preferences for AS services and respondents' features.

Characteristics		***Respondents confirming their used mode***	***Respondents choosing AS services***
Age	18-25	43.9%	56.1%
	26-35	53.2%	46.8%
	36-45	46.2%	53.8%
	46-55	40%	60%
	>56	60%	40%
Gender	Female	46.3%	53.8%
	Male	49.6%	50.4%
Education	High school or lower	44.22%	55.8%
	Bachelor's or Master's Degree	54.1%	45.9%
	PhD or specialization course	36.1%	63.9%
Occupation	Student	52.5%	47.5%
	Employee	47.6%	52.4%
	Self-employed	45.5%	54.5%
	Manager	42.9%	57.1%
Frequency	Annually	50%	50%

	Biannually	63.2%	36.8%
	Three-Monthly	32.4%	67.6%
	Monthly	45.2%	54.8%
	Weekly	40%	60%
Travel Purpose	Work	42.1%	57.9%
	Study	40%	60%
	Free Time	50%	49.3%

Firstly, the intention to use AS services seems to be mainly influenced by occupation, travel purpose and air travel frequency. Respondents who declared to work as manager or self-employed show higher willingness to use AS services compared to students and employees. Moreover, people who travel for business and study reasons would be more interested in fast connections between airports and urban areas made by FVs compared to people who travel for leisure. Another important factor, which seems to be relevant in addressing users' preferences, is the education level. People who got a PhD or a specialization course show a significantly higher intention to use AS services compared to people with a lower education level. Then, it emerges that unshared AS alternatives has been chosen by female respondents. This result might indicate different privacy perceptions depending on gender, which ultimately influence transport mode choices. Furthermore, a significant average difference in the intention to use AS services can be seen between people who travel frequently by plane (three-monthly or more) and the ones who travel annually. Furthermore, an important variable that could influence users' choices is the travel distance to reach the airport. User's preferences to use AS services increase as the travel distance to reach the airport increases. In fact, as reported in Figure 3.3., the percentage of users confirming their last used ground transport mode to reach the airport against the AS alternatives as first choice, drops in the 90 km scenario, which seems the most suitable distance range for starting conveniently AS services. Although, for the 30 and 60 km scenarios, most of the respondents seem to prefer their last used ground transport mode. However, in these two latter scenarios the AS fourth alternative has been chosen as first choice on average, by 40% of the respondents, which suggests that AS services could be competitive with ground transport modes even for short distances (30-60 km).

Finally, some respondent's characteristics seems to have only a limited influence on the willingness to use AS services. For instance, gender does not seem to significantly affect people AS alternatives choices, while only a slight difference has been detected for younger respondents (18-45 years) against older ones (higher than 45 years), the former seeming to be more inclined to use AS services on average.

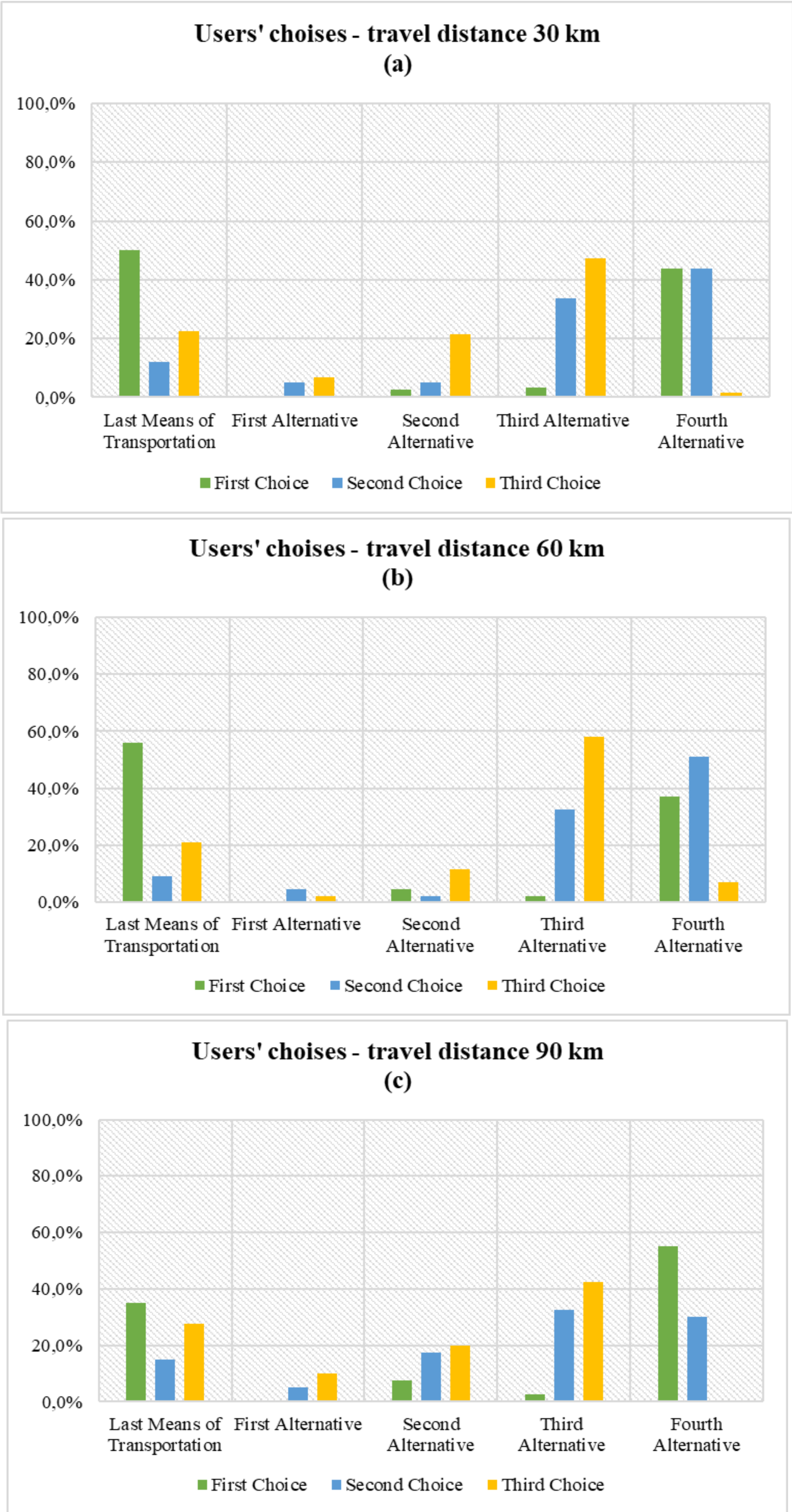

Figure 3.3. – Respondents' preferences for 30(a), 60(b) and 90(c) km.

3.5. Model Calibration

Data collected by both RP and SP surveys have been used to calibrate some discrete choice Multinomial Logit models and a Mixed Logit model, run by the free software Biogeme (Bierlaire, 2020). The choice set is composed of three SP alternatives – AS 2, AS 3 and AS 4 (see also Section 3.3.) – and the chosen RP transport mode, i.e., Private Car (PC), taxi, train and Public Transport (PT). No respondents have chosen Alternative 1, which in fact is the worst one and acted as "control alternative" for detecting potential biases.

Firstly, three different MNL model specifications have been tested in order to better identify the importance of the different variables and understand the factors that drive UAM demand.

The first MNL calibration model, which can be identified as the reference case, includes six relevant variables: monetary cost (MC), total travel time (TTT), privacy (P), age (Age), frequent flyer (FF) and "RP mode choice" (RP-C) dummy variable, which takes value 0 if the respondent chooses one of the AS alternatives and value 1 if the respondent confirms the initially chosen RP mode (Table 3.6.). Total travel time has been measured in hours and the monetary cost has been measured in €/100. Privacy takes value 1 for all the alternatives that allow a private run and 0 otherwise. Age and frequent flyer are still dummy variables (0,1). If the respondent is young (less than 35 years) the age variable takes value 1, while frequent flyer takes value 1 if travel frequency is higher than biannually.

Table 3.6. – Estimated Coefficients for the MNL - Model 1.

Variables	Alternatives						
	PC	Taxi	Train	PT	AS 2	AS 3	AS 4
TTT (h)	-0.69 (-2.07)	-0.69 (-2.07)	-0.69 (-2.07)	-0.69 (-2.07)	-0.69 (-2.07)	-0.69 (-2.07)	-0.69 (-2.07)
MC (€/100)	-2.46 (-4.76)	-2.46 (-4.76)	-2.46 (-4.76)	-2.46 (-4.76)	-2.46 (-4.76)	-2.46 (-4.76)	-2.46 (-4.76)
RP -C	/	/	/	/	-1.02 (-3.7)	-1.02 (-3.7)	-1.02 (-3.7)
Age<35	/	/	1.21 (4.5)	1.21 (4.5)	/	/	1.21 (4.5)
P	0.66 (2.34)	0.66 (2.34)	/	/	0.66 (2.34)	/	/
FF	/	/	/	/	/	/	1.2 (4.16)

* Not significant at 5% level (t-test in brackets)

Adjusted ρ^2 0.265
VOT 28 €/h
LL= *-194.69*

The results of Model 1 show the importance of monetary costs, whereas the total travel time seems to have a minor impact on the demand. In addition, using a private ride, age factor and being a frequent air traveller seem to positively affect the choice of AS services. Furthermore, as expected, users that confirm their initial RP choice are less likely to use AS services to reach the airport. The second MNL model (Table 3.7.) has been specified by adding a variable that aims to capture the users' experience regarding automation (e.g., driving assistance services), called "affinity to automation" (AtoA). Affinity to automation is a dummy variable that takes value 1 if the respondent declares no experience with driving assistance systems. The other variables are measured as in Model 1. As for the new introduced variable, its negative sign shows the existence of some scepticism towards advanced autonomous transport modes by users who have a low level of experience on driving assistance services. However, the "AtoA" variable is not significant at the fixed level (5%), and although the reluctance for autonomous vehicles should be considered because it could negatively affect the use of AS services, nevertheless it seems that in general users give more relevance to level of service factors rather than to autonomous/automated technologies.

Table 3.7. – Estimated Coefficients for the MNL - Model 2.

Variables	*Alternatives*						
	PC	Taxi	Train	PT	AS 2	AS 3	AS 4
TTT (h)	-0.75 (-2.24)	-0. 75 (-2. 24)	-0. 75 (-2. 24)	-0. 75 (-2. 24)	-0. 75 (-2. 24)	-0. 75 (-2. 24)	-0. 75 (-2. 24)
MC (€/100)	-2.33 (-4.47)	-2.33 (-4.47)	-2.33 (-4.47)	-2.33 (-4.47)	-2.33 (-4.47)	-2.33 (-4.47)	-2.33 (-4.47)
RP -C	/	/	/	/	-0.92 (-3.2)	-0.92 (-3.2)	-0.92 (-3.2)
Age < 35 years	/	/	1.19 (4.43)	1.19 (4.43)	/	/	1.19 (4.43)
P	0.60 (2.09)	0.60 (2.09)	/	/	0.60 (2.09)	/	/
FF	/	/	/	/	/	/	1.22 (4.23)
AtoA	/	/	/	/	-0.39* (-1.33)	-0.39* (-1.33)	-0.39* (-1.33)

* Not significant at 5% level (t-test in brackets)

Adjusted ρ^2	0.265
VOT	32.2 €/h
LL =	*-193.81*

Finally, the third MNL model (Table 3.8.) has been specified in order to test the influence of variables such as occupation (shadow variable for the average income), car availability, CA (measured as the ratio between the number of cars and driving licenses per family unit) and travel reason, TR (reference: leisure). Occupation and travel reason are dummy variables, particularly occupation takes value 1 if it is different from “student” or “unemployed”, while travel reason takes value 1 if it is equal to leisure. The other variables are measured as in the previous two models. In this specification, privacy and air travel frequency have been neglected as some preliminary tests do not show relevant additional information. From the results it emerges that valuable working positions (and consequently the annual income) would increase the propensity to use AS services. Same effects have been observed for taxi and train. Taxis have some similarities with AS services, because both are thought for providing fast, private and high-level transport services. As for train, a high number of respondents travelled by high speed trains (with higher costs and lower travel time compared to regional trains) to reach the airport. Again, there would be a similarity with rather expensive but fast AS services. On the other side, a high ratio between the number of cars and driving licenses per family unit seems to be an obstacle to the use of AS services, but also to the use of all the other alternatives that are different from private cars. Finally, people who travel for leisure seem to have less propensity to use AS services; however, the estimated coefficient is not significant at the fixed level (5%).

Table 3.8. – Estimated Coefficient for the MNL – Model 3.

Variables	*Alternatives*						
	PC	Taxi	Train	PT	AS 2	AS 3	AS 4
TTT (h)	-0.81 (-2.36)	-0.81 (-2. 36)	-0.81 (-2. 36)	-0.81 (-2. 36)	-0.81 (-2. 36)	-0.81 (-2. 36)	-0.81 (-2. 36)
MC (€/100)	-1.92 (-2.59)	-1. 92 (-2.59)	-1. 92 (-2.59)	-1. 92 (-2.59)	-1. 92 (-2.59)	-1.92 (-2.59)	-1. 92 (-2.59)
RP -C	/	/	/	/	-0.92 (-3.29)	-0.92 (-3.29)	-0.92 (-3.29)
Age < 35 years	/	/	/	1.14 (5.93)	/	/	1.14 (5.93)
CA	/	-0.69 (-1.98)	-0. 69 (-1.98)	-0. 69 (-1.98)	-0. 69 (-1.98)	-0. 69 (-1.98)	-0. 69 (-1.98)
Occupation	/	0.5 (1.97)	0.5 (1.97)	/	0.5 (1.97)	/	0.5 (1.97)
TR	/	/	/	/	-0.51* (-1.68)	-0.51* (-1.68)	-0.51* (-1.68)

* Not significant at 5% level (t-test in brackets)	
Adjusted ρ²	0.237
VOT	42.18 €/h
LL=	*-201.45*

Some common results can be deduced from the three MNL models. All the calibrated models confirm the importance of age in the willingness to use shared AS services, the relevance given by users to privacy as well as to ground transport modes that are already satisfactory for them, which could be a key obstacle to the development of AS services. Finally, the different models have similar adjusted ρ^2 values, but the first two have a slightly better value.

To explore the existence of sample heterogeneity, a ML model (Train, 2009; Brownstone et al. 2000; Yannis and Antoniou, 2007; Baek et al, 2021) has also been tested for analysing user's behaviour.

The tested ML model has been specified as Model 1 (see Table 3.6.), but travel time and cost coefficients have now been considered to have a lognormal distribution, which is often used for coefficients that are expected to have the same sign for each respondent (Train, 2009), as in the case of time and cost.

Table 3.9. – Estimated Coefficient for the ML – Model 4.

Variables		*Alternatives*						
		PC	Taxi	Train	PT	AS 2	AS 3	AS 4
TTT (h)	*mean*	-7.12 (-4.01)	-7.12 (-4.01)	-7.12 (-4.01)	-7.12 (-4.01)	-7.12 (-4.01)	-7.12 (-4.01)	-7.12 (-4.01)
	standard deviation	1.01 (3.82)	1.01 (3.82)	1.01 (3.82)	1.01 (3.82)	1.01 (3.82)	1.01 (3.82)	1.01 (3.82)
MC (€/100)	*mean*	-9.98 (-4.21)	-9.98 (-4.21)	-9.98 (-4.21)	-9.98 (-4.21)	-9.98 (-4.21)	-9.98 (-4.21)	-9.98 (-4.21)
	standard deviation	1.96 (3.75)	1.96 (3.75)	1.96 (3.75)	1.96 (3.75)	1.96 (3.75)	1.96 (3.75)	1.96 (3.75)
RP - C		/	/	/	/	-1.58 (-4.01)	-1.58 (-4.01)	-1.58 (-4.01)
Age <35		/	/	1.24 (3.74)	1.24 (3.74)	/	/	1.24 (3.74)

P	0.45* (1.76)	0.45* (1.76)	/	/	0.45* (1.76)	/	/
FF	/	/	/	/	/	/	1.25 (2.91)

* Not significant at 5% level (t-test in brackets)

Adjusted ρ^2	0.381
LL=	-180.15

The results (Table 3.9.) show that all the variables are significant at the fixed level (5%), except for privacy, which is significant at 10%. The adjusted ρ^2 value is better than the ones in the MNL calibrations, which is a common result in mixed-logit applications because the estimation of ML models results in a substantial improvement of fit over MNL models (Hensher, 2001). Travel time and cost variables seem to play a relevant role in choosing the transport mode; in addition, their variance parameters are significant, thus showing the existence of sample heterogeneity.

3.5.1. Model results and discussion

The first relevant result that emerges from all the calibrated models is the importance of the monetary cost variable (MC), which is highly significant in almost all the models. This result confirms the score assigned by the respondents to the different variables in the specific survey part, as described in Section 3.3. The service cost is considered the most significant variable with an average score of 4.23 (out of 5). In details, 83% of young respondents (18-35 years) assigned a score 4 or 5 (out of 5) to the service cost. Particularly, young users would use AS services if it were possible to share the route – and thus the monetary costs – with other passengers. On the other hand, only a limited number of people seems available to pay more to travel on a private route. In Model 1 and Model 2, the privacy (P) coefficient, which identifies private rides, has a similar value and is significant at the assigned level. In addition, it should be noted that only 24% of respondents who assigned a score 4 or 5 to privacy were younger than 35, thus suggesting that privacy is more important for older people (> 35 years) compared to young people (18-35 years). This result suggests that the main target users for AS services should be young travellers sharing a run, at least in the first stage of AS implementation.

The RP mode choice variable (RP-C), which has been introduced in all the considered specifications, is significant in all the calibrated models. As it can be seen, users' preference for the ground mode they usually utilize has a negative effect on the choice of advanced flight alternatives for reaching the airport. Particularly, for relatively short distances (between 30 and

60 km) from the airport, data have showed that users prefer to travel by their last used ground transport mode, which is confirmed again by model calibration.

Another common result in Model 1 and Model 2 is the positive influence of air travel frequency (FF) for the intention to use AS services. Like the privacy coefficient, the FF coefficient has similar values and significance levels in the two different model specifications, and it could also play a relevant role in the development of AS systems as accustomed air travellers are more likely to use FVs. This result is confirmed also by Model 4, where the coefficient value is quite equivalent to the first two models. Again, this could be useful to identify target groups to whom address primarily AS services.

Model 2 introduces a dummy variable for user's confidence towards automation and new technologies (AtoA), which should measure how and whether the experience with driving assistance systems could affect the willingness to use AS services. Although the coefficient is not significant at the considered level, however it emerges that a lack of experience with innovative systems could have a negative impact on the intention to use AS services. This has been found also for automated vehicles, both private and public ones, by confirming that user confidence in innovative systems is not immediate although safety standards are declared to be guaranteed.

From Model 3, an increasing ratio between the number of car and the driving license per family unit (CA) limits the use of all the other alternatives, except of course, private car. This confirms some other findings in the literature, as car ownership and private car use generally discourage travellers from choosing shared transport modes. In other words, the comfort provided by private cars, even though affected by congestion issues and high management costs, overcome the potential benefits of other transport modes, e.g., cheaper or more reliable modes. Moreover, the "Occupation" variable has a positive effect on the choice of transport modes that might be more expensive but can reduce travel times, like AS services or high-speed trains.

Although the variable related to travel reason (TR) resulted not significant at the considered level, however, the results show that users who travel for leisure tend to have a lower willingness to use AS services. This service would provide fast but expensive connections between airports and city centres, and it could be more suitable for business travellers.

Model 4 has allowed to analyse potential sample heterogeneity, particularly for time and cost variables – the same specification as in Model 1 has been used. Despite having a heterogeneous sample, the model confirmed the importance of travel time and monetary cost in choosing AS services. However, the coefficient values in Model 4 are higher than the ones obtained in Model 1, which is expected from previous literature results.

