

The present work was submitted to the Institute of Aerospace Systems

presented by

Myriam VILAR LLIDÓ

Student ID No.: 383098

Bachelor-Thesis

Evaluation of Urban Air Mobility Systems Considering Regulatory and Operational Constraints

Aachen, August 3rd, 2018

Supervising professor:
Assistant supervisor:

Univ.-Prof. Dr.-Ing. Eike Stumpf
Michael Husemann, M.Sc. RWTH

1st examiner:
2nd examiner:

Univ.-Prof. Dr.-Ing. Eike Stumpf
Dr.-Ing. Ralf Hörnschemeyer

Bachelor's Thesis
For Myriam Vilar Llidó
Matriculation number 383098

**Univ.-Prof. Dr.-Ing.
Eike Stumpf**

Wuellnerstrasse 7
52062 Aachen
GERMANY

Phone: +49 241 80-96804
Fax: +49 241 80-92233

Aachen, September 3, 2018

**Evaluation of Urban Air Mobility Systems
Considering Regulatory and Operational Constraints**

For the past few decades, the range of urban means of transportation has been widening significantly as a consequence of society's needs increasing and becoming more demanding when it comes to urban mobility. Such continuous growth of coexistent ground vehicles around city centers is becoming a millstone for society as it is leading to issues, such as traffic jams, increasing CO₂ emissions and other air pollution. However, reducing the variety of urban transport cannot solve these problems, as the population size is constantly enlarging, and thus, so is the mobility demand. Therefore, the solution to supply urban mobility without further overcrowding the city centers is to incorporate the airspace as a new transportation dimension. This thesis aims at evaluating the implementation of urban air mobility with the purpose of alleviating ground congestion and ultimately, improving the urban quality of life.

In order to determine the most efficient way of implementing urban air mobility, this bachelor's thesis considers the following aspects: Why will urban air mobility be accepted by society, what type of vehicle will carry out preferred transportation mode, what limitations might arise and what regulations must be complied. With the purpose of answering these questions, this thesis provides a synthesis of a previous extensive reading about how social demand of mobility has evolved, as well as an assessment of several models of air vehicles with the aim of determining the most suitable design. By considering relevant navigation laws that an air vehicle must fulfill when integrated in the urban airspace, this thesis provides a tradeoff between optimal technical parameters and legislation limits. Consequently, a set of improvements on the initial selected vehicle are suggested in order to obtain an optimum design which accomplishes an entire satisfaction of the regulations while fulfilling the society's mobility requirements.

The thesis comprises following tasks:

- Literature research on the emergence of social demand of mobility
- Literature research on airspace legislation
- Synthesis of external research
- Study of already-proposed prototypes of personal air vehicles
- Implementation of external research to suggest improvements of results
- Documentation of the process and results

The thesis starts on May 15th, 2018 and is supervised by Mr. Michael Husemann, M.Sc.

Acknowledgements

First and foremost I offer my sincerest gratitude to my supervisor Mr Michael Husemann, M. Sc., who was abundantly helpful and offered invaluable assistance, support and guidance over the journey of this Bachelor's thesis.

Special thanks to my friends studying in RWTH Aachen, for making the library a pleasant place to work. Also, to my friends in Spain, who despite the kilometres between us, have supported me unconditionally. Their motivation and humour have made the journey easier and a lot more enjoyable.

I am also greatly indebted to my entire family, for putting all their faith in me. Most importantly, none of this would have ever been possible without the continued and unwavering support of my parents José Luis and Miriam, and my brother Alejandro. In these cases, words simply are not sufficient.