Moreover, the distance between the airport and the trip origin seems to have an important role for the development of AS services. In fact, the willingness to use AS systems rises as the distance increases. For shorter distances the advantages of AS services, mainly linked to the high cruise speed of the FVs (and the possibility to fly over congested areas), are overcome by the increased time that users would experience at the vertiport and to reach the vertiport itself.
Finally, in Model 1 and Model 2 a similar Value of Time – respectively 28 €/h and 32 €/h – has been estimated, whereas the VOT obtained in Model 3 is slightly higher (42.18 €/h). The estimated VOTs – which are averaged over the different alternatives considered in this analysis (from public transport to AS services) and for people with different age, occupation, educational level, and other socio-economic categories – overall are in line with the results obtained in other studies regarding UAM services. Particularly, values are close to the ones that have been obtained for the Munich scenario (Fu et al., 2019), where different VOTs have been estimated separately – from PT (27.47 €/h) to Air Taxi services (44.68 €/h). It is also worthwhile to note that here the airport access trips are considered, which are perceived more important – and then more valuable – than other trips (i.e., commuting). In fact, reliability, efficiency and fastness of ground transport modes for reaching the airport are relevant factors for travellers, that do not want to risk losing their flight due to deficiencies in ground access transport modes (Postorino et al., 2019). Then, it is realistic to consider that users' willingness to pay for saving time – and avoid, for example, flight loss risks – is significantly higher for air travellers than for commuters. As final comment about the VOT values, although there is some difference between the VOT values obtained by Models 1&2 and Models 3, it is too early to say which value would be more realistic, because UAM services are still far from being effectively realized and fully understood by potential users. Finally, as for Model 4 the VOT value has not been computed, based on the criticisms outlined by several authors (see for example Hess and Polack, 2004) about the bias due to the use of the ratio of means approach – generally used for computing VOT values – which is rather high in asymmetrical distributions like the lognormal.

3.6. Summary

In this chapter, the main key factors driving users' choice for AS services have been explored. Particularly, the obtained results might be considered preparatory to design suitable AS services in an UAM context. A first aspect is the importance given by younger people to the monetary costs of the service and the value of privacy for older users. This information can be used by stakeholders (especially service providers) to offer different types of AS services based on user categories. For example, it could be convenient to design shared runs targeted to young users having lower costs per passengers, which in addition can be useful to increase the load factor and maximize the revenues. Furthermore, before launching AS services stakeholders should evaluate users' satisfaction towards ground transport modes that are potentially competitive with AS services to ensure suitable demand levels. Since leisure travellers seem less interested in AS services than business travellers, another indication is to schedule these services based on the departure of business flights, which are usually identified as those offered primarily by full-service airlines at a time that ensures return trips in the same day. It is worthwhile to note that business travellers are often frequent flyers with high-income occupation. Therefore, targeting these groups is also consistent with the findings that frequent flyers and high-level income workers are more likely to use AS services. Finally, the most suitable distance for offering AS services is more than 60 km from the airport. Nevertheless, the opportunity to skip airport security controls – and save time – because they could already be done at the vertiport could make even shorter connections convenient.

Although the achieved results could be useful to identify the most important factors that stakeholders should consider attracting AS demand and to define some preliminary user's profile, however there are a few limitations affecting the study. The four models were calibrated by using SP data, which may suffer from some biases with respect to the calibrations obtained by RP data, as well-known from the literature on this topic. Furthermore, although the different models are specified with several socio-economic variables, however they do not include other variables that can affect users' choices such as security or safety or psycho-aptitude variables. Finally, the sample is mainly composed of young students or employees, while some other categories should be included for a wider estimate of the travellers' aptitudes.

After the analysis of the main demand features for AS services, the next chapters focus on the transport supply sub-system, both in terms of ground infrastructures and aerial network.

CHAPTER 4 – MODELLING UAM SUPPLY SYSTEM

This chapter is built upon the journal article:

- *Brunelli, M., Ditta, C.C. and Postorino, M.N., 2023. New infrastructures for Urban Air Mobility systems: A systematic review on vertiport location and capacity. Journal of Air Transport Management, 112, p.102460.*

The paper focuses on the main methods to design, planning and locate UAM ground infrastructures.

4. MODELLING UAM SUPPLY SYSTEM

4.1. Transport supply model introduction

The supply model allows simulating and planning transport services, infrastructure performances and constraints, as well as the main external effects like environmental pollution and energy consumption. In particular, the supply model topology relies on graph theory used to model relations between pairwise objects. The *transport network*, which is the basis of the supply model, consists of the set of nodes *N*, the set of links *L* and the vector of link costs *c* that measures link performances (Cascetta, 2001). The *nodes* are points with different space and/or time coordinates where the transport services can occur, by also representing the starting and ending points of trips in the study area. The *links* represent physical infrastructures and/or activities connecting the nodes identified in the graph. A sequence of consecutive links connecting an initial node (Origin, O) and a final node (Destination, D) defines the trip *path*, where each path is uniquely associated to an O-D pair. The *cost function* associated to each link measures the link performances (e.g., travel time, monetary cost) (Cascetta, 2001). The above-mentioned elements are essential for an appropriate specification of the transport supply system. However, planning and designing the UAM supply model is more challenging than other ground transport supply, since it would consist of 1) a ground supply model, involving UAM ground infrastructures to ensure the accessibility to the aerial services, which also have to be integrated with others transport modes in urban and suburban areas, and 2) an aerial supply model to guarantee FV flight operations and an effective level of service in the low airspace. In particular, the UAM ground infrastructures can be considered as the main nodes of the aerial supply model, as O/D points of FV trips.

To effectively implement the system, in this Chapter the UAM ground infrastructures will be examined, by reviewing the current models and methods in the literature to plan, design and locate such infrastructures in urban/suburban environments. The aerial supply models to simulate UAM operations in low airspace will be discussed in Chapter 5.

4.2. UAM ground infrastructures: Vertiports

The ground infrastructures design and location issues are the most significant among the challenges that the UAM supply system introduction entails. These infrastructures assigned to FVs for take-off and landing, parking, and recharging batteries have been commonly named *vertiports*. Several "vertiport" definitions can be found (EASA, 2021), and vertiports, skyports[7], vertistations, vertibases (NUAIR, 2020) are the most common terms generally referred to infrastructures with 5 to 10 take-off and landing pads. The vertihubs are identified as bigger infrastructures, with a high number (more than 10) of take-off and landing pads. Furthermore, vertipads and vertistations are smaller vertiports with one to three landing pads (Yedavalli and Cohen, 2022). In the following, the words vertipads, vertiports and vertihubs are used respectively for identifying small, medium and large UAM infrastructures.

The land occupancy required by a vertiport depends on its layout, which in turn depends on the planned number of pads and stands, so vertiport design and its location are interrelated. According to some studies (EASA, 2021), the vertiport suitable placement in urbanized areas can represent a relevant issue. For instance, wide, dense and congested urban areas with high income – such as New York, Los Angeles or Paris – are the most appropriate candidates to develop UAM services (Straubinger and Rothfeld, 2018). In fact, in these cases the potential demand level is proper for starting such services and the congested road conditions, together with the distances to be covered within the city, make the air services potentially more appealing than surface transport. To support UAM launch, Lineberger et al. (2019) suggest a seamless connection between ground and aerial mobility, by highlighting the importance of vertiport location to develop a multimodal transport network. However, in such dense urbanized areas it could be difficult to identify appropriate places where to allocate vertiports, given the high number of constrains (i.e., lack of space, noise restriction). Thus, vertiport location is a core element of on-demand aerial systems because it affects aspects such as the demand share and the total travel time (Rothfeld et al., 2019; Rothfeld et al., 2018). Especially, vertiport access and egress times are key factors to improve the attractiveness of UAM systems and they can be handled by a suitable vertiport location (Straubinger et al., 2020). Furthermore, the amount of vertiports, other than their location, in the service area has impacts on the attracted demand (Rothfeld et al., 2018).

Still, the vertiport design and location affect the vertiport capacity. In the air transport context, the term *maximum throughput capacity* (or saturation capacity) identifies the expected number of movements that can be performed in 1 hour on a runway system avoiding ATM rules disruption, by assuming continuous aircraft demand (De Neufville et al., 2013). Generally, the concept of (effective) capacity refers to the number of handled movements at a fixed level of delay, while throughput is referred to the actual airport number of arrivals and departures in a

[7] https://skyports.net/landing-infrastructure/

defined period of time. In this Chapter, vertiport capacity and vertiport throughput are used as synonym to indicate the number of operations (arrivals and departures) at a vertiport in a given time period, and where differences might be relevant, they will be explicitly considered.

In the following sections, a specific analysis of current vertiport layouts (included its effects on capacity) and location methods has been conducted, which are relevant factors for the successful implementation of UAM services. In addition, transport mode integration – i.e., between urban air transport services and urban ground transport modes – has been considered, which depends mainly on vertiport location. Other technical issues linked to vertiports, such as integration with electric grid, structural requirements and so on, have not been investigated because the focus is on transport networks.

The analysis has been realised by grouping the significant literature into two sets: 1) vertiport design and capacity, and 2) vertiport location. For each set, the most relevant variables, methods, research gaps and results have been examined and compared, in order to provide an overview about how vertiport design and capacity features could influence future UAM service implementation, as well as how the number and location of vertiports would affect the transport demand.

4.3. Vertiports layout and locations methods

4.3.1. Vertiports layout design

The UAM services feasibility in urban areas has been verified through simulations concerning test cases or real contexts. Most of these simulations have considered unlimited vertiport capacity (Rothfeld et al., 2018; Balac et al., 2019; Wu and Zhang, 2021), although the identification of the maximum number of flight operations at such ground infrastructures for a specific time period is a crucial aspect. Vertiport layout, station space and capacity requirements are important features of these infrastructures, which precede the choice of their location (Rajendran and Srinivas, 2020) and are closely linked to the size of the expected aerial vehicles. Some studies have considered specific FVs (or eVTOLs) prototypes to plan the vertiport elements, whereas some others have compared different prototypes in order to identify the "critical" one, similarly to what happens for designing the airport layout (Ashford et al., 2011). Nowadays, regulations on vertiports are in the early stage, as it emerges in the document presented by EASA, which describes "*prototype technical specifications for the design of vertiports*" (EASA, 2022). Given the lack of regulation for the vertiport layouts, current research is mainly based on heliport design regulations, because heliports are the ground infrastructures having the highest similarities with vertiports. Most of the studies reported in this section are based on regulations provided by the Federal Aviation Administration (FAA) “AC 150/5390-2C: Heliport Design” (2012) and the International Civil Aviation Organization (ICAO) “Annex 14 – Aerodromes – volume II – Heliports (2013). According to FAA regulations on Helicopter (FAA, 2012), the most important factors in designing heliport elements are the rotor diameter and the overall length or Maximum Dimension of helicopters. For most of the FVs prototypes, the distance between the two furthest rotors, or Tip-to-Tip Span (TTS), is equal to the flying vehicle Maximum Dimension (MD).

Recently, FAA has published new design guidance for vertiports (FAA, 2022), which are intended to give some indications for vertiport design specifically based on the emerging VTOL aircraft. However, such indications refer to nine emerging aircraft currently in development and have to be intended as a first attempt to address the vertiport design problem specifically. In fact, in the document it has been noted that “*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 in the future, as additional performance data is gleaned about these emerging VTOL aircraft. The AC will detail categories of vertiport facilities requiring different design criteria depending on the characteristics of the aircraft they plan to support as well as the activity levels at the facility.*” (FAA, 2022, page 3). The core elements of vertiport layouts are pads, gates, and stands. *Pads* are sites where FVs can take-off and land. Some specific areas can be identified for each pad, particularly a Touchdown and Lift-Off area (TLOF), surrounded by a Final Approach and Take-Off area (FATO), and an associated safety area (SA) to ensure safe operations. Those areas could have a circular, square, or rectangular shape. In order to have independent TLOF operations, a minimum 61m horizontal separation between FVs over the vertiport surface is required. *Gates* are sites where passengers are picked up and dropped off by FVs, with a suitable surrounding safety area – having different dimensions depending on the type of operations – to ensure a right separation among FVs on the vertiport surface. Finally, *stands* are used as parking places for aircraft (Preis *et al*., 2021; Vascik and Hansman, 2019). Table 4.1 and Figure 4.1. summarise the sizes adopted in most of the studies considered in this section.

Table 4.1. – Vertiport element dimensions based on FAA "AC 150/5390-2C: Heliport Design".

	TLOF	FATO	Gate area	Taxi route ground	Taxi route hover
Size	1 TTS	1.5 MD	1 MD	1.5 TTS	2 TTS

		Gate SA hover	Safety Area (SA)	Gate SA ground
Size		Gate size + max (3m, $\frac{1}{3}$TTS)	FATO + max (6m, $\frac{1}{3}$TTS) for each side	Gate size + 3m

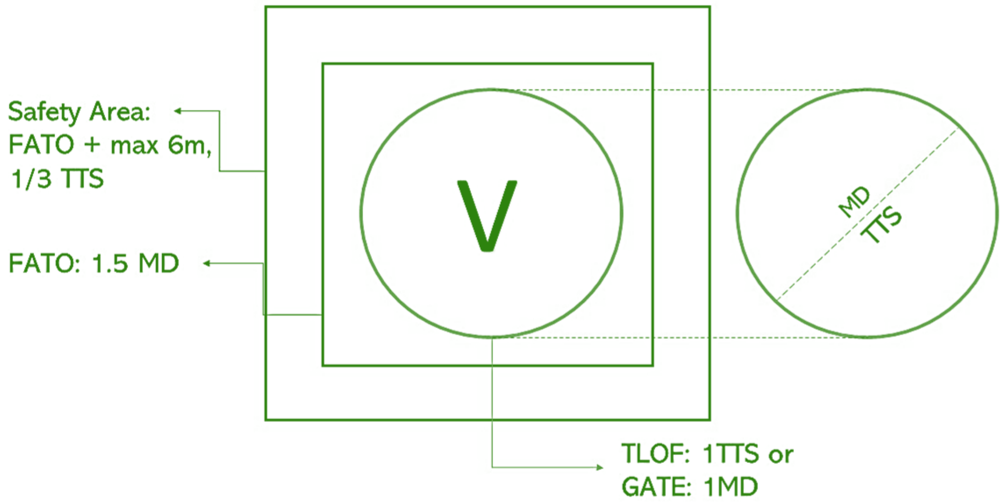

Figure 4.1. – Vertiport element dimensions based on FAA "AC 150/5390-2C: Heliport Design".

Most of the available studies on vertiport layouts consider that these three elements (pad, gate, stand) could be linked by some sort of taxiways, which would have different features depending on ground or hover operations, where ground (taxi) operations are defined as "*the surface movement of a wheeled helicopter under its own power with wheels touching the ground*" (FAA, 2012), whereas a hover (taxi) operation is a helicopter movement above the surface.

In the literature, some vertiport layouts have been proposed mainly within simulations and case studies. Most of them are based on what is currently used in helipad design, particularly satellite, pier and linear layouts (Vascik and Hansman, 2019; Preis, 2021) as showed in Figure 4.2. In some other studies, more complex layouts have been designed, such the ones proposed by Zelinski (2020), where four independent pads are placed in each corner of three different squared vertiport layouts (Figure 4.3.), or those proposed by Taylor et al. (2020), which range from a multifunctional single pad to a bigger layout with two separated pad and multiple gates.

Identifying a suitable layout is not trivial because it depends on the available space, which might be a problem in densely urbanized areas. Some studies developed appropriate tools in order to design the vertiport layout according to the available space, mainly identified in building rooftop surfaces (Taylor et al., 2020; Preis, 2021). Similarly, a vertiport virtually located in the airport parking garage rooftop of Cologne Bonn Airport (Feldhoff and Soares Roque, 2021) would be characterised by 1 TLOF and 6 gates; all the elements are designed by considering an FV with MD = 12 m. Another layout proposed by Schweiger et al. (2021) is characterized by passenger terminal area and vertiport surface completely separated, with boarding procedures realized by the "VTOL elevator" in order to avoid mixing transit of passengers on the ground with FV surface operations.

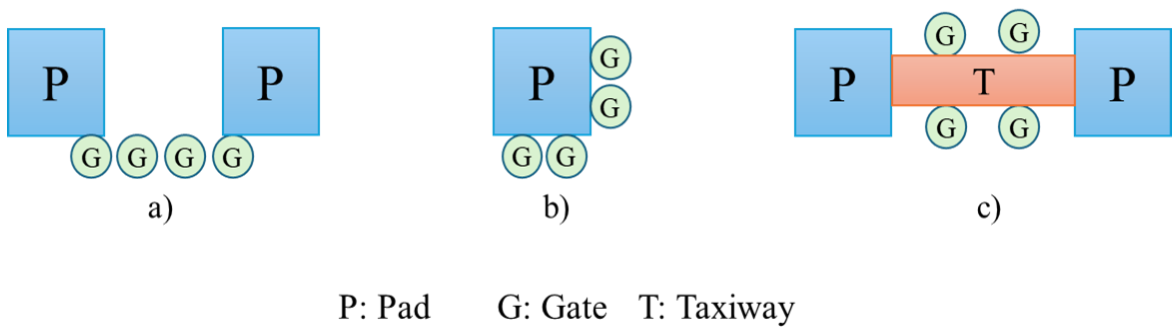

Figure 4.2. – Examples of Linear (a), of Satellite (b) and Pier (c) vertiport layouts.

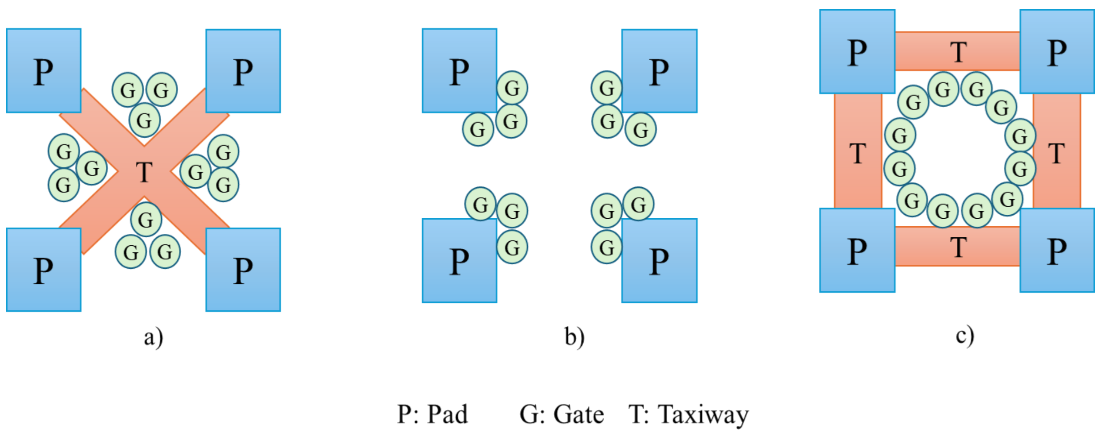

Figure 4.3. – Examples of squared vertiport layouts with 3 gates for each TLOF: Central (a), Disconnected (b) and Perimetral (c).

To estimate the size of the main vertiport elements – i.e., pads, gates and stands – Vascik and Hansman (2019) and Zelinski (2020) considered MD=13.72m, thus the TLOF diameter was fixed at 13.72m. On the other hand, Preis (2021) used three aerial vehicle types: small, medium and large, with a TTS equal to 5.1 m, 8 m and 15.7 m respectively.

Finally, some FV producers suggested similar vertiport layouts, based on the common, existing regulations on helipads. For example, vertiport configurations similar to single pad, linear and pier layouts have been proposed by Skyports[8] and Lilium[9].

4.3.2. Vertiport design problem and capacity

In order to assess the vertiport capacity, current studies have focused on the time needed for FV to clear TLOF pads during arrival and departure procedures. In fact, the vertiport capacity depends on the time required for take-off and landing as well as on the vertiport layout. From one hand, pads must be cleared quickly in order to be available for other vehicles; on the other hand, different numbers of TLOFs and gates, as well as their organization on the vertiport surface, have impacts on the vertiport capacity.

An early study estimated that the landing time at vertiport would be 75s and the take-off time would be 60s (Holden and Goel, 2016). Numerous analyses have adopted similar time values for these operations, as showed in Table 4.2., although recently 180s is proposes as arrival and departure times, accordingly with a "*discussion with the air navigation service provider in Germany*" (Feldhoff and Soares Roque, 2021).

To compute the pad number able to satisfy a given travel demand, some studies have modelled each vertiport (or vertipad) as a M/M/1[10] queue system, by assuming suitable values for take-off and landing times as well as for the average FV load-factor (Goodrich and Barmore, 2020; Preis, 2021). Hypotheses on the maximum average waiting time have allowed to verify how the initial vertipad throughput would change and how strategies such as the use of larger FVs with higher seat capacity and load-factor, or pads that can execute independent air operations, might reduce the number of required vertipads and then the required land spaces (Goodrich and Barmore, 2020). Furthermore, different layouts have been designed for different vehicle sizes and the capacity for several vertiport layouts composed of pads, gates, and taxiways (time

[8] https://skyports.net/landing-infrastructure/

[9] https://lilium.com/newsroom-detail/designing-a-scalable-vertiport

[10] The Kendall notation is generally used to describe queueing models. In this case, the used notation is M/M/s where the first *M* denotes the "input", i.e. the exponential distribution of the time between two arrivals; the second *M* identifies the "queue-discipline", i.e. the exponential distribution of the service time; *s* indicates the "service-mechanism", i.e. the number of service channels (Kendall, 1953).

parameters reported in Table 4.2.) based on independent TLOFs has been estimated by setting an Integer Programming (IP) problem (Preis, 2021). The resulting model was also able to identify if bottlenecks were caused by pad or gate operations. The number of gates required by TLOF areas to maximise throughput has been expressed as an IP problem (Vascik and Hansman, 2019), by finding that the number of gates *per* TLOF rises as the turnaround time increases or arrival and departure times decrease, and *vice versa*. A strong influence of surface times (i.e., ground operation times) on the number of gates *per* pad has also been observed, by analysing the vertiport capacity through a First-Come-First-Served (FCFS) scheduling approach (Guerreiro *et al.,* 2020). It emerges that a FCFS approach can lead to a decrease of vertiport throughput, also for a single vertipad configuration (Goodrich and Barmore, 2020). Nevertheless, for on-demand operations, a FCFS could be the best option from the user perspective. Still, the IP problem is employed to analyse the vertiport capacity in terms of passenger demand, by considering three different layouts (i.e., linear, satellite, pier) designed following FAA and EASA design indications released in 2022 (FAA, 2022; EASA, 2022; Ahn and Hwang, 2022).

Vertiports with the same features and independent TLOF operations have also been tested under different wind conditions by using the theoretical model of FCFS approach to evaluate size and capacity under the hypothesis of a maximum number of 5 gates *per* TLOFs (Zelinski, 2020). The results have shown that vertiport layouts with a high number of gates connected with different pads (also called “taxi connectivity”) could operate also under severe wind conditions. Most of the studies presented above assumed independent TLOF operations and no stands in vertiport layouts. However, a suitable availability of stands, as well as independent TLOF operations, might increase the throughput also for unbalanced arrivals or departures (Vascik and Hansman, 2019). Moreover, the same study showed that partially dependent operations, which consist in paired departure flights or paired arrival flights on adjacent pads, would lead to a substantial capacity increase compared with dependent operations, and to less unbalanced operations compared to independent pads.

Finally, it is worthwhile to note that congestion on the vertiport surface, especially during peak hours, could decrease the overall throughput. Microsimulation of ground operations is an approach to investigate congestion problems on vertiport surface, which allows verifying different layouts also by using agent-based models (Preis et al., 2021).

Table 4.2. – The most relevant variables and approaches in studies on vertiport capacity.

Authors	***Take off/ Landing operating time***	***Surface time (*)***	***Speed***	***Approach***	***Capacity***
Ahn and Hwang (2022)	60s	15s taxiing time + 300s Turnaround time		IP problem to evaluate the maximum throughput of several layouts	80 passenger/h for each TLOF pad with 4 gates
Feldhoff and Soares Roque (2021)	180s	1800s (30 min) battery loading + 60s taxi time		Operational simulation during daytime with good weather conditions	9.6 movements/h
Goodrich and Barmore (2020)	72 s		cruise speed of 130 knots	M/M/1 queueing model with an average waiting time less than 4 min	Strongly dependent on number of TLOF and gates
Guerreiro *et al*. (2020)	60s	From 120s (minimum) to 900s (15 min) (average)		FIFO queueing model to estimate vertiport capacity with no assumption on vertiports layouts	No more than 38 operations per hour
Preis (2021)	From 30s to 90s depending on vehicle type	60s, 300s or 1200s (20min) depending on the operation		IP problem to evaluate the maximum throughput of several layouts	60 to 780 movements/h depending on the layout and dimensions
Vascik and Hansman (2019)	From 15s to 90s	Turnaround time 30-600s Taxi time 5-90s	Ground speed < 20 knots	IP approach to evaluate the maximum throughput with different operations and number of elements	Strongly dependent by the number of gates per TOLF
Zelinski (2020)	60s	480s (8 min) spent at the gates + average taxi time depending on the layout	average taxi speed of 4 ft/s	3 vertiport layouts tested under wind constraints	Strongly dependent on the layout configurations

(*) if not explicitly reported, turnaround time is included in taxi time and battery time

4.3.3. Vertiports location requirements and constraints

Another important issue to be solved – related to UAM ground system implementation – is the identification of the most suitable places where vertiports should be located, as they are the access/egress nodes of the aerial supply model. The number of existing heliports in urban areas, which at a first attempt could be used as vertiports, is too low to support the expected UAM operations, which might be a key constraint especially in the long-term (Vascik and Hansman, 2017). In fact, in order to provide a good urban accessibility and attract transport demand, vertiports should be easily available in space by ground transport modes, as part of a multi-modal, interconnected air-ground transport system. It is worthwhile to note that changes in ground accessibility and travel time could lead to transformations in the city structure, land rents and commuting connections (Straubinger and Rothfeld, 2018).

The main, relevant factors considered to evaluate the appropriateness of potential locations are: 1) physical spaces required for vertiports, which depend on FVs features, size of passenger service buildings, air vehicle charging areas and needs for future expansions; 2) obstacle clearance; 3) environmental constraints.

The first aspect has been implicitly discussed in the previous sections. As for the last two, obstacle clearance involves the volume surrounding vertiports, which have to be obstacle free for not hindering FVs operations, while environmental constraints mainly deal with the need to limit noise impacts and to operate in suitable wind conditions.

In order to use efficiently existing resources, some locations such as parking garages, bus terminals, hotels have been analysed by investigating specific parameters, such as passenger accessibility, existing obstacles, noise impacts on the adjacent buildings, expandability, applicability and strategic availability (Feldhoff and Roque, 2021). In addition, potential obstacles at each intended vertiport site have been numbered to provide a “free space” indicator.

A key aspect for locating vertiport is the existence of overflight limit of adjacent private properties, explored by Antcliff (2016). The aforementioned study proposes to provide aerial transport services by improving existing infrastructures to be used as vertiports, to minimize land consumption and the amount of private owned land affected by operations. For instance, in urban environments cloverleaf interchanges are proposed to be used as vertiport sites, in order to avoid overflying adjacent private properties, ensure better ground accessibility by minimizing ground travel times, and limit noise impacts. As for this latter, the study suggests that the additional noise due to FVs would be less perceived given that cloverleaf interchanges are generally very noisy.

Candidate locations have to consider environmental constraints, mainly related to wind characteristics and noise impacts in the urban context. Particularly, the wind actions could affect flight operations, thus, it is necessary to assess wind directions and speed distributions in zones where the vertiports would be located (Otte *et al*., 2018), also in order to prevent the "canyon effect" due to the heterogeneous structure of the urban environment. It is worthwhile to note that vertiport siting restrictions are also related to the downwash effect, which is defined as the air forced down by the aerodynamic action of rotor blades in motion, generated by the landing and take-off operations (Crane, 1997). In particular, downwash effects involve not only the vertiport Safety Area, but also the neighbouring areas, especially if the vertiport is not significantly elevated. Based on an adaptation of the "Australian Government Civil Aviation Safety Authority Part 139 (Aerodromes) Manual of Standards 2019", EASA (2022) has established different "*maximum downwash velocities*" according to the type of area affected by that effect (e.g., public areas within or outside the vertiport boundary; vertiport areas where flight crew or passengers move; buildings and other structures).

Finally, the identification of suitable areas for vertiports is crucial to set UAM services because interconnection with ground transport systems must be guaranteed.

For all these reasons, this important issue has been investigated and some factors potentially affecting the choice of appropriate areas have been selected (Preis, 2021) and analysed. These factors have been grouped according to five main criteria (airspace clearance, building/architecture, community approval, surrounding transport system, other), and categorized into four expected effects, such as positive effect, unclear effect, negative effect, make-or-break effect. The analysis showed that the most relevant factor affecting vertiport location is the proximity to the intermodal nodes and the final destinations of individual journeys. These results are in line with the perspective that UAM services – and then the vertiport location as access points to such services – are intended as part of a multi-mode, multi-service transport system, which will satisfy different types of transport needs ranging from reliability and fastness to resilience and safety.

4.3.4. Vertiport location: analytical methods

Besides the physical constraints and requirements related to vertiports location, some analytical approaches have been explored which currently are proposed to solve the vertiport location problem. Particularly these approaches can be grouped on geographic information systems (GIS data comparison approach), algorithmic (K-means approaches) and optimization problems (function objective-based approaches) (Figure 4.4).

The Geographic Information Systems (GIS), usually employed to analyse and compare different types of spatial data, have been used in the literature as tools for selecting suitable places where to allocate vertiports. Particularly, studies have focused on the weighted overlay of several factors such as socioeconomic variables (e.g., population, jobs densities, median income), points of interest (POI) for tourists, positions of relevant ground transport nodes, existing heliports, potentially suitable spots (e.g., rooftops) and prescriptive factors such as noise constraints, no flying zones (schools or military areas) and ground accessibility variables (Fadhil, 2018; Delgado Gonzalez, 2020).

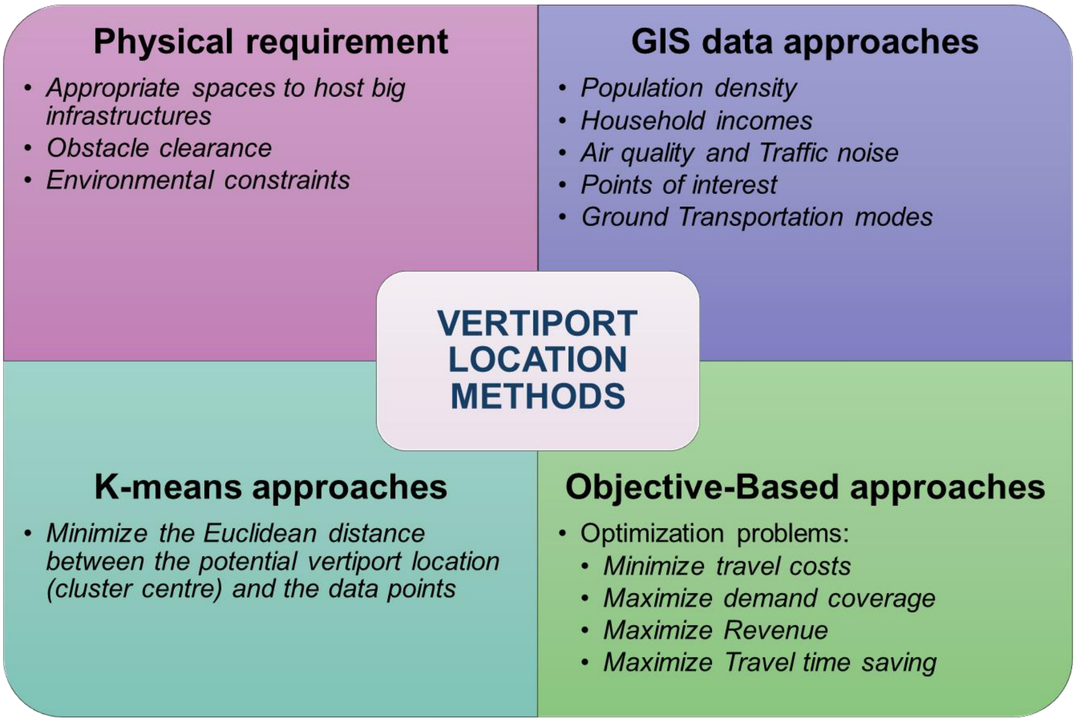

Figure 4.4. – Methodologies identified for vertiports placement.

Socio-economic and infrastructure features in the services areas are preliminary factors to be considered for selecting suitable vertiport locations, which have to be well connected with the existing ground transport systems in order to be easily accessible to potential passengers. However, flight regulations and their effects on the use of lower airspace are even more significant due to they could lead to a limitation of UAM operations, which will reduce the number of suitable areas where vertiports can be placed. To ensure safe operations, the concept of *geofences* around fixed obstacles – such as buildings, antennas, cranes – are introduced to identify suitable areas and avoid problems related to privacy, noise and wind gust (Bauranov and Rakas, 2021). From a practical point of view, the introduction of geofences virtually increases the volume of the obstacles and reduces the available ground area as well as the airspace for UAM operations. For example, by considering city areas characterized by a significant density of high buildings, such as Manhattan but also the urban areas of San Francisco or Los Angeles, the introduction of 30 m geofence would produce a severe reduction of the suitable airspace for UAM operations (Kim and Yoon, 2021).

Table 4.3. summarizes the most suitable places for vertiports as explored in the literature through a GIS approach, which are city centres (with high job densities and office rent prices), areas with high-income residents, spaces close to POIs and interchange transport nodes (e.g., airports, train stations) for ensuring multimodal trips. As for these latter, given the existing high levels of noise pollution at interchange transport nodes, noise externalities produced by FVs would generate only marginal, the adequacy increases if vertiports are placed near those areas.

Table 4.3. – Main variables and results for locating vertiports by using GIS approaches.

Author(s)	***Variables***	***Constraints***	***Simulated area(s)***	***Results***
Delgado Gonzalez (2020)	Population, population density, median household incomes, median gross rent, air quality, traffic noise, POIs	Rooftop footprint and flatness	Manhattan	Only 5.6% building with high suitability. Little amount of space for vertihubs.
Fadhil (2018)	Population density, median income, office rent price, POIs, major transport nodes, annual transport cost, job density, extreme commuting, existing noise	No fly zones on schools and military areas	Monaco and Los Angeles	The best candidates are major transport nodes, areas with high income and city centre.
Kim and Yoon (2021)	Population density on daytime and night-time	Airspace reduction caused by geofences	Manhattan and San Francisco	The presence of geofences reduce vertiport suitability

Another relevant analytical method uses K-means algorithms to group data points into a certain number (K) of clusters to locate vertiports. The different clusters are identified by minimizing the average squared Euclidean distance between the centroids – or cluster centres – and the data points (Schütze *et al*., 2008).

The centroid ($\vec{\mu}$) of a cluster (ω) is defined as:

$$\vec{\mu}(\omega) = \frac{1}{|\omega|}\sum_{\vec{x}\in\omega}\vec{x} \qquad \text{(Eq. 4.1)}$$

The Residual Sum of the Squares (RSS) is the squared distance between the centroid and each vector summed over all vectors, which represents a measure of how well the centroid represents its clustered data:

$$RSS = \sum_{k=1}^{K} \sum_{\vec{x}\in\omega_k} |\vec{x} - \vec{\mu}(\omega_k)|^2 \quad \text{(Eq. 4.2)}$$

To obtain representative clusters, the algorithm searches for the minimum RSS. To run the K-means algorithm, the number of clusters (K) is fixed before starting the process. Very shortly, the algorithm proceeds with K cluster centres randomly selected (the *seed*) and then changes the currently selected centroids in order to minimize RSS (Schütze et al., 2008).

In the UAM literature, this method has been employed to minimize the distance between the potential vertiport location (identified as cluster centre) and the data points, which are the trip origin and destination points obtained from available commuting trip data (Table 4.4.). As an example, a K-means algorithm based on eqs. (4.1) and (4.2) was used to allocate different vertiports starting from commuting trip data of Seoul metropolitan area (Lim and Hwang 2019; Jeong et al., 2021). The vertiport number is an input data for K-means algorithms, so that its identification has great relevance both for the vertiport location and the vertiport network. In addition, by considering several scenarios with different vertiport numbers and by comparing travel times for car, PT and UAM services after locating vertiports by a K-means algorithm, it has been observed that suitable locations of vertiports is more important than their number. In other words, increasing the number of vertiports after a given number has not positive effects on the total travel time (Lim and Hwang, 2019). This study has also highlighted that vertiport access and egress ground travel times might dominate UAM total travel time, depending on number and location of vertiports. Then, to promote the development of UAM services it will be important to provide short vertiport access and egress ground travel times by considering vertiports as nodes of multi/intermodal transport systems.

K-means algorithms provide vertiport locations according to data points and, possibly, some other relevant information. After obtaining preliminary results, it could be convenient to re-allocate vertiports suitably in the neighbouring of the centroids, when the identified location could generate problems such as noise and flight prohibitions (Jeong et al., 2021). Furthermore, re-allocation can be adopted to use efficiently already existing resources. Parking lots and helipads are examples of the places selected during the repositioning procedure. Some modification to the K-mean algorithm have also been proposed to solve some drawbacks. An iterative constrained clustering approach was developed in order to introduce flexibility in the number of vertiports to be allocated (Rajendran and Zack, 2019; Sinha and Rajendran, 2022). This iterative method allows starting the K-means algorithm with a given number of vertiports, but such number is iteratively increased until several constraints are satisfied. In addition, to improve the K-means results, a "warm start technique" was also proposed in order to create an initial seed generation solution, composed by locations selected by considering multimodal transport systems and tourism options (Rajendran and Zack, 2019) or several socio-economic variables (Sinha and Rajendran, 2022).

Table 4.4. – Summary of studies using K-means algorithms and their variants.

Authors	***Approach***	***Location***	***Algorithm constraints***
Lim and Hwang (2019)	Traditional K-means algorithm	Seoul	Preliminary definition of the vertiports number (i.e. cluster number)
Jeong, So and Hwang (2021)	Traditional K-mean algorithm		
Rajendran and Zack (2019)	Iterative K-mean algorithm with warm start technique based on multimodal transport	New York	Travel time saving, limitation on access/egress distance, threshold on demand fulfilment rate and willingness to fly
Sinha and Rajendran (2022)	Iterative K-mean algorithm with warm start technique based on socio-economic variables		

Furthermore, some results have emerged by maximizing or minimizing different objective functions for locating suitably vertiports, in particular by extending the Hub Location Problem (HLP). HLP approaches find the optimal locations of hub nodes in a network, in order to satisfy a given goal – the "objective" – such as minimizing O/D pair distances or travel times or maximizing profit from hub facilities (Farahani *et al.*, 2013).

In the UAM context, users leave from an origin O, reach the nearest vertiport, fly to the destination vertiport and finally move towards the final destination D. A set of studies explored the optimal location of vertiports by minimizing the total travel cost of the system, particularly the generalized travel cost, which includes travel costs, fixed and operating costs of facilities, and collision risk costs (Shin *et al.*, 2022). Another study investigated how travel times could change with the choice of optimal vertiport locations by formulating the vertiport location problem as an Uncapacitated Single Allocation *p-hub* median Location Problem (USAMpHLP), which minimizes the travel time to get airports from the origin points (Rath and Chow, 2019). The problem introduces several constraints, such as the *p* vertiport number and the so-called single allocation (i.e., travel demand at each origin O is satisfied *via* a single vertiport). In addition, the choice to reach an airport by vertiport or ground transport is a decision variable in the optimization problem. In a further study, Rath and Chow (2021) have considered demand coverage maximization to find vertiport optimal locations, by analysing elastic demand response and introducing short-term and long-term price scenarios to define vertiport location in urban contexts. In this case, the vertiport location problem includes two parts: the "*ridership maximization problem*", which optimizes air taxi ridership for OD pairs, and the "*revenue maximization problem*", which maximizes the revenue generated by air taxi ridership. To take into account the existence of zones characterized by environmental constraints (e.g., restrictions for airspace or ground areas), also said "non-hubable", the Uncapacitated Single Allocation p-Hub Median Problem (USApHMP) has been formulated still to maximize demand coverage.

In several research, a *location-allocation problem* approach was chosen to identify suitable places where allocate vertiports. Socio-economic factors and accessibility parameters have been employed to select suitable places by 1) maximizing demand coverage and 2) minimizing the travel cost (Arellano, 2020). This approach has been adopted to place vertiports and simulate UAM networks in Munich, Paris and San Francisco areas by using only motorized travel demand data (Rothfeld *et al.*, 2021).

Optimization algorithms to maximize the UAM demand coverage have been used by exploiting mode choice models calibrated for specific areas (Rimjha *et al.*, 2021). In particular, an iterative algorithm has been used to identify the optimum vertiport locations able to satisfy the UAM demand, given the desired number of vertiports (to be placed in the study area) and the assumed UAM cost per passenger mile.

With the same purpose, Zeng *et al*. (2020) propose an optimization method to find the optimum distribution of vertiports (called "droneports" in the paper) based on a pre-specific vertiport number to satisfy a point-to-point service, both for parcel delivery and passenger transport demand coverage. The problem is specified to obtain the optimum vertiport number that maximizes subzone and area coverage.

Another approach was proposed by Holden and Goel (2016) in two steps. The first one is the identification of a given number of vertiport locations by using the K-means algorithm, which has led to 100 feasible vertiport locations by considering long-distance trip data (more than 20 miles). Then (second step), the 100 vertiport locations have been chosen as starting point to select an optimal subset (e.g., 25, 35, 50 and 70 vertiports) able to maximise the total trip coverage and satisfy a set of constrains (e.g., at least 40% faster compared to ground trips, all riders are covered by one itinerary and minimum distance between two vertiports).

Finally, vertiport optimal locations that maximize travel time saving have been found by using an IP optimization model and data such as population, household income, mode of transport and the origin and destination pairs for home-work trips (Daskilewicz *et al.*, 2018). A summary of the different objectives and approaches used to locate vertiports in urban areas is reported in Table 4.5.

Table 4.5. – Summary of different objectives and the approaches used by the examined studies.

Author(s)	***Objective to be optimized***	***Modelling***
Arellano (2020)	*Travel costs (minimize)*	Location – Allocation Problem
Rothfeld et al. (2021)		
Chen et al. (2021)		Constrained Hub Allocation Problem
Rath and Chow (2019)		
Shin et al. (2022)		
Arellano (2020)	*Demand coverage (maximize)*	Location – Allocation Problem
Holden and Goel (2016)		Large-scale integer program used to select optimal vertiport position under several constraints
Rath and Chow (2021)		Constrained Hub Allocation Problem
Rimjha et al. (2021)		Optimization Algorithm based on a calibrated mode choice model
Zeng et al. (2020)		Optimization Location – Coverage Method
Rath and Chow (2021)	*Revenue (maximize)*	Constrained Hub Allocation Problem
Daskilewicz et al. (2018)	*Travel time saving (maximize)*	Vertiports placement to maximize travel time savings compared to ground transport

As general result, all these objective function models confirm that for travel time saving a correct vertiport positioning is more important than having a great number of infrastructures, while in terms of demand fulfilment and access/egress maximum travel distance, it emerged that the number of vertiports is as relevant as their placement.

4.4. Summary

In this Chapter vertiports have been analysed as part of the UAM network model – i.e., interchange nodes between ground-air and air-air transport modes. The main literature findings previously discussed are summarised as follows. Among some others, aspects related to vertiport suitable location and operational features are of utmost importance. As an example, vertiports located within or close to airport areas could support travels to/from the airport over the short distance (100-150 km) for the integration of air-to-air services, by increasing the airport potential catchment area especially for regions lacking in ground transport services to access/egress the closest airport. Still considering the vertiport-airport relationship, the suitable location of vertiports in the airport neighbouring areas plays a key role in intercepting latent or unexpressed air transport demand. In addition, the operational features of vertiports, mainly measured in terms of capacity and/or throughput, represent an important aspect depending not simply on management rules, but also – and mainly – on size, layout and surrounding environment. Indeed, vertiport design refers to the different approaches proposed for setting possible layouts and their effects on capacity, whereas vertiport location refers to the methods used to choose suitable areas to allocate vertiports by taking into account their role as both infrastructure elements of the UAM network and service stops for transport demand. Since vertiports will be the ground infrastructure from which FVs will take-off and land, their capacity and position – which must allow safe landing/take-off operations – could severely affect UAM service performances.

To summarize the relevant findings from the literature, the number of gates per TLOF is one of the most important features in designing vertiports. As expected, its underestimation reduces the vertiport capacity/throughput, whereas its overestimation rises the vertiport size without strongly increasing its capacity/throughput. In addition, size increment is not always allowable due to potential constraints in the surrounding environment – e.g., buildings, ground obstacles, unsuitable transport ground links among the others. The identification of the suitable number of gates per TLOFs is an essential design factor, which depends on the FVs arrival/departure time and vertiport operations (e.g. boarding and deboarding time, battery charging time and taxi time). Furthermore, independent TLOFs could sharply increase vertiport throughput while stands would help mitigating the negative effects of unbalanced arrivals and departures. Finally, vertiport layouts have to be chosen by considering turnaround times and wind conditions in order to maximize throughput and guarantee safe operations for any weather conditions. For example, studies showed that satellite layouts have better performances with small turnaround time and require little space, which make them suitable for dense urban areas. However, satellite configurations are strongly penalized in case of unfavourable wind conditions. On the other hand, perimetral, central, pier and linear layouts are more resilient to weather conditions and have better performances on unbalanced arrivals and departures, but they need a large amount of space compared to satellite layouts. As vertiports are nodes of the UAM network, the advantages and disadvantages of the different layouts must be considered with respect to the context and the exigencies, with the main aim to develop effective and efficient UAM services. As for location issues, which have effects on UAM service accessibility and inter/multi-mode service integration, several studies referred to HLP approaches for finding optimal location with respect to criteria such as minimizing travel costs and/or maximizing transport demand coverage. Most of the studies dealing with vertiport location considered main transport nodes and high-income regions as the most relevant variables in the objective functions. For this reason, places such as airports, financial districts and city centres have been found to be the most suitable areas where to locate vertiports. Another important result found by this analysis is that the vertiport position is more relevant than their number for travel time saving. However, flight regulation constraints and the presence of a high number of obstacles in lower airspace could limit vertiport integration in the surrounding environment. Therefore, the development of an efficient aerial supply model, where vertiports are the main nodes, is essential also to introduce new ground infrastructures and to ensure an improvement of the whole transport system from a holistic perspective where both ground and aerial urban modes coexist.

CHAPTER 5 – UAM AERIAL SUPPLY MODEL: 3D URBAN AIR NETWORK

This chapter is built upon the journal article:

- *Ditta, C.C. and Postorino, M.N., 2023. Three-Dimensional Urban Air Networks for Future Urban Air Transport Systems. Sustainability 15, no. 18: 13551,*

and the conference paper:

- *Ditta, C.C., Postorino, M.N., 2023. A 3D Urban Aerial Network for New Mobility Solutions. In: Braubach, L., Jander, K., Bădică, C. (eds) Intelligent Distributed Computing XV (pp. 277-286). IDC 2022. Studies in Computational Intelligence, vol 1089. Springer, Cham.*

These papers propose an innovative 3D network model for UAM scenarios operations and preliminary tested its application.

5. UAM AERIAL SUPPLY MODEL: 3D URBAN AIR NETWORK

5.1. Introduction

As introduced in Chapter 4, services provided by usual ground transport systems and their performances are simulated by using the "transport supply" model, which includes technical and organizational aspects of the physical transport supply in order to represent the topological and functional structure of the system (Cascetta, 2001). Combining existing ground transport networks with UAM networks could represent a great opportunity for urban and suburban mobility and it would be a challenge for shaping a new evolution of large metropolitan areas.

Although many issues must still be solved – from the aerial vehicles features to safety, environmental concerns and scenarios simulations which are crucial for including the new "air mobility" in urban environments (Cohen and Shaheen, 2021; Brown and Harris, 2020; Bauranov and Rakas, 2020; Postorino and Sarnè, 2020) – the basic supply concepts can be applied to represent UAM transport services as well.

As already introduced, the UAM supply model includes the set of vertiports to allow service accessibility and the aerial supply model that will simulate connections and performances of planned UAM services. The focus is here addressed to the aerial network model – i.e., the *Urban Air Network* (UAN) – to support operations in urban low airspace by taking into account ground UAM network design and flight requirements.

UAN implementation involves the *vertical* dimension, which is expected to provide advantages for overcoming ground congestion and improving mobility. Particularly, a three–dimensional UAN should guarantee: i) effective connections between POIs in urban areas; ii) suitable travel times and/or shorter travel distances with respect to ground ones; iii) effective and safe flight paths; iv) not adverse effects on overflown environment.

As discussed in Chapter 2, UAN operability have to be supported by data sharing and processing between FVs and ground air traffic control centres that could both avoid air traffic congestion, thanks to *ad hoc* communication networks (e.g., FANET (Chriki et al., 2019); WSNs (Jawhar et al., 2015, Ho et al., 2011), and keep safe separations among FVs (Wang et al. 2007). These latter aspects are similar to what is expected – and partially operating – in Cooperative, Connected and Automated Mobility (CCAM) that will use communication opportunities – as V2V and V2I (Demba & Möller, 2018; Djahel et al.,2015) – to allow trips by Connected and Automated Vehicles (CAVs). Knowing data related to the status, positioning and speed of each FV in UANs is one of the prerequisites for UAM operability. Two types of approaches have currently been specified to manage low–altitude urban air traffic: 1) integrated control system such as UTM or U–Space Concept (Prevot et al, 2016; SESAR, 2017); 2) route management directly realized by autonomous aerial vehicles with on–board technology, such as sense–and–avoid supported by algorithms for route guidance (Yang & Wei, 2020).

In the above perspective, a three–dimensional Urban Air Network (3D–UAN) model that includes the third (vertical) dimension is proposed to link trip Origin/Destination points by sequence of aerial, dynamic links where a suitable cost function has been defined. In detail, the 3D-UAN model is composed of nodes, corresponding to vertiports and/or singular points in the urban context, and links connecting such nodes. Each layer is connected to the others by suitable vertical links. A link cost function has been defined to guarantee FV separations, avoid conflict points, and allow suitable traffic flow levels to ensure uncongested conditions and meet link capacity criteria. It is worthwhile to note that the network has been conceived to support flight operations based on the "see and avoid" concept (Chand et al., 2017), and each link is bi-directional. In other words, FVs can use one or the opposite link direction depending on: 1) their O/D pair; 2) the status of the link, which might be enabled or disabled in the required direction based on the flight direction of another FV that is using the same link and/or the link spare capacity.

In the next sections, an overview of preliminary aerospace structures intends to highlight the main characteristics and operational requirements that an aerial supply system has to meet, in terms of topology and FV traffic management. Then, based on fundamentals emerged in the literature, the proposed 3D-UAN model is presented and discussed, as key subject of this thesis.

5.2. Urban Air Network Background

To enable operations in low airspace and particularly in uncontrolled (class G) aerospace, in recent literature a multilayer graph model, where links represent some kind of "airways" (corridors) and nodes allow transfers between layers, has been proposed (Samir Labib et al., 2019). In this model, FVs can move along "corridors" without direct communication with a central control system (such as UTM); they are guided by both rules defined on the corridors themselves (speed limits, flight headings, and maximum traffic capacity) and information exchanged by V2V communications (Demba & Möller, 2018). The geometrical features of the corridors depend on 1) type of FV that will occupy them (e.g., different sizes influence corridor cross sections); 2) distance between the POI (origin/destination nodes); and 3) presence of fixed obstacles in the airspace.

The literature on UAN models that are designed explicitly for UAM services is rather poor. Most studies have focused on the characteristics and potential constraints of the lower airspace where FVs would move (Schalk and Peinecke, 2022; Xu et al., 2020). Although not directly addressed to model UANs for UAM services, nevertheless these studies are useful to identify properly both features and properties that meet the technical and operational requirements of such networks.

The Metropolis project (Sunil et al., 2015) proposes four different urban concepts to study changing capacity: i) Full Mix, ii) Layer, iii) Zone and iv) Tube. Simulations conducted in Metropolis project, to validate these four concepts, showed that a layered concept is optimal for urban air mobility services (e.g., personal air transport or delivery drones).

In detail, the Full Mix concept would be involved in free flight contexts – such as 'non–structured airspace' – where air traffic is subjected to physical constraints, (e.g., weather, fixed obstacles), and FVs would handle autonomously separation and trajectory by on–board sensors and software (He et al., 2020). In this context, the UAN model would simply identify a topological structure with links – i.e., aerial corridors – where flights are allowed, and nodes at crossing points of such corridors and/or at vertiports.

The Layer concept includes an airspace designed in several layers, where separation among FVs is ensured by combining position, speed, and altitude settlement. This airspace structure is expected to reduce conflicts by limiting the relative speeds between FVs that cruise at the same altitude. Furthermore, the Layer concept meets the main features of a 3D–UAN, where different layers are identified, each one with its own horizontal structure and connections between layers that are ensured at specific points (nodes).

The Zone concept refers to circular and radial zones. Circular zones are used likewise ground roundabouts, while the radial zones connect and allow traffic towards the circular zones.

Finally, the Tube concept provides a fixed structure with pre-planned, conflict-free routes, like a graph where nodes identify specific points and tubes (i.e., links) connect two nodes. In this structure, time separation between FVs is considered as the "fourth dimension"; when a FV passes a node, it "occupies" such node for a given interval and during this time no other FV can pass this node. This layout allows a multi-layer structure; particularly, operations in the lower levels are reserved for short range flights, while the higher levels would be used for long range flights.

Another concept for modelling lower airspace and identifying UAN structures is offered by AirMatrix (Pang et al., 2020). The AirMatrix network establishes an airspace structure, divided into uniform air blocks arranged on multiple levels, which provides standardized units for urban

airspace management. By assigning a different number of air blocks to each layer, the AirMatrix intends to manage the number of FVs that can move in the airspace by considering constraints like the number of waypoints, crossing points, and flight flexibility. Flight operations are managed by a trajectory-based approach, i.e., starting from predetermined waypoints (origin and destination), FVs move between successive, intermediate waypoints to complete their path. This model assumes corridors where FVs are moving and might be considered a preliminary structure for providing UAM services. A simulation has been carried out to evaluate FV operation performance indicators such as average travelled distance and travel time. The results have shown that improvements are needed to handle an increasing number of FVs operations.
In the Dynamic Delegated Corridors (DDCs) framework (Lascara et al., 2019), airspace volumes or tunnels – identified in classes A-D – similar to airways are considered (Figure 5.1.). The air traffic separation is entrusted to the autonomous decisions of FVs, which are supposed to be equipped with advanced tools ensuring see-and-avoid capabilities, navigation precision, and V2V connections. Corridor size and operating time may change and can be enabled (open/closed) according to weather conditions and air traffic density. DDCs are also supported by an Automated Decision support service and might be seen as a dynamic UAN model, where links can be enabled or disabled according to some criteria.
More recently, Wang et al. (2022) introduced an air traffic planning methodology to ensure UAM operations by defining a fixed-route structure modelled as a graph, wherein volume segments act as links, supporting two-way traffic, and vertiports and delivery points act as nodes. Vertical links are added to connect the horizontal volume segments and a cylindrical airspace volume is identified – in which density points have been specified to measure the flow pattern constraints – designed to capture the complexity in each node. In addition, an objective function based on linear dynamic systems and specified as the sum of node complexities incorporates temporal and spatial information, such as link congestion and operational efficiency, to measure air traffic interaction.

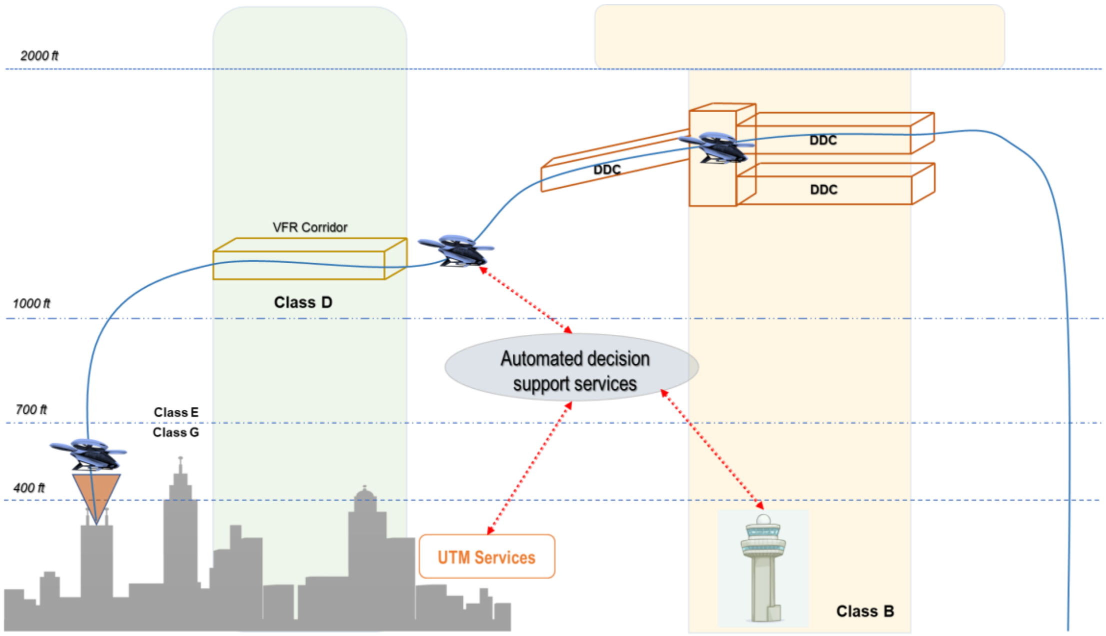

Figure 5.1. – Dynamic Delegated Corridors (DDCs) airspace concept.

To minimize node complexity and optimize the UAM flow pattern in the proposed structure, a two-step algorithm (i.e., Simulated Annealing and Dafermos' metaheuristic algorithm) is explored, by generating solutions to balance the path complexity in OD pairs and manage structure congestion. Other studies, based on a free flight aerospace approach (i.e., a specific topological structure is not defined in the low airspace), identify ground and low airspace constraints by employing 3D GIS maps and evaluate strategic UAM paths by using collision avoidance methods (Causa et al., 2022; Safadi et al., 2023). In Tang et al. (2022) a semi-structured approach is explored, which adopts a layered airspace topology with free flight at each layer where only the conflicting points between different routes were considered in. Thus, at first the shortest path for each O/D pair is computed by well-known shortest path algorithms (e.g., Dijkstra) in order to identify the flight collision configurations and their minimum temporal separation. Then, the route intersection information is employed for flight de-confliction and a pre-departure flight level assignment plus departure delay integration is proposed to solve conflicts, and the FVs follow with direct routes between vertiports (free flight approach) at the identified layer.

Starting from the above perspective, a 3D-UAN model will be introduced below, which complements and improves some preliminary studies presented in the literature (Lascara et al., 2019; Samir Labib et al., 2019). Particularly, the concept of dynamic corridors has been integrated with the multi-layer and airways' structure, based on Layer concepts, by defining a three-dimensional graph associated to ad-hoc link cost and node headway-time functions.

5.3. The proposed 3D-UAN Model

5.3.1. The 3D-UAN structure

The proposed UAN model is based on a multilayer three-dimensional graph (3D–UAN) (Figure 5.2) supporting UAM services for passengers and freight in the very low and uncontrolled airspace – i.e., 0-500 ft AGL (Antcliff et al., 2016). The graph includes *ad hoc* links, like DDCs, which are intended to be suitably enabled or disabled based on the information provided by data collected and transmitted by both connected FVs (He et al.2020) and a centralized control system. As available data are thought to be both real time and off-line (the latter being time series data), 3D-UAN operations will depend on both real time and off-line data processing. It is assumed that FVs will share data on their position, speed, operating status, and environmental conditions with both other vehicles and the control centre by using V2V and V2I/V2X communication technologies (Demba & Möller, 2018; Djahel et al.,2015).

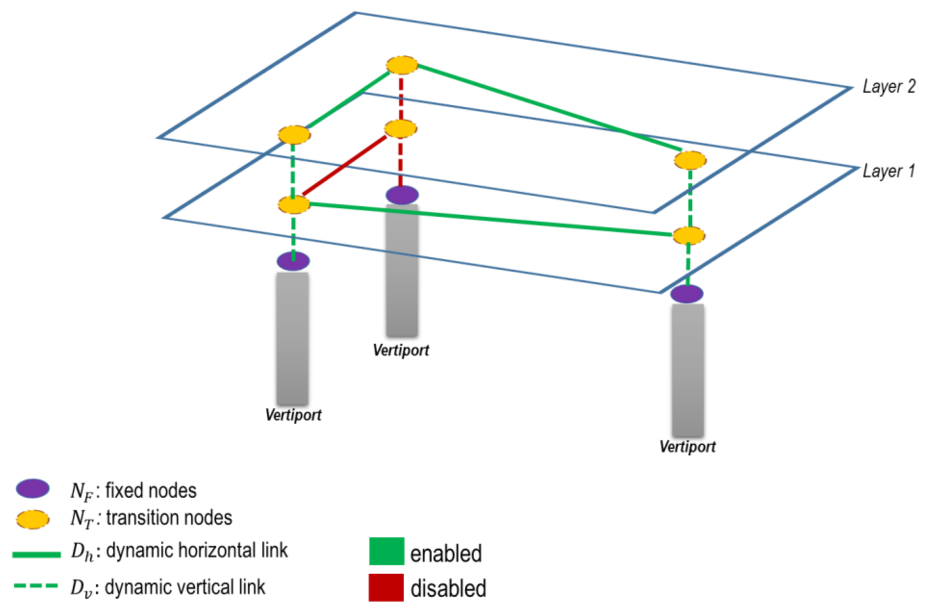

Figure 5.2. – Three-dimensional Urban Air Network (3D-UAN) model.

Layers, nodes, links, and link cost functions are the significant elements of the proposed 3D-UAN model for UAM operations. In detail, for each layer L a two–dimensional graph G_L is defined, which includes the set of *Transition Nodes* ($N_{T,L}$), the set of *Dynamic Links* (D_L) and the set of *Fixed Nodes* ($N_{F,L}$) at the starting layer.

Fixed nodes are identified in the access and egress points of the UAM network (i.e., locations having vertiport roles), while *transition nodes* correspond to positions where horizontal crossings and switches to an upper or lower layer are enabled. Note that some transition nodes have the same position as fixed nodes except for the vertical coordinate – for example, at vertiports vertical switches may also occur.

Dynamic Links (in the following also simply links) connect pairs of nodes, both fixed and transition. Each link $d_{m,L}$ represents the connection between two fixed nodes on the same layers or between a node – fixed or transition – in layer L and a node – fixed or transition – in another upper or lower layer. Dynamic links $d_{m,L}$ belong to the set $D_L = \{d_{m,L}\} \mid m = \{1, 2\ldots K_L\}$, where K_L is the total number of links for layer L. They can be considered as air corridors that will be enabled or not based on traffic capacity and environmental conditions (e.g., accumulation of operational delays, adverse weather conditions). In addition, their geometrical features may change depending on the flight vehicle's characteristics and safe distance. Particularly, link length among two fixed nodes is related to FV energy consumption. In fact, the recharging facilities will be located at vertiports (Wu & Zhang, 2020), and then setting the maximum distance between them is crucial for ensuring safe flights. Furthermore, the size of each FV can affect link cross sections by requiring an increase in the vertical separation for larger FVs (i.e., greater distance between the layers, vertical link length increase and changes in transition node positions) to guarantee suitable protection volumes around them (Healy et al.,2019).

Due to the 3D nature of the network model, the dynamic link set consists of horizontal and vertical link subsets, respectively:

$$D_{h,L} = \{ h_{mL}\} \subset D_L \mid m = \{1, 2\ldots\}$$

$$D_{v,L} = \{ v_{mL}\} \subset D_L \mid m = \{1, 2\ldots\}$$

Horizontal and vertical links allow only some specific flight operations – i.e., landing and take-off operations, as well as layer transitions, are permitted only on links belonging to the vertical link subset – while connections in the same layer occur only along links belonging to the horizontal link subset. Therefore, a given FV will move between layers by using vertical dynamic links, while horizontal dynamic links permit transfers within the same layer.

The final 3-D Graph (Θ) includes the bi–dimensional graphs, G_L, and the subsets of vertical dynamic link $D_{v,L}$:

$$\Theta = \bigcup_{L=\{1,\ldots,n\}} G_L \cup D_{v,L} \qquad \text{(Eq. 5.1)}$$

$$\text{with} \quad G_L = \left(N_{F,L}, N_{T,L}, D_{h,L}\right)$$

5.3.2. The 3D-UAN model cost function

Besides the three-dimensional graph conceptualization, an *ad hoc* link cost function has been set to complete the aerial supply model and to meet properly the service requirements.

By omitting the subscripts *L* and *m* for simplicity, the following link cost function $\mathbf{c}(\mathbf{T_t}, \mathbf{T_g})$ has been associated with each link of Θ:

$$\boldsymbol{c}(T_t, T_g) = \begin{cases} T_{t_i} & \text{for } i = 1 \\ T_{t_i} + T_{g_{(i,i-1)}} & \forall\, i > 1 \end{cases} \qquad \text{(Eq. 5.2)}$$

where *i* is the *i-th* FV using the dynamic link $d_{m,L}$ at a given time period; T_{t_i} is the travel time of *i* on the generic link; $T_{g_{(i,i-1)}}$ is the time gap between *i* and *i–1*. In detail, the travel time T_{t_i} varies according to the link – horizontal *vs*. vertical. For horizontal links, T_{t_i} is the running time T_{r_i} if $i = 1$, which depends on FV features and possible air rules. If there are more than one FVs on the same link, i.e., $i > 1$, the additional time $T_{g_{(i,i-1)}}$ ensures a suitable separation between two subsequent FVs. This condition allows keeping safe travel conditions among FVs flying the same path.

For vertical links, T_{t_i} may be climbing (T_{a_i}) or descent (T_{f_i}) time depending on the link direction – i.e., towards upper layers or towards lower layers. Again, the additional time $T_{g_{(i,i-1)}}$ ensures a suitable separation between two subsequent FVs also along vertical links.

Therefore, eq. (5.2) may be specified as follows:

$$c_{h,L}(T_r, T_g) = \begin{cases} T_{r_i} & \text{for } i = 1 \\ T_{r_i} + T_{g_{(i,i-1)}} & \forall\, i > 1 \end{cases} \qquad \text{(Eq. 5.3)}$$

$$c_{v,L}(T_a, T_f, T_g) = \begin{cases} T_{a_i} & \text{for upper layer transitions, } i = 1 \\ T_{a_i} + T_{g_{(i,i-1)}} & \text{for upper layer transitions, } i > 1 \\ T_{f_i} & \text{for lower layer transitions, } i = 1 \\ T_{f_i} + T_{g_{(i,i-1)}} & \text{for lower layer transitions, } i > 1 \end{cases} \qquad \text{(Eq. 5.4)}$$

It is worthwhile to note that the cost function, particularly the travel time component, is conceptually a random variable because of some external factors, such as weather conditions. However, in this first version of the UAN model, the cost function has been considered deterministic. In other words, times and network status correspond to ideal conditions where no external and/or internal disturbances exist, so that the final status might be considered the best condition under some scheduled services.

Furthermore, to ensure controlled departures from fixed nodes $N_{F,L}$ and the effective flow distribution over the 3D-UAN, aerial vehicles have to comply with an assigned *headway time* at each fixed node before starting the journey, which may be considered a waiting time component as detailed in the headway function $\boldsymbol{h}(I_{N_F})$:

$$\boldsymbol{h}(I_{N_F}) = I_{N_{F_i}} + \sum_{j=1}^{n-i} I_{N_{F_{i-j}}} \quad \text{(Eq. 5.5)}$$

where I_{N_F} is the headway time associated with each aerial vehicle before take-off and depends on the variables $T_{r_{i-1_{h_{mL}}}}$, $T_{a_{i_{v_{mL}}}}$ and $T_{g_{(i,i-1)d_{mL}}}$ specifically designed for each dynamic links:

$$\mathbf{I_{N_F}}\left(\mathrm{T_{a_{v_{mL}}}}, \mathrm{T_{r_{v_{mL}}}}, \mathrm{T_{g_{d_{mL}}}}\right) = \begin{cases} \mathrm{T_{g_{(i,i-1)v_{mL}}}} + \left[\mathrm{T_{r_{i-1_{h_{mL}}}}} + \left(\mathrm{T_{g_{(i,i-1)h_{mL}}}} + \mathrm{T_{a_{i_{v_{mL}}}}}\right)\right] & \text{if i} - \text{1 positioning ahead of destination node } \mathrm{N_{T,L}} \\ \mathrm{T_{r_{i-1_{h_{mL}}}}} + \left(\mathrm{T_{g_{(i,i-1)h_{mL}}}} + \mathrm{T_{a_{i_{v_{mL}}}}}\right) & \text{if i} - \text{1 positioning over destination node } \mathrm{N_{T,L}} \end{cases} \quad \text{(Eq. 5.6)}$$

In Eqs. (5.5) and (5.6) *i* is the *i–th* FV departing from the generic fixed node $N_{F,L}$ and flying to the generic transition node $N_{T,L}$; *j* refers to the FV ahead *i*, and *n* is the total number of FVs using the 3D-UAN at a given time. In detail, the *i-th* FV must wait at the fixed node $N_{F,L}$ a *headway time* $\boldsymbol{h}(I_{N_F})$ such that collisions – among it and other FVs crossing the network – do not occur at the next transition node, and separation time $T_{g_{(i,i-1)}}$ is constantly guaranteed in each link $d_{m,L}$. Finally, the generalized link cost function is obtained by combining both $\boldsymbol{h}(I_{N_F})$ and $\boldsymbol{c}(T_t, T_g)$, i.e., node and dynamic link cost functions.

Once the cost functions have been defined, it is possible to identify minimum cost paths from origin to destination points, which depend on the number of FVs on those links in the given reference time (e.g., *i*=1, *i*>1). Suitable paths meeting minimum cost criteria may be computed by using iterative shortest path algorithms (e.g., Dijkstra, 1959) or A* (Fu et al., 2006), based on the identification of link sequences allowing the minimum travel cost. Among some criteria for identifying suitable paths, FVs are allowed to switch layers in transition nodes only a limited number of times depending on route length. The layer switch constraint is also useful to guarantee savings in battery autonomy and travel time. In fact, layer switches involve greater energy consumption to perform hover operations, for which a reduced speed is also needed (Beyne & Castro, 2022), which causes a consequent increase in the overall travel time.

As already introduced, the computation of the link cost is based on both off-line and real time data, the latter supposed available due to V2V and V2I/V2X communication technologies. This double aspect allows applying the 3D-UAN model to both scheduled and unscheduled air services. For scheduled services (such as AS and Intercity services) the shortest path is computed before FV departures. Thus, the network can be used in "steady state" mode, and minimum paths are identified in advance depending on the expected points of conflict and number of flight operations, and by detecting which links can be enabled in respect of capacity and safety issues (Ditta & Postorino, 2023).

For an on-demand service (such as AirTaxi), the network dynamic features are crucial. In this case, information on the occupancy status of the dynamic links has to be shared in real time. In this condition, both each FV and the control centre, which receive and share data with each other and among the other connected FVs, would compute the shortest path by processing such data. During the trip, if a dynamic link reaches its capacity limit, it will be “disabled" to keep safety standards and avoid traffic jams and disruptions on the network. FVs will be distributed over the network by recomputing the shortest paths in the current conditions such that conflict free trips are still guaranteed.

It is worthwhile to note that real time data exchange and monitoring are crucial for scheduled services as well. If there is any kind of disruption on one or more links, the new path’s computation is similar to what occurs for unscheduled services, and the information will be provided in real time by a similar computation, i.e., based on data received from the control centre and from the other connected FVs.

To summarize, the 3D–UAN model allows simulating the expected UAM services described in section 2.4. – i.e., Air Taxi, Airport Shuttle, Mega-city and Intercity flights – by ensuring connections between origin/destination pairs.

In this first version of the model, both path and departing slot assignment for each FV follow a priority criterion that depends only on the service scheduling. In particular, the take-off and landing priority criterion must be compatible with the time gap on the links and headway time at the fixed nodes, also guaranteed by the see-and-avoid approach related to communication techniques among FVs. In the event that an on-demand service interoperates with a scheduled one, the scheduled flights will have priority, and the on-demand flight between two scheduled flights will be allowed if the time gap is enough. However, in the case of emergency flights, such as Air Ambulance, scheduled flights have no longer priorities.

CHAPTER 6 – 3D-UAN MODEL APPLICATIONS

This chapter is built upon the journal articles:

- *Brunelli, M., Ditta, C.C. and Postorino, M.N., 2022. A Framework to Develop Urban Aerial Networks by Using a Digital Twin Approach. Drones, 6(12), p.387.*

- *Ditta, C.C. and Postorino, M.N., 2023. Three-Dimensional Urban Air Networks for Future Urban Air Transport Systems. Sustainability 15 (18), 13551.*

These papers set out some simulation case study of the UAM supply framework and 3D-UAN model proposed.

6. 3D-UAN MODEL APPLICATIONS

6.1. Introduction

The 3D-UAN model and the frameworks described in the previous chapters have to be tested to check the compliance and the suitability of the assumptions made. Due to the novelty of UAM concept, the prototype stage of FVs and the non-existence of vertiports infrastructures in real scenarios yet, the network model and the proposed methodology have been applied to a simulated test case. The hypotheses are that the FV flow is the result of deterministic behavioural rules mainly applied to the interaction of FVs with each other and with the infrastructures.

Due to the rising employment of digital twins or digital models to simulate and assess transport systems in real physical scenarios, this approach has also been applied to explore some UAM features for a case study. A digital twin can be defined as the digital model of a physical system that is regularly updated by the exchange of information between virtual and physical systems. In recent years, the technological innovations have transformed the way to study and simulate processes and systems. Digital twins are a core part of many models of real systems, and they can be used to simulate, design and process several application scenarios (VanDerHorn and Mahadevan, 2021) as well as to test, simulate, design and plan new solutions in the transport field – such as operations of Connected Autonomous Vehicles (CAVs) (Wang et al., 2020) or airport operations (Saifutdinov et al., 2020; Conde et al., 2022) – or to recreate a virtual population in order to realize agent-based simulations (Anda et al., 2021).

Digital twin models can be used for designing and developing UAM applications, such as vertiport location problems, airspace and air vehicle management. More in detail, a digital twin framework could be useful to identify the positioning of vertiports – which requires specific conditions as reported in section 4.3. – by incorporating the 3D-UAN model to identify safest flight paths suitable for FVs.

In this chapter, two different applications are described:

1. simulation of UAM services, like AS and Intercity flights, by adopting the specified 3D-UAN model, and indirect estimate of CO_2 emissions due to FVs moving on the 3D-UAN (such as those linked to operational, disposal phase charge), which have been compared with those released by fuel engine cars in the same conditions in the Italian context;

2. digital twin approach to simulate the UAM supply model in a real-world context (the city of Bologna, in Northern Italy) in order to identify vertiports and air corridors on which to set UAM services, also by combining a baseline 3D-UAN.

6.2. 3D-UAN Test Scenario: UAM services application

In order to assess the proposed 3D-UAN model and discuss some preliminary performances, a simulation scenario is here described, which focuses on the analysis of a scheduled UAM service – such as Airport Shuttle or Intercity services. In such scheduled services, flight plans and procedures are established before each departure, the only variations being linked to unforeseen events such as adverse weather conditions, instrument disruptions, and emergency management. However, as introduced in Section 5.3., it has been assumed that ideal conditions occur, without disturbances with respect to the scheduled plan, in order to obtain a network status that can be considered ideal too.

It is worthwhile to note that the application refers mainly to the aerial network; in other words, the access/egress times to fixed nodes – i.e., vertiports – and the time required for the "ground" operations to be carried out (e.g., embarkation, disembarkation, security checks) are neglected and only the air travel time on the 3D-UAN for some origin/destination pairs is considered. In fact, the total travel time for the entire journey also includes the ground leg component, which depends on vertiport locations and ground mode features. The computation of ground times is outside the scope of this application.

The network structure used to test the 3D-UAN model is depicted in Figure 6.1. Note that each link is reversible – for vertical links, the two directions are separated by suitable horizontal distances. The travel direction for a horizontal link will depend on its occupancy and safety conditions, i.e., no FVs running in opposite directions are allowed to use the same link at the same time. The test network includes four layers at 100 meters from each other. At ground-level (L_0, 0 m AGL), accessibility to the air network occurs through four fixed nodes, corresponding to four vertiports. Each layer includes at least four transition nodes, which have the same position as the fixed nodes but different vertical coordinates. The remaining transition nodes have a different position – both horizontal and vertical coordinates – with respect to fixed nodes. Both fixed and transition nodes are connected by vertical dynamic links to the next layer (Figure 6.1.).

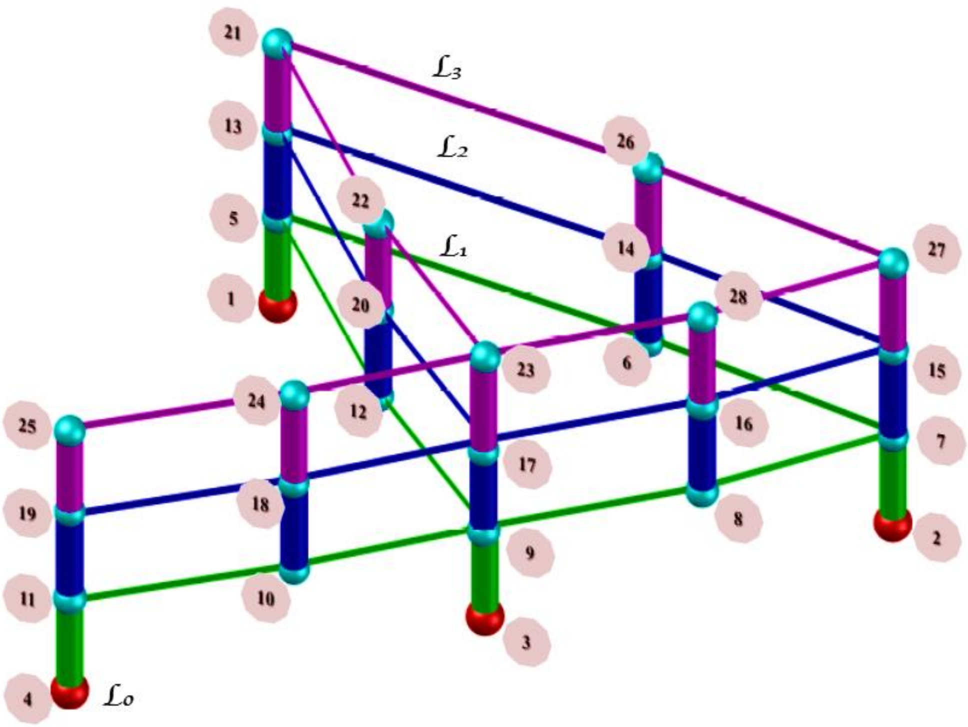

Figure 6.1. – The 3D-UAN structure used in the test application.

The main features of 3D–UAN, i.e., nodes, horizontal and vertical dynamic links are shown in Table 6.1. In summary, the aerial network has 4 layers (included the ground level), 28 nodes (including 4 vertiports), 40 vertical dynamic links, and 48 horizontal dynamic links (both directions).

Table 6.1. – Dynamic link and Nodes feature in the 3D–UAN test scenario.

Vertical Links			Horizontal Links		
	Dynamic links*	***Length (km)***		***Dynamic links****	***Length (km)***
$\mathbf{L_0 - L_1}$	1–5	0,1	*Layer* $\mathbf{L_1}$	5 – 6	25,08
	2–7	0,1		6–7	31,05
	3–9	0,1		7–8	15,26
	4–11	0,1		8–9	20,81
$\mathbf{L_1 - L_2}$	5–13	0,1		9–10	18,03
	6–14	0,1		10–11	21,21
	7–15	0,1		9–12	17,69
	8–16	0,1		12–5	21,63
	9–17	0,1	*Layer* $\mathbf{L_2}$	13–14	25,08

	10–18	0,1		14–15	31,05
	11–19	0,1		15–16	15,26
	12–20	0,1		16–17	20,81
$\mathbf{L_2} – \mathbf{L_3}$	21–13	0,1		17–18	18,03
	22–20	0,1		18–19	21,21
	23–17	0,1		17–20	17,69
	24–18	0,1		20–13	21,63
	25–19	0,1	Layer $\mathbf{L_3}$	21–22	21,63
	26–14	0,1		22–23	17,69
	27–15	0,1		24–25	21,21
	28–16	0,1		23–24	18,03
				26–21	25,08
				26–27	31,05
				28–27	15,26
				28–23	20,81

Fixed Nodes	Layer $\mathbf{L_0}$		
	1, 2, 3, 4		
Transition Nodes	Layer $\mathbf{L_1}$	Layer $\mathbf{L_2}$	Layer $\mathbf{L_3}$
	5, 6. 7, 8, 9, 10, 11, 12	13, 14, 15, 16, 17, 18, 19, 20	21, 22, 23, 24, 25, 26, 27, 28

*Only links in one direction are reported for space reasons.

The application scenario considers the lift+cruise eVTOL prototype developed by Airbus (CityAirbus NextGen[11]) as reference FV, which can reach 120 km/h (cruising speed) and has a range of 80 km. By considering the baseline scenario, a maximum capacity limit of two FVs in the same time interval has been assigned to each link, depending on the link lengths and the FV speed (Table 6.2.). The average cruising speed allowed on the horizontal links is considered equal to 100 km/h, while on the vertical links (including take-off and landing phases), it is 45 km/h (Rothfeld et al., 2018; FAA-H-8083-21B, 2019). This average speed value was chosen based on the CityAirbus NextGen data, which should also support issues related to flight safety.

[11] https://www.airbus.com/en/innovation/low-carbon-aviation/urban-air-mobility/cityairbus-nextgen

Table 6.2. – Dynamic link features in the baseline scenario.

Dynamic Link Characteristics	
Maximum link capacity (number of FVs)	2
Average cruise speed on horizontal links	100 km/h
Average cruise speed on vertical links	45 km/h

Fourteen FVs have been considered operational during the simulation, traveling between six origin/destination pairs (Table 6.3.).

Table 6.3. – FVs assigned to O-D pairs.

	Origin Node	***Destination Node***	***Range***
$\mathbf{FV_1}$	1	2	56 km
$\mathbf{FV_2}$	2	4	75 km
$\mathbf{FV_3}$	4	2	75 km
$\mathbf{FV_4}$	1	4	55 km
$\mathbf{FV_5}$	1	3	39 km
$\mathbf{FV_6}$	1	2	56 km
$\mathbf{FV_7}$	2	1	56 km
$\mathbf{FV_8}$	2	4	75 km
$\mathbf{FV_9}$	2	4	75 km
$\mathbf{FV_{10}}$	1	4	55 km
$\mathbf{FV_{11}}$	1	3	39 km
$\mathbf{FV_{12}}$	1	2	56 km
$\mathbf{FV_{13}}$	1	4	55 km
$\mathbf{FV_{14}}$	1	3	39 km

The simulation has been run for 70 minutes to explore the 3D-UAN model and, at the same time, allow all the involved FVs to reach their designated destinations. The simulation scenario started at time t_0=0, in which the first FV took off from vertiports 1, 2 and 4. To keep a safe time gap between the next two FVs flying the same link, the value of $\mathrm{T_g}$ has been set equal to 2 minutes. The headway time $\boldsymbol{h}(I_{N_F})$ has been ensured at fixed nodes before each departure. Particularly, $\mathrm{FV_1}$, $\mathrm{FV_2}$ and $\mathrm{FV_3}$ take-off at time $\mathrm{t_0}$ and their headway times I_{1_1}, I_{2_2} and I_{4_3} are equal to 0. Then, the minimum cost paths between OD pairs have been computed by a shortest cost path algorithm (Dijkstra, 1959) based on dynamic link requirements and constraints – i.e., links crossed in both directions and maximum capacity. By using eqs. (5.2) – (5.6), time gap and headway time introduced above, the link costs have been calculated and the minimum paths for each FV have been identified (Table 6.4.).

As previously stated, the simulation scenario refers to a scheduled service, and the air traffic flow expected on each link is known before FVs take-off, based on a considered timetable. Consequently, some dynamic links have been enabled and disabled depending on capacity and collision avoidance issues.

Table 6.4. – Results of the 3D-UAN model for the simulation scenario.

OD pair	Path		Link cost*	Path cost*	Travelled distance*	OD pair	Path		Link cost*	Path cost*	Travelled distance*
1 – 2	**FV$_1$**	1 – 5	0,13	33,9	56,3	2 – 4	**FV$_2$**	2 – 7	0,13	45,7	75,7
		5 – 6	15,05					7 – 8	9,16		
		6 – 7	18,63					8 – 9	12,49		
		7– 2	0,13					9 – 17	0,13		
	FV$_6$	1 – 5	6,53	40,3	56,3			17 – 18	10,82		
		5 – 6	15,05					18 – 19	12,73		
		6 – 7	18,63					19 – 11	0,13		
		7 – 2	0,13					11 – 4	0,13		
	FV$_{12}$	1 – 5	12,93	47,2	56,7		**FV$_9$**	2 – 7	6,53	51,9	75,5
		5 – 13	0,13					7 – 8	9,16		
		13 – 21	0,13					8 – 9	12,49		
		21 – 26	15,05					9 – 10	10,82		
		26 – 27	18,63					10 – 11	12,73		
		27 – 15	0,06					4 – 11	0,13		
		15 – 7	0,13				**FV$_{10}$**	2 – 7	8,67	54,3	75,7
		7 – 2	0,13					7 – 15	0,13		
4 – 2	**FV$_3$**	4 – 11	0,13	45,5	75,5			15 – 16	9,16		
		11 – 10	12,73					16 – 17	12,49		
		10 – 9	10,82					17 – 18	10,82		
		9 – 8	12,49					18 – 19	12,73		
		8 – 7	9,16					19 – 11	0,13		
		7 – 2	0,13					11 – 4	0,13		
2 – 1	**FV$_7$**	2 – 7	2,27	36,3	56,5	1 – 4	**FV$_4$**	1 – 5	2,27	49,5	78,8
		7 – 15	0,13					5 – 12	12,98		
		15 – 14	18,63					12 – 9	10,62		
		14 – 13	15,05					9 – 10	10,82		
		13 – 5	0,13					10 – 11	12,73		
		5 – 1	0,13					11 – 4	0,13		
1 – 3	**FV$_5$**	1 – 5	4,4	28,1	39,5		**FV$_8$**	1 – 5	4,4	51,9	79,0
		5 – 12	12,98					5 – 13	0,13		
		12 – 9	10,62					13 – 20	12,98		
		9 – 3	0,13					20 – 17	10,62		
	FV$_{11}$	1 – 5	10,8	34,8	39,7			17 – 18	10,82		
		5 – 13	0,13					18 – 19	12,73		
		13 – 20	12,98					19 – 11	0,13		
		20 – 17	10,62					11 – 4	0,13		
		17 – 9	0,13					1 – 5	15,07	2,9	79,2

		9 – 3	0,13					5 – 13	0,13
	$\mathbf{FV_{14}}$	1 – 5	17,2	41,5	39,9		$\mathbf{FV_{13}}$	13 – 21	0,13
		5 – 13	0,13					21 – 22	12,98
		13 – 21	0,13					22 – 23	10,62
		21 – 22	12,98					23 – 24	10,82
		22 – 23	10,62					24 – 25	12,73
		23 – 17	0,13					25 – 19	0,13
		17 – 9	0,13					19 – 11	0,13
		9 – 3	0,13					11 – 4	0,13

*Distances are in km, costs are in minutes.

As it can be seen from Table 6.4., all the layers of the 3D-UAN are used to ensure optimal travel times and flight safety. In fact, flying vehicles FV_7, FV_8, FV_{10} and FV_{11} cross layer L_2 to reach their destination, while FV_{12}, FV_{13}, FV_{14} switch to layer L_3 because of both the capacity limits reached in lower layers and the requirement of T_g=2 min on each link. Furthermore, at time t_Δ = 22 min from t_0, the link dynamic features are useful to manage the FV flow on the aerial network suitably. In fact, at node 9, FV_2 switches to L_2 to avoid collision with FV_3, which is flying in the opposite direction; consequently, link (9 – 10) is disabled while links (9 – 17) and (17 – 18) are enabled before FV_2 arrives. By considering the 3D-UAN at the time t_Δ=22min, the link occupation status and the distance travelled by the FVs are reported in Table 6.5. These results make it possible both to assess whether the various dynamic links are enabled and disabled as intended and to identify potential conflict points on routes.

Table 6.5. – Dynamic links status and FVs position at t_Δ = 22 minutes.

t_Δ = 22 min		***Occupied link***	***Travelled distance****
1 – 2	$\mathbf{FV_1}$	6 – 7	36,54
	$\mathbf{FV_6}$	6 – 7	25,88
	$\mathbf{FV_{12}}$	21 – 26	14,97
4 – 2	$\mathbf{FV_3}$	10 – 9	36,54
2 – 4	$\mathbf{FV_2}$	17 – 18	36,42
	$\mathbf{FV_9}$	8 – 9	25,88
	$\mathbf{FV_{10}}$	16 – 17	22,20
2 – 1	$\mathbf{FV_7}$	14 – 13	32,87
1 – 3	$\mathbf{FV_5}$	12 – 9	29,43
	$\mathbf{FV_{11}}$	13 – 20	18,64

	$\mathbf{FV_{14}}$	21 – 22	7,86
	$\mathbf{FV_4}$	12 – 9	32,99
1 – 4	$\mathbf{FV_8}$	20 – 17	29,31
	$\mathbf{FV_{13}}$	21 – 22	11,41

*Distances are in km.

From the obtained results, it comes out that setting three layers for fourteen FVs operating a 70-minute service generally allows acceptable network operations. All the network layers had to be used, which increased the total time spent due to several climb/descendent manoeuvres. The performance analysis reported in Figure 6.2. shows interesting and satisfactory results in terms of total travel costs and travelled distances, although introducing bidirectional links could lead to network overuse.

Constraining the dynamic links to a capacity value of two FVs in the same time interval guarantees a suitable safety level while maintaining service quality. Then, the hypothesized value T_g = 2 min is suitable to avoid conflict points and disruptions along the routes by keeping suitable separations between FVs, and it might be considered an optimal time gap for this test.

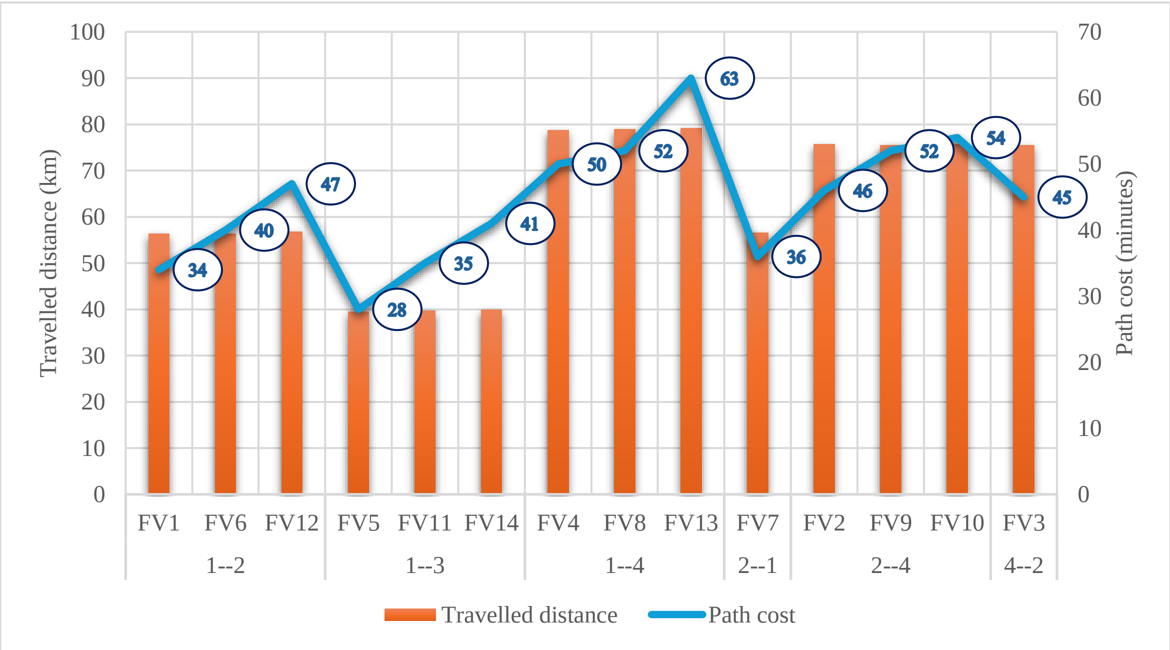

Figure 6.2. – FVs performances on the tested 3D-UAN per each OD pair.

The analysed simulation scenario shows that the proposed cost function produces reasonable results. Running time mainly influences FV flows on network links, while the time gap and the consequent headway time may produce waiting times that can occur only at fixed nodes.

Furthermore, the opportunity to move between layers depending on traffic needs allows optimal flow assignment and at the same time keeps safety standards. As opposed to ground transport systems there are no critical points – such as traffic light intersections – where significant, additional waiting time can affect the total path costs. Finally, the use of the dynamic link properties – i.e., enabled or disabled – depends on the choice to identify (in real time) the shortest paths between origin/destination pairs.

To apply the proposed 3D-UAN model to an on-demand services (such as Air Taxi), it is required to use ad-hoc communication networks (FANET, WSN) (Khayat et al., 2021) and continuous data exchange (e.g., FV positions, cruise speed, link status) between the individual FV and the air traffic control centre in order to compute real time shortest paths. However, the 3D-UAN model is the same as applied in the simulation scenario above. As an example, the event highlighted at time t_{Δ}=22 min – i.e., link (17 – 18) enabled to ensure FV_2 transit – can be associated with an on-demand simulation, since links enabled and disabled dynamically depending on traffic conditions appear to be satisfactory for this type of service. FVs themselves may coordinate among them autonomously through the FANET system (Chriki et al, 2019).

By comparing with other studies reported in the literature, the proposed 3D-UAN model has a more comprehensive architecture as it proposes a well-defined network structure, which in principle includes the support of communicating networks, and the link and node cost functions (5.2) and (5.5), which allow computing the performances of the aerial network, also from the user's perspective.

The 3D-UAN model has some innovative aspects with respect to the airspace models proposed in the current literature for UAM services (Table 6.6). At a first comparison based on Table 6.6, most of the existing models have a fixed Airspace Structure, which could generate some restrictions, particularly when introducing on-demand services. On the contrary, in the 3D-UAN model the integration of dynamically activated corridors/airways, combined with the opportunity to move on different flight levels by entirely exploiting the third dimension, overcome the potential limitations of previous models in the literature. In detail, the 3D-UAN model combines the characteristics of a structured and controllable airspace using many layers at suitable altitudes for complying with aviation safety standards with the free flight flexibility by considering Transitions Nodes and Dynamic Links, which can be adapted in real-time when it needs.

As for ATM, two main approaches may be identified from Table 6.6: i) those based on the collision avoidance principle and communication between FVs to compute the air routes; and ii) those that, starting from an objective function, evaluate the complexities at the node and along the links to get the optimum paths. The proposed 3D-UAN model combines the above two approaches for aerial traffic management. In fact, the proposed cost function guarantees the minimum travel times and the separation standards between FVs, by using information about air traffic on the network, which is collected through V2V and V2I technologies. Differently from the existing models that focus on one of the two methods, this framework exploits both the criterion of collision avoidance, which might also be used for simulating the network status in case of unforeseen events, and a structured objective function that satisfies the transport system principles, by ensuring the shortest path computation between O/D pairs.

Table 6.6. – Existing Airspace models vs. introduced 3D-UAN model.

Models	***Airspace Structure***	***Air Traffic Management***
AirMatrix network (Pang et al., 2020)	Uniform air blocks arranged on multiple levels.	Predetermined trajectory-based approach where FVs follow a set of waypoints assigned through conflict points detection
Dynamic Delegated Corridors (Lascara et al., 2019)	Airspace volume or tunnels like airways.	Air traffic separation is entrusted to FVs decisions (see-and-avoid) and supported by an Automated Decision support service on ground
Multilayers Model (Samir Labib et al., 2019)	Obstacle-free points in the different layers including corridors/airways.	Pre-determined path planning by minimising travel time and energy separately
Cylindrical volume with fixed-route structure (Wang et al., 2022)	Air network modelled as a graph, with volume segments as links and droneports as nodes.	Path planned through objective function specified as the sum of node complexities incorporates temporal and spatial information
*Aerospace free flight approach (*Tang et al., 2022)	3D GIS map provides the obstacle-free airspace involving several layers.	Pre-departure flight level assignment involving collision – avoidance method
3D – UAN Introduced	Multilayer structure including Dynamic Links, Fixed Nodes (vertiports) and Transition Nodes	Shortest Path calculated through ad hoc cost function including travel time, gap time among FVs on links and waiting time at vertiport and information

Finally, although the 3D-UAN framework can also be used for optimizing fleet and services, in this study the focus has been on the model feasibility for supporting UAM services. In other words, in this preliminary experiment the 3D-UAN model has not been used for optimizing the network, but for simulating the network status under some known conditions – e.g., scheduled services and/or on-demand services. Therefore, disturbances and potential disruptions are not the focus of this thesis.

6.2.1. A preliminary analysis of CO_2 emissions and comparison with ground vehicles

The eVTOLs have been the key drivers for starting the concept of UAM services. Such FVs do not produce CO_2 emissions directly during operations – in fact eVTOLs are equipped with DEP engine (Ma et al., 2022). However, operational and disposal phases may release CO_2 gas into the atmosphere (André and Hajek, 2019). Particularly, to be operational FVs have to be recharged, and then they might contribute, indirectly, to CO_2 emissions based on how the electricity needed to recharge them has been produced.

In order to preliminarily explore the environmental impacts of UAM services in the framework of the proposed 3D-UAN model, an analysis of the indirect $kgCO_2$ produced in the simulation scenario tested in the previous section has been performed. Such emissions have been compared with fuel engine car emissions in the same context, i.e., same travelled distances in comparable traffic flow conditions. Particularly, the comparison has been referred to the Italian situation by considering some emission indexes estimated by ISPRA[12] (Italian Institute for Environmental Protection and Research). The emission index (EI_{el}) in the power sector for electricity and heat production has been used, which only comes from fossil sources. Such index has been used for UAM trip CO_2 emissions, from the generation to the consumption of electricity needed to allow FV operations (Table 6.7.). As for cars, the average emission factor for the car fleets circulating in Italy (EI_{car}) has been selected by the ISPRA national database[13], which is updated consistently with the COPERT version 5.5.1[14] estimation model (Table 6.7.). The EI_{car} factor is related to car fleet powered by petrol, diesel, LPG (Liquefied Petroleum Gas) and CNG (Compressed Natural Gas) fuels.

Table 6.7. – Emission Index for electricity production and car's passenger estimated by ISPRA.

EI_{el} (gCO_2/kWh)	*452,1*
EI_{car} (gCO_2/km)	*162,84*

[12] https://www.isprambiente.gov.it/it
[13] https://fetransp.isprambiente.it/
[14] "COPERT is the EU standard vehicle emissions calculator, which uses vehicle population, mileage, speed and other data such as ambient temperature and calculates emissions and energy consumption for a specific country or region." https://www.emisia.com/utilities/copert/versions/

In this analysis, the power required by each FV in the simulation scenario described in previous section 6.2. has been estimated by applying the approach proposed by Mudumba et al. (2021), which propose eqs. (6.1) – (6.4) to estimate the power required at different flight phases – hover, climb, cruise, and descent:

$$P_{hover} = \frac{mg}{\eta_h}\sqrt{\frac{\delta}{2\rho}} \qquad \text{(Eq. 6.1)}$$

$$P_{cruise} = \frac{mg}{\eta_c}\frac{V_{cruise}}{\frac{L}{D}} \qquad \text{(Eq. 6.2)}$$

$$P_{climb} = \frac{mg}{\eta_c}\left(ROC + \frac{V_{climb}}{\frac{L}{D}}\right) \qquad \text{(Eq. 6.3)}$$

$$P_{descent} = \frac{mg}{\eta_c}\left(ROD + \frac{V_{descent}}{\frac{L}{D}}\right) \qquad \text{(Eq. 6.4)}$$

where m is the total FV mass; g is the gravity acceleration; L/D is the lift-to-drag ratio; δ is the FV disk loading; η_h is the hover system efficiency; η_c is the climb and cruise system efficiency; ρ is the air density at sea level; ROD and ROC are Rate of Descent and Rate of Climb respectively; V_{cruise}, V_{climb} and $V_{descent}$ are speeds adopted in different flight phases – cruise, climbing and descent.

Here, FV characteristics (Table 6.8.) are based on available information from CityAirbus NextGen, while lacking data have been assumed by considering the features of a generic lift-cruise eVTOL prototype (André and Hajek, 2019; Kasliwal et al., 2019). Finally, climb, cruise, and descent average speeds are the ones used for the simulation scenario. CO_2 indirect emissions for the UAM tested service have been computed by employing the following equation (Mudumba et al., 2021):

$$CO_{2(UAM)} = EI_{el}\left(\sum_{k\,\in flight\ phase} P_k \cdot t_k\right) \qquad \text{(Eq. 6.5)}$$

where P_k is the power required by each FVs in a different flight phase and t_k is the travel time in a distinct flight segment (i.e., estimated link costs, see Table 6.4.).

As for fuel engine car trips, CO_2 emissions have been computed by using the emission index EI_{car} and the travelled ranges between O/D pairs, which have been assumed to be the same as in the tested scenarios (see Table 6.3).

Table 6.8. – FVs (eVTOLs) main characteristics.

Reference	***Variable***	***Value***
CityAirbus NextGen - Airbus	FV total mass *m* (kg)	2200
André and Hajek (2019)	Disk loading δ (N/m^2)	627,5
André and Hajek (2019)	L/D	8
Kasliwal et al. (2019)	ROC (m/s)	5
Kasliwal et al. (2019)	ROD (m/s)	-5
International standard Atmosphere	ρ (kg/m^3)	1,225
André and Hajek (2019)	η_c	0,63
André and Hajek (2019)	η_h	0,765

Emissions have also been computed *per* passenger. It has been assumed that FVs can accommodate the pilot and two passengers, and the indirect gas emissions have been evaluated for 42 people. For car trips, 21 passengers have been considered by adopting an average car occupancy rate of 1.6[15], while the number of cars on the ground transport network has been assumed to be the same as in the 3D-UAN scenario (14 vehicles).

The total *kgCO₂* has been computed for both FV and car trips and *per* passenger travelling between the same O/D pair by FVs on the 3D-UAN and cars on the ground. The results are reported in Table 6.9.

Table 6.9. – FVs and car emissions $kgCO_2$ estimated on the simulation scenario.

Indirect CO_2 FV trip emissions	***CO_2 car trip emissions***
393,52 $kgCO_2$	131,25 $kgCO_2$
Indirect CO_2 emissions per passenger	***CO_2 emissions per passenger***
8,19 $kgCO_2$	5,86 $kgCO_2$

In the considered scenario and context – the travelled distances between O/D pairs being the same – the results show that FV operations produce more CO_2 gases than car trips, also in terms of emissions per passenger. This is an interesting, preliminary result, which must be further investigated. Although some studies (Cohen et al., 2021; Velaz-Acera et al., 2023) and some

[15] https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics

market analyses (Coykendal et al., 2022) propose UAM as a reduced carbon emission alternative to “traditional” mobility, there are some other studies that show less optimistic expectations with respect to the environmental impacts generated by UAM services (Zhao et al., 2022). This preliminary analysis is rather in line with this latter study, although it refers to a specific electricity generation case and then cannot be generalized to other contexts. It should be noted that currently eVTOL prototypes – such as Volocopter and Joby – have been investigated in terms of their main technical properties and characteristics, but the operational features of the different flight phases required for providing a real service like the tested one have not been completely explored yet. This is another source of uncertainty for the obtained results because some data had to be assumed based on other studies and hypotheses, which represents a probable limitation. In any case, although many aspects and elements require further in-depth investigations, these results show that using e-vehicles does not automatically correspond to a lower environmental impact, and attention must be paid to the way the electricity is generated, which applies to both aerial and terrestrial e-vehicles.

6.3. Digital Twin for UAM scenarios

6.3.1. Digital Twin Framework methodology

Another application has been implemented to test the possible introduction of UAM services in real contexts by employing a digital twin model.

Digital twin approaches to simulate processes and evolutions of territorial systems have becoming more and more usual, with the aim, among many others, of i) describing in a quantitative and detailed way the physical world; ii) predicting the effects of actions; iii) planning and managing urban transport networks (Jian et al., 2021; Schrotter et al., 2020; Sánchez-Vaquerizo, 2020).

As for territorial systems, and urban environment in particular, the required data for modelling the system generally refer to socio-economic and anthropic features as well as to the landform. Also, the digital twins of complex systems, such as urban environments, could be fed by off-line data and/or data collected in real time, depending on the aim. With respect to a simple 3D urban model based only on geometrics data, the digital twin of an urban environment considers socio-economic and anthropic information that may be obtained by official sources (e.g., municipalities) or specific surveys – such as population and job densities, median income, working places, recreational areas, building type and POIs. Such data require only periodic (not real time) updates. On the contrary, some other data – such as traffic flows, pollution levels, traffic noise and meteorological condition – have to be collected in real time by sensors located suitably in the urban area.

A digital twin model could also be useful for the analysis and simulation of transport systems that do not currently exist, such as UAM systems in metropolitan areas. In this perspective, the digital twin model may be applied to identify suitable areas for locating vertiports and establishing urban air corridors in the lower airspace for FVs operations.

The amount of available information related to the city characteristics affects the digital twin representation of UAM scenarios that can be developed. The basic information useful for the vertiport positioning – particularly locations and integration with ground transport systems – and for identifying aerial corridors in the lower airspace, both size and direction, are:

- Digital Terrain Model (DTM);
- Building height;
- Intended use of the building (or building type, such as schools, hospitals and churches);
- Socioeconomic variables (e.g., population density, workplaces, leisure spaces);
- Ground transport infrastructures (e.g., roads, rails, terminals);
- Places where people can gather (e.g., stadium, main squares, pedestrian areas).

These variables have been exploited to locate vertiports and aerial corridors in order to test an UAM scenario in a real context.

Figure 6.3. describes the relation among Digital Twin, Vertiport Location and 3D Urban Air Network (3D-UAN), which are the three interrelated elements here considered. The “context data” may be different depending on the nature of the problem that the digital twin model would help resolving. The digital twin and related data are thought to support the location of vertiports and the configuration of a suitable 3D-UAN. Some data are similar, although used for different goals. To solve the vertiport location problem, relevant data includes, for instance, anthropic features – such as height of buildings – as well as socio-economic characteristics that would identify travel needs and then potential transport demand for UAM services. The considered problems (3D-UAN and vertiport location) are not independent, in particular the location of vertiports will affect some of the nodes of the 3D-UAN (i.e., the “Fixed Nodes”) and then the corresponding links, which are the relationships between nodes, and represent urban aerial routes between relevant points.

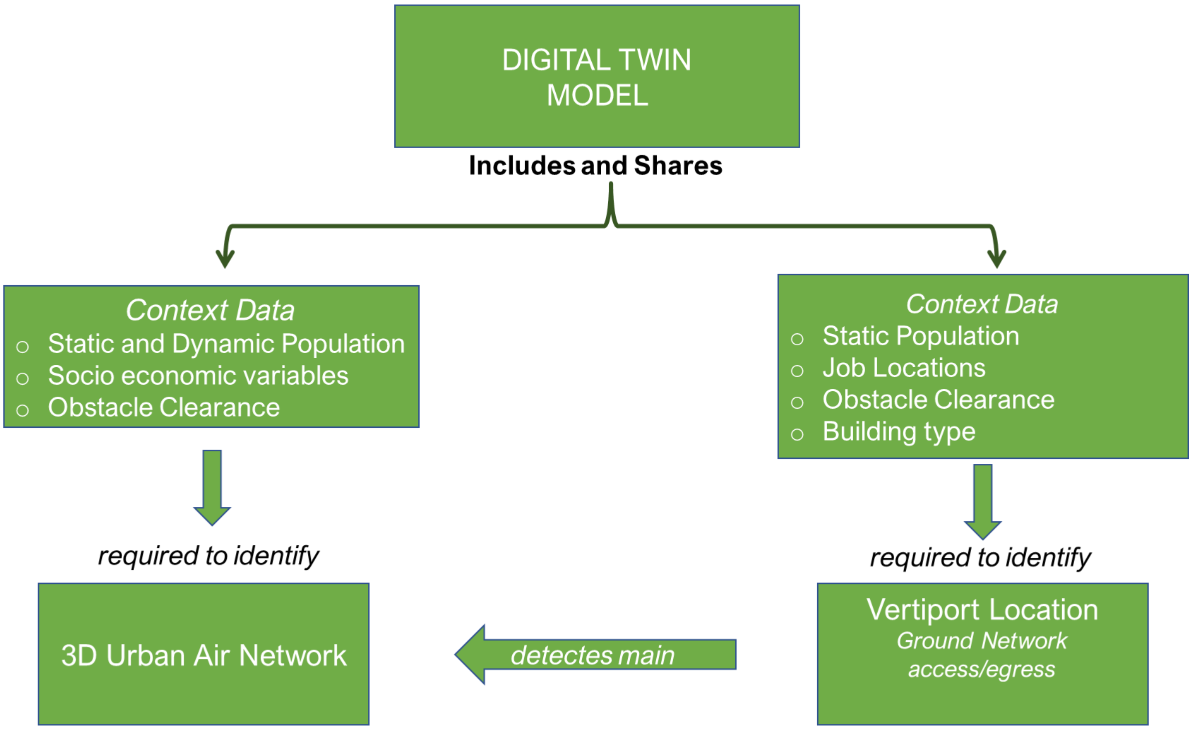

Figure 6.3. – Relation among Digital Twin, Vertiport Location and 3D-UAN.

It is worthwhile to note that urban aerial routes have to satisfy several constraints within the urban context – such as technical constraints, safety aspects and privacy issues – and then, still based on the digital twin model employment, additional nodes could be identified in order to set aerial routes that will meet such constraints.

6.3.2. Digital Twin application in Bologna metropolitan area

Bologna is an Italian city located in the Northern part, with a population of almost 390,000 inhabitants. Some characteristics that may represent relevant challenges for the introduction of UAM services are: (1) the relevant number of medieval towers in the 3D city centre; (2) the land morphology, i.e., the northern part of the city is on a flat area, while the southern one is placed on a hilly surface (Figure 6.4.). These characteristics, which introduce a high number of obstacles for FV operations and vertiport location, make the city of Bologna an interesting case study.

To realize the city digital twin, a GIS tool (QGIS software[16]) has been used to merge and process a high amount of information, based on freely available data that has been gathered by different sources (i.e., municipalities and cadastral data). First, a DTM for the entire city was used as a baseline. Data on buildings such as height, type (e.g., schools, hospitals, churches, sport and

[16] https://www.qgis.org/en/site/

leisure facilities), shape and size have been collected and added together with information on population density referring to the different city districts. Green areas such as parks have been modelled explicitly because they are places where people group. The main ground transport infrastructures (roads, railways), the public transport stops, and the airport area have then been added to the city model. Finally, uncovered rivers or streams have been included because FVs could overfly them to minimize the risk of collision.

The graphic representation of the city digital twin (Figure 6.4.) includes the DTM on the background, the buildings in red colour, roads and railways in light blue and blue respectively, and parks in green. More data, as real time data, may be included depending on availability. From this perspective, a digital twin of a city could provide significant support to design, place and manage vertiports as it contains detailed information that allows one to identify space occupancy, obstacle clearance, acoustic impacts and accessibility to ground services, but also potential demand based on socio-economic features as well as limitations for safety and security issues. In more detail, information on building heights allows the identification of potential spaces for locating vertiports, or, on the contrary, the areas that cannot be used to this aim.

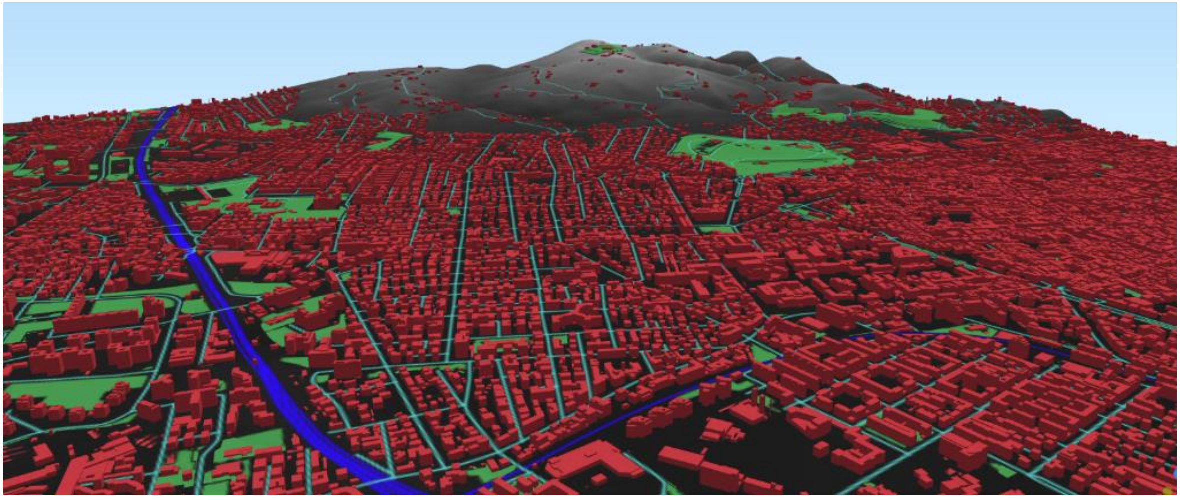

Figure 6.4. – Graphic representation of different information in the Bologna digital twin.

Similarly, obstacles (e.g., antennas) would prevent the use of such areas for locating vertiports. At the same time, population density, position of interchange ground nodes and suitable socio-economic indexes (e.g., high-income areas) would facilitate the identification of spaces potentially allocable to host vertiports. Integrating socio-economic and trip data, in particular concerning passengers' origin and destination points inside the study area, is useful for optimal vertiport positioning.

High-density areas associated with high-income, which are attractive for starting UAM services and then locating vertiports for accessing such services, generally correspond to densely urbanized areas, where space is rarely available. Furthermore, space availability does not refer simply to the area occupied by the vertiport infrastructure, but also to a suitable volume around it for allowing safe landing and take-off manoeuvres.

The advantage of the digital twin city in this context is to use multi-criteria approaches for identifying vertiport location also facilitated by the visual representation.

Finally, externalities generated by the vertiport can be assessed based on some aerial traffic hypotheses. Moreover, as the vertiport will be accessed mainly by ground transport modes, additional externalities due to the multi-modal ground transport systems can be considered and estimated – e.g., noise impacts, which is the most perceived one by the population, can be assessed, and it might represent another criterion used to identify the optimal vertiport location with respect to residents.

6.3.3. Vertiport location and 3D-UAN integration by Digital Twin

Figure 6.5. reports a preliminary solution where the vertiport location has been identified based on the information of Bologna digital twin. Particularly, vertiport location suitability has been identified by the method proposed by Fadhil (2018), based on the weighted overlay of different features. In more detail, the suitability, *S*, may be defined as (Eastman, 1999):

$$\mathrm{S} = \sum \mathrm{w_i x_i} \cdot \prod \mathrm{C_j} \qquad \text{(Eq. 6.5)}$$

where w_i is the weight assigned to factor *i*, X_i is the criterion score of factor *i* and C_j is a constraint. Particularly, the standardised factors are combined by means of weighted linear combination and the results are summed to arrive at a multi-criteria solution. Then, the result is multiplied by the product of the intersected constraints.

Factors and constraints are identified in the digital twin database of the case study; in particular, the main factors are population density, job density, median income, the characteristics of ground transport and the main POIs, while the constraints are elements that prevent the location of a vertiport in a given area (e.g., space unavailability, low airspace obstacles, proximity to schools, and vulnerable buildings). As for weights, in this first attempt they have been identified based on some preliminary results, also in the work by Fadhil (2018). The selected factors for the weighted overlay are summarized in Table 6.10. A different radius for POIs with respect to public transport stops – respectively 1000 m and 500 m – has been identified, as points of interest are expected to be less frequent than public transport stops, which generally are 500 m from each other in city central areas.

Table 6.10. – Factors and constraints used in the vertiport location procedure.

		Type of Information
Factors	Population Density	Residential population per km2 for each census unit
	Job Density	Number of job activities for each census unit
	Median Income	Annual median income in a census unit
	Ground Transport	For each census zone, number of PT (train, bus, sharing mobility) stops within a radius of 500 m
	Points of Interest	For each census zone, number of POIs (especially tourist attraction) within a radius of 1000 m
Constraints	Space unavailability	Insufficient space to accommodate a vertiport and dependant infrastructure
	Low Airspace Obstacles	Existing high altitude obstacles in the area surrounding the vertiport
	Vulnerable Buildings	Buildings that require a buffer zone as they are the headquarter of sensitive activities (schools, hospitals, barracks, etc.)

From Eq. (6.6), a preliminary vertiport location has been found close to the main train station, which is characterized by a large square that would facilitate safe manoeuvres. The identified area is also close to both the city centre, with several POIs in the surroundings, and an important interchange node, with train and bus services that would improve intermodality between ground and aerial services. It is worth noting that the assigned weights and constrains used in Eq. (6.6) reflect, from one side, the importance given to several factors and from the other side the unfeasibility of some locations based on criteria such as building *geofence*, obstacles and so on, as it emerges from the digital twin database.

The area is also characterized by a high value of population and job density. Although high population and job densities might be considered a constraint for vertiport location, the considered *geofence* data would guarantee suitable distances from relevant buildings and at the same time a suitable, potential demand for UAM services. Based on the chosen factors, weights and constraints, the airport area, which is also close to the city, has not been identified as a potential solution for locating the vertiport. For example, in this case the population density is not so high as in the city centre, and intermodality is not as relevant as in the location close to the train station.

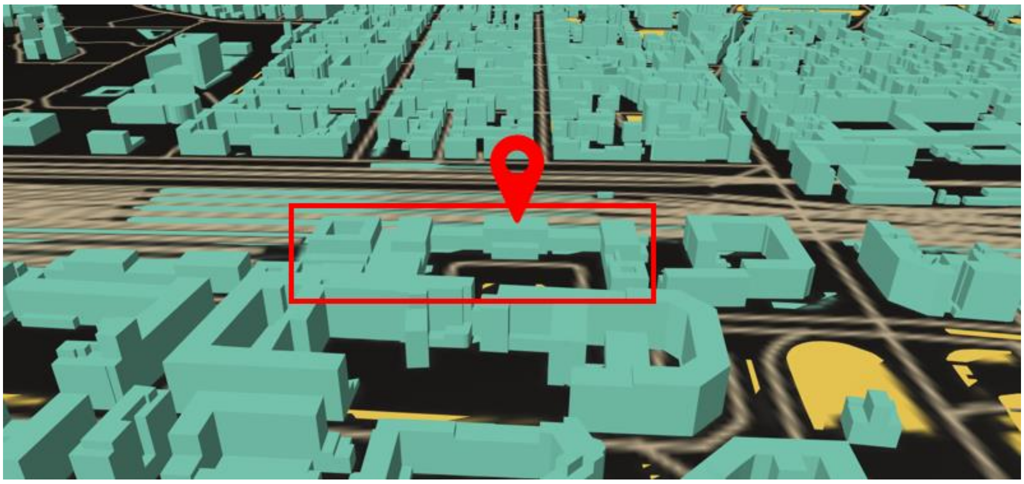

Figure 6.5. – Example of vertiport location (Bologna digital twin model).

While this solution has been found by considering simple constraints and weights coming from the literature, more precise solutions may be found by improving the set of data in the digital twin and by adding further constraints related to environmental impacts or minimization of access time to the vertiports, which in this example have not been considered as not all the data were available at this stage. As for environmental impacts in particular, several hypotheses on the expected traffic at the vertiport could provide different solutions, thus also suggesting capacity limits to guarantee good life quality levels to the community living around the vertiport. Finally, the airports are expected to host vertiports inside or close to their neighbourhood (Desai et al., 2021), especially for aerial AS services. Mainly for airports close to urban areas (city airports) – but generally for airports serving a given territorial system – the digital twin should also include information on aircraft take-off and landing trajectories (and the consequent obstacle limitation surfaces) in order to consider the potential risks due to FVs movements in airport area and the related possible interferences with traditional aviation. By considering the digital twin model of the metropolitan area of Bologna three vertiports have been identified (Figure 6.6), which are, respectively, at the airport (vertiport 1), at the main station (vertiport 2) and in a city area with high population, job density and median income (vertiport 3). It is worth noting that this result has been obtained by using freely available data. More accurate results and possibly different vertiport locations and/or number might be obtained by using a more detailed database.

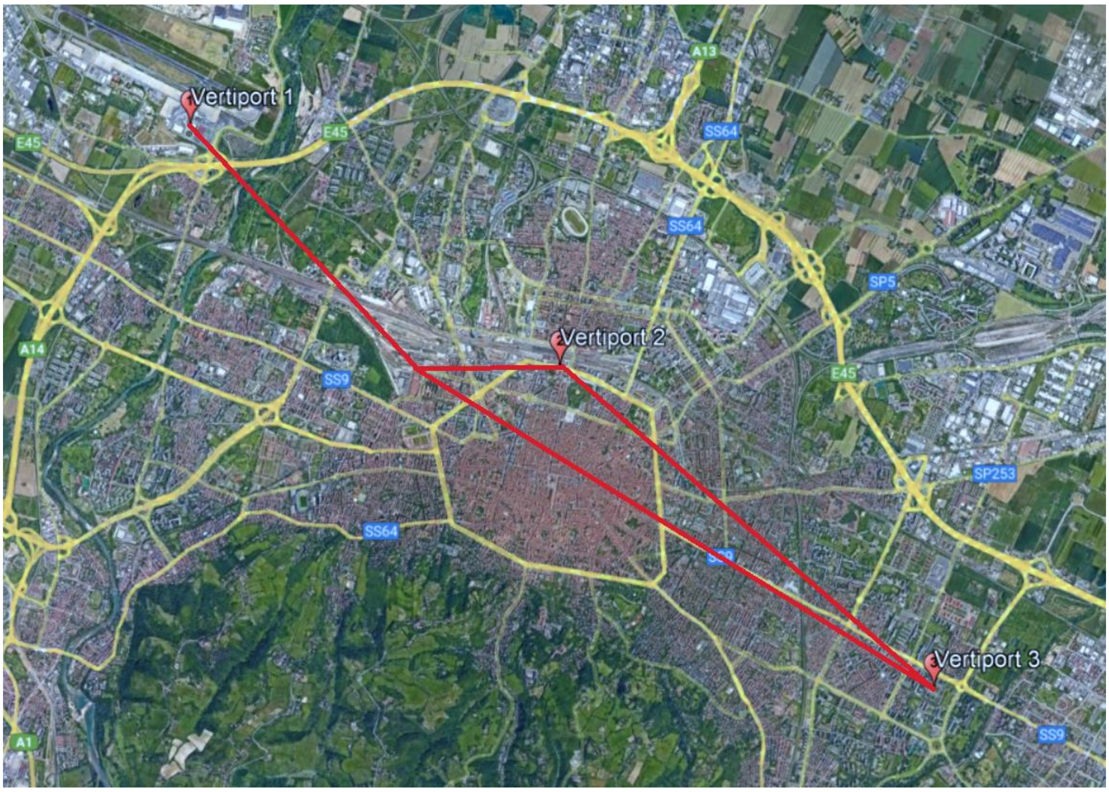

Figure 6.6. – Vertiport location integrating 3D-UAN case study.

Starting from the vertiport locations, the routes linking them have been set using eqs. (5.2) – (5.6.), Dijkstra algorithm, and the information provided by the digital twin model about local orography and barriers. Where available, data about local environmental features have also been considered. Particularly, some constraints to avoid conflicts with traditional aviation have been introduced in the digital twin model. As for the urban environment, the presence of high buildings – such as historical towers and modern skyscrapers – has prevented the connection of vertiport 1 with the other remaining two by a straight line (see Figure 6.6.).

The obtained 3D-UAN network (Figure 6.7) includes links and vertiports, whose features are reported in Table 6.11 and Table 6.12, respectively. Due to the information contained in the digital twin model (i.e., DTM and building heights) and the introduced constraints to avoids obstacles along the dynamic air corridors, the altitude (see Table 6.12) of the first layer (L_1) resulted at 200m ASL (the highest building roof is at 184 m), while the following one (L_2) is at 250 m ASL (distance between L_1 and L_2 = 50 m).

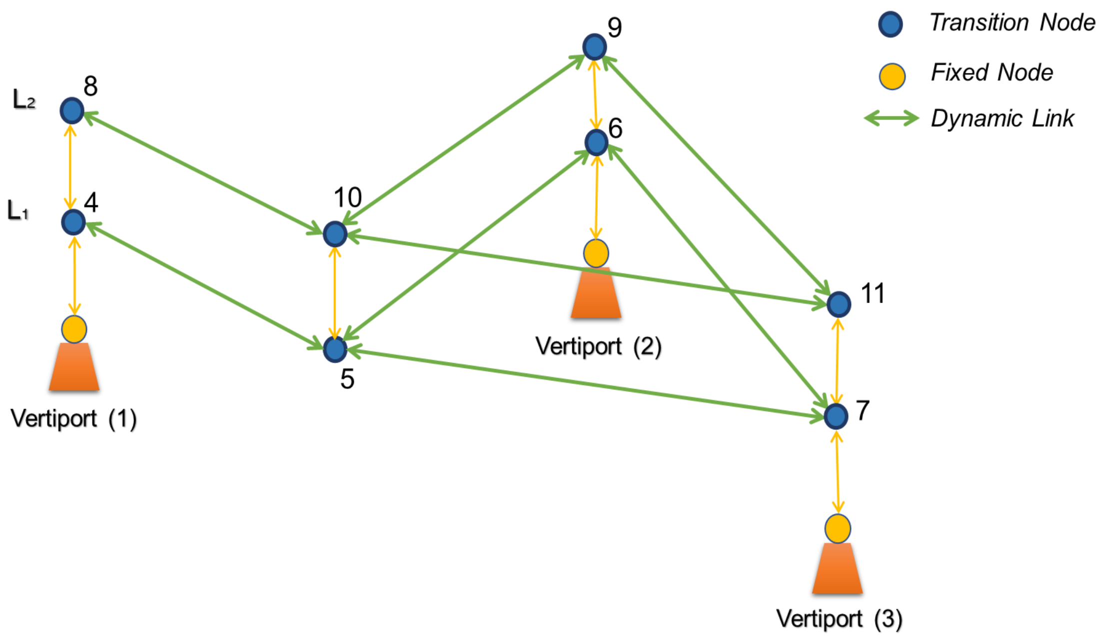

Figure 6.7. – The scheme of 3D-UAN model for Bologna city case scenario.

The average cruising speed allowed on the horizontal links is considered equal to 90 km/h, while on the vertical links (included take-off and landing phases) it is 50 km/h. This average speed value was chosen based on the data distributed by Volocopter prototype[17], which should also support aspects related to flight safety.

Two scenarios have been investigated, which have been set as follows:

(a) scenario S_1: time gap between successive departures T_g =180 s

(b) scenario S_2: time gap between successive departures T_g =120 s.

Table 6.11. – Dynamic link in the 3D-UAN simulated.

Bidirectional Link			
Horizontal	**Length (m)**	***Vertical***	**Length (m)**
4–5	3310	1–4	160
8–10	3310	2–6	140
5–7	6670	3–7	110
10–11	6670	4–8	50
5–6	1700	5–10	50
10–9	1700	6–9	50
6–7	5190	7–11	50
9–11	5190		

[17] https://www.volocopter.com/en/solutions/volocity

Table 6.12. – Vertiport elevation data.

Vertiport	***Elevation ASL (m)***
Node 1 (Airport)	40
Node 2 (Main Station)	60
Node 3 (Populated–High income area)	90

For both scenarios, the dynamic link features are reported in Table 6.13. Furthermore, for S_1 and S_2, six FVs have been considered connecting specific origin/destination pairs, and their shortest paths have been computed (Table 6.14.). Additionally, a T_g value has been assigned to fixed nodes, particularly for each scenario: FV $_{(1)}$ and FV $_{(2)}$ takes-off at the same time t_0 and $T_{g1} = 0$; FV $_{(3)}$ and FV $_{(4)}$ takes-off at time t_1 and $T_{g2} = t_0 + T_{g_{(1,2)}}$; FV $_{(5)}$ and FV $_{(6)}$ takes-off at time t_2 and $T_{g3} = t_1 + T_{g_{(3,4)}}$. Table 6 reports a detailed analysis of the two scenarios over different periods of time.

Table 6.13. – Dynamic link features.

Dynamic Link Features		
Maximum link capacity (number of FVs)	*Average cruise speed (horizontal links)*	*Average cruise speed (vertical links)*
2	90 km/h	50 km/h

Table 6.14. – O/D nodes, travelled distances and path costs in the two scenarios.

	Origin Node	***Destination Node***	***S1: Travelled Distance (m)***	***S1: Path Cost (s)***	***S2: Travelled Distance (m)***	***S2: Path Cost (s)***
FV $_{(1)}$	3	1	10.250	418,64	10.250	418,64
FV $_{(2)}$	2	1	5310	222	5310	222
FV $_{(3)}$	3	1	10.250	418,64	10.250	418,64
FV $_{(4)}$	2	1	5310	222	5310	222
FV $_{(5)}$	3	1	10.250	418,64	10.350	605,84
FV $_{(6)}$	2	1	5310	222	5310	222

Table 6.15. – Dynamic link status and FV position in the two tested scenarios.

	Scenario 1: Tg = 180 s						***Scenario 2: Tg = 120 s***					
	0	**120 s**	**180 s**	**240 s**	**360 s**	**420 s**	**0**	**120 s**	**180 s**	**240 s**	**270s**	**360 s**
$FV_{(1)}$	N^{*}_{3}	(7-5) **	(7-5)	(7-5)	(5-4)	\	N_3	(7-5)	(7-5)	(7-5)	(7-5)	(5-4)
$FV_{(2)}$	N_2	(5-4)	(5-4)	\	\	\	N_2	(5-4)	(5-4)	\	\	\
$FV_{(3)}$	\	\	N_3	(7-5)	(7-5)	(7-5)	\	N 3	(7-5)	(7-5)	(7-5)	(7-5)
$FV_{(4)}$	\	\	N_2	(6-5)	(5-4)	\	\	N_2	(6-5)	(6-5)	(5-4)	\
$FV_{(5)}$	\	\	\	\	N 3	(7-5)	\	\		N_3	(11-10)	(11-10)
$FV_{(6)}$	\	\	\	\	N_2	(6-5)	\	\		N_2	(6-5)	(5-4)

* N = *node*
(.) ** = *link*

From Table 6.14 and 6.15 emerge that, in a small urban context (such as the city of Bologna), a time gap T_g = 180 s between successive departures would not generate air traffic congestion, even if there are crossing routes. A different result is obtained in the case of T_g = 120 s. In this scenario, $FV_{(5)}$ has to exploit the dynamism of the links and switches to the next layer to ensure flight safety and avoid link congestion. Due to the information stored regarding the air traffic conditions, by both FV and the control centre, the link (7–5) is disabled for transit, while the vertical links (7–11) and (8–4), and the horizontal links (11–10) and (10–8) are enabled, ensuring a suitable air transport service.

Finally, for the effective use of digital twin framework in UAM scenarios, several aspects should be considered. First, it is important to validate the accuracy and the precision of the gathered data before their integration into the digital model. For example, inaccuracies in the measurement of building heights would compromise safety and produce problems in the risk management process as well as vertiport location, which strongly depends on obstacle clearance. Secondly, continuous digital twin data update is required to reproduce the actual conditions of the represented system. For example, if cranes are introduced inside the city for construction aims, which are possible obstacles to drone operations, the 3D-UAN should be verified and changed, if necessary, in order to avoid these hindrances.

CHAPTER 7 – CONCLUSIONS

7. CONCLUSIONS

The technological evolution towards fast, automated and connected services has also involved the transport systems. Several innovative solutions are being identified to improve urban and suburban mobility, particularly characterized by high levels of road congestion and environmental pollution.
In this context, Urban Air Mobility (UAM), also known as Advanced Air Mobility (AAM), promises to realize aerial, fast and dynamic connections between cities and among different city areas. This pioneering air transport system, which involves the 3rd spatial dimension, is encouraged by recent technological developments of Unmanned Aerial Vehicles (UAVs) and electric Vertical Take-Off and Landing (eVTOL) aircraft – as well as Vehicle-to-Vehicle (V2V) and Vehicle-to-Everything (V2X) communications techniques, Detection and Avoidance (DAA) sensors, advanced battery systems. The intended goal is to provide air services for carrying passengers and goods in metropolitan and sub-urban environments. Although many advancements have been made for making prototypal eVTOLs or FVs operational, there are still many issues to be solved in terms of infrastructures that would support the implementation of an aerial transport system in urban areas.

This thesis has analysed some main elements that will specify UAM transport systems, in order to contribute to fill the gap of some open research issues. As well known, modelling the transport system require modelling the transport supply and demand suitably, and in this research work both UAM supply and demand models have been explored.

The analysis started by exploring the current literature on uncontrolled low airspace management, on main features of novel FVs that will operate in those systems and on early aerial application scenarios identified for the UAM concept. This review laid the basis in order to set up the main assumptions, firstly to analyse the demand features for UAM services and then to propose a supply framework to ensure FV procedures and mobility services.

Although the entire analysis was conducted to build a system that can allow passenger and goods mobility, the examination of demand features focused mainly on passenger transport services, in particular on the UAM Airport Shuttle use case. Indeed, the Airport Shuttle is considered the one with greater advantages among UAM use cases. To explore the key factors driving users' choice, a SP survey was carried out and some MNL models together with a ML model were specified and calibrated. The calibration results show that high ratio between car and driving licence per family unit and limited experience with driving assistance systems would limit the successful implementation of AS services. Also, it is emerged that this service can be preferred by high-income people who travel frequently by plane. As for age, young people seem to prefer AS shared services in which the ticket cost can be divided with the other passengers, whereas older customers (more than 35 years) would prefer AS private run alternatives. Then due to lack awareness of flying alternatives, travellers prefer to confirm the choice of ground transport modes they generally use, particularly for distances in the range 30-60 Km. Finally, the averaged Values of Time have been estimated for the tested MNL models, which are quite in line with the results obtained in current literature for UAM similar services.

Afterwards, this work has focused on UAM supply system analysis both related to ground infrastructures and aerial network. Firstly, a comprehensive review on vertiports has been provided by exploring the main approaches, and the related results, to design and locate vertiports, with a special focus on capacity. Approaches and results have been achieved from the existing literature dealing with vertiport requirements, both explicitly or implicitly – as part of more inclusive topics, i.e., UAM service and network simulations. Thus two main aspects, which affect transport operational and management issues, have been examined: the vertiport design and the vertiport location. Vertiport design concerns the different approaches proposed for setting feasible layouts and their effects on capacity, whereas vertiport location refers to the methods used to choose suitable areas where allocate the facilities, by considering their role as both infrastructure elements of the UAM networks and service stops for transport demand. Since vertiports will be the main nodes of aerial supply systems, their capacity, which must allow safe landing/take-off FV operations, could severely affect UAM service performances.

The key innovative element of this research project is the UAM aerial supply model. A main issue to introduce UAM concept among current transport systems is the urban low airspace structure and management. To this aim an innovative framework has been proposed. A multi-layer network model (3D-UAN) incorporating the concept of dynamic corridors – which are identified in the network links (both horizontal and vertical) and can be enabled or disabled according to link spare capacity and safety issues – has been formulated. As also emerged in the airspace literature, layer frameworks allow to represent the airspace as a set of two–dimensional planes, which are connected by vertical corridors. In the context of urban aerial transport systems, this layer-based space structure has been organized into an aerial transport network composed of nodes and links with specific characteristics, also defined by the link cost functions that make it possible to compute the shortest paths based on the minimum travel cost criterion. Other than link travel time on both horizontal and vertical links, a suitable time gap on links and the headway time at fixed nodes have been assumed between next FV departures in order to guarantee suitable separations between FVs and avoid collisions on routes.

Furthermore, a test scenario was simulated in order to assess the 3D-UAN model feasibility. The test scenario involved a scheduled UAM transport service (as Airport Shuttle), in which origin and destination points are preliminarily established. Fourteen FVs have been assigned to the aerial network by using a shortest path algorithm combined with the specification of singular dynamic links. The obtained results confirm the suitability of some initial hypotheses (two FVs per link and a 2-minutes time gap between them) and show that the 3D-UAN model provides appropriate outcomes in terms of path costs in relation to the travelled distances even if all the layers are occupied. It also emerged that using bi-directional dynamic links on the same layer could lead to network overuse. Still, a preliminary analysis of the indirect CO_2 emissions produced when a scheduled aerial service is provided, within the proposed 3D-UAN framework, has been carried out. In detail, the $kgCO_2$ produced by FVs (indirect emissions linked to the electricity generation for the recharging phase) and cars (fuel engine direct emissions) have been compared in the simulated scenario, all transport features being the same and the necessary emission indexes referring to the Italian context. The results show that the tested UAM use case generates higher levels of CO_2 than car trips per passenger travelling the same distances, which does not guarantee an effective advantage in proposing the UAM system as a sustainable alternative to traditional transport systems in terms of greenhouse emissions. However, such results depend on the way the electricity is generated in the considered context, which could lead to different results in other contexts. Whatever the context, careful attention must be paid to the important aspect of how e-vehicles are charged, or, in other words which is the source for generating electricity.

Finally, a digital twin framework has been defined to preliminary simulate the overall UAM supply model in real context, particularly in a medium size city and its metropolitan area in Italy. At first, the location of the vertiport close to the main train station in the city area – identified by applying the methodologies examined in this work – confirmed some of the suggestions and preliminary results in the literature. The identified area has some interesting features, such as high levels of population and job densities, which would generate demand levels for supporting UAM services and suitable ground connections, and they would assure great accessibility to the vertiport from the remaining part of the city. Then, the 3D-UAN structure has been set in the study area by identifying also three vertiports through the digital twin information on the most important factors and constraints to set safe aerial routes. Furthermore, a preliminary simulation of the aerial traffic flows has been provided, based on the cost functions proposed in the 3D-UAN model. In a real operational context, detected traffic data could also be added to the digital twin of the system as time series data useful for figures and off-line scheduling purposes. In fact, in the case of scheduled services, the computation of the shortest path and assignment of FVs at specific enabled links is performed before the departure of each aerial vehicle, based on pre-trip information regarding the origin and destination points of FVs. Then, information regarding static and dynamic populations could be relevant for dynamically adapting the 3D-UAN in order to avoid overflying crowded locations. Similarly, information on dynamic and static population density could be used to adjust the dynamic corridors to reduce the externalities produced by FVs, e.g., noise emissions during the day or night, respectively. Moreover, information on how much a specific location is busy can also be useful to design and adapt the aerial network, while information on areas subjected to urban canyon effects may help in refining the optimal routes. In short, the opportunity to use a digital twin approach at a high detail level will help system designers and urban planners to evaluate and implement procedures to realize successful UAM supply systems able to support the existent ground transport systems.

To summarize, the main research contributions of this thesis are as follows:

- The overall analysis of the UAM transport system, both in terms of transport supply and demand aspects, currently not treated exhaustively in the literature, which can allow to identify the main issues related to this novel system.
- The analysis of the main demand features for AS services, both in terms of figures and model calibrations, which provides suggestions to stakeholders and policy makers, but also for future demand studies, also relating to other UAM services (e.g., on-demand AirTaxi).
- The systematic review on the main findings concerning vertiport layout and location, and their related issues from the transport, operational and management point of view, which can contribute to the design and planning of urban transport systems where both on-ground and aerial transport sub-systems coexist.
- The proposed 3D-UAN model, which could represent a suitable structure to simulate the aerial traffic operations of the new UAM services. Its distinctive dynamism suits the needs of an urban aerial environment characterized by several constraints and requirements.

- The use of a digital twin approach for identifying vertiport locations and setting the structure of the 3D-UAN in a real test case (city of Bologna).
- The results obtained by simulating the environmental impacts (indirect CO_2 emissions) of a test case, which suggest some further analyses – but also some thoughts – for assessing the sustainability of novel transport solutions.

Although the preliminary results obtained are particularly encouraging, some further research is required.

In regards of demand analysis, due to the lack of information on effective UAM operations, data collected by SP surveys can include some biases, which would affect the user choice. Other analyses are required when more accurate information on UAM systems will be available.
The introduction of vertiports – particularly close or within existing major ground nodes – should be carefully studied in order to both ensure an improvement of the whole transport system and avoid that ground congestion problems, already affecting the ground transport nodes, might get worse.
Finally, by considering the 3D-UAN test scenarios, some constraints have been set – such as a reduced average cruising speed value and a low value of the maximum capacity – which have to be relaxed to understand which are the effective limits of a UAM transport system. Similarly, to test the potentialities of the supply model, some elements have to be further explored – such as higher speeds, greater number of FVs, and longer travel ranges.

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