Content

1	Introduction	1
2	The Evolution of Urban Mobility	3
2.1	The Rise of Cities	3
2.2	Urban Mobility at a Tipping Point.....	4
2.3	Urban Air Mobility	7
3	Personal Air Vehicle.....	10
3.1	Introducing the PAV	10
3.2	Concept Designs and Approaches	12
3.3	Examples of Modern PAVs	15
3.4	The PAV Market.....	20
3.5	Volocopter 2X.....	25
4	Socio-Economic and Technological Challenges.....	32
4.1	Safety	33
4.1.1	Weather	35
4.1.2	Induced Errors.....	38
4.1.3	Cyber-Security	39
4.2	Environment.....	41
4.2.1	Energy Consumption.....	42
4.2.2	Noise	44
4.2.3	Further Environmental Aspects	46
4.3	Technical and Operational Limitations.....	47
4.3.1	Automation and Autonomy.....	48
4.3.2	Infrastructure required by the PAVs	49
5	Laws and Regulations	51
5.1	Certifications.....	51
5.1.1	Vehicle Certification	52
5.1.2	User Certification	54

5.2	Airspace Management	58
5.2.1	Airspace Classes	60
5.3	Airspace Safety	65
5.3.1	Air Traffic Management	65
5.3.2	Terrorism.....	68
6	Integration of UAM.....	70
6.1	Case Study	71
6.1.1	Airspace Integration Principles for UAM.....	72
6.1.2	Airspace Integration Strategies for UAM	73
6.1.3	Enabling Capabilities	83
6.2	Improvements on the Reference PAV	90
6.2.1	Overall Scenario.....	90
6.2.2	Volocopter 2X 2.0.....	91
7	Summary and Outlook.....	95
	List of References	97

List of Figures

Figure 2.1: Share of urban and rural populations, 1950-2050 (as a proportion of total population) [3].....	5
Figure 2.2: Air passengers carried, including domestic and international aircraft passengers of air carriers registered [12].....	9
Figure 3.1: PAV Categories [44].....	13
Figure 3.2: Uber Elevate eCRM-001 model [27]	16
Figure 3.3: NASA X-57 Maxwell [28]	17
Figure 3.4: Total sUAS Revenue – World Market, Forecast: 2014 to 2019 [30]	18
Figure 3.5: Volocopter 2X [23]	20
Figure 3.6: EHang 184 [24]	21
Figure 3.7: Variables that influence a consumer’s motivation [41]	22
Figure 3.8: Research and development parameters that influence the PAV design [41] ...	23
Figure 3.9: Interior of Volocopter 2X’s cockpit. [33]	28
Figure 4.1: Exterior view of a Volocopter 2X rotor [57]	37
Figure 4.2: Percentage of Highly Sleep Disturbed (HSD) based on responses to questions on awakenings, difficulty falling asleep, and sleep disturbance for aircraft (a), road (b), and rail (c) noise [68]	45
Figure 5.1: Historical pilots hired at major airlines vs. new commercial pilots created [92]	57
Figure 5.2: Airspace profile [94]	61
Figure 5.3: Example of the geofencing system GEO [106]	64
Figure 5.4: The Gordian Knot applied to the sense and avoid issue of PAVs [101]	69
Figure 6.1: Contributions of different airspace integration strategies as a function of PAVs density [103]	81

Figure 6.2: Infrastructure to integrate and scale UAM [33] 94

List of Tables

Table 3.1: Structural dimensions of the Volocopter 2X [34]	29
Table 3.2: Performance parameters of the Volocopter 2X [34]	30
Table 3.3: Synthesis of the Volocopter 2X's design specifications and the R&D parameters	31
Table 4.1: Overview of fatal accidents and fatalities 2016 vs. 10-year average (2006-2015) [61]	39
Table 6.1: Summary of operational differences for UAM starting points [103]	77

Abbreviations

ADS-B	Automatic Dependent Surveillance-Broadcast
AFR	Autonomous Flight Rules
AGL	Above Ground Level
AIAA	American Institute of Aeronautics and Astronautics
AIM	Aeronautical Information Manual
AMSL	Above Mean Sea Level
ATC	Air Traffic Control
ATM	Air Traffic Management
BVI	Blade Vortex Interaction
CAT	Commercial Air Transport
CFIT	Controlled Flight Into Terrain
DEP	Distributed Electric Propulsion
EASA	European Aviation Safety Agency
ELA	European Light Aircraft
eVTOL	Electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
FF	Free Flight
FIMS	Flight Information Management System
FMS	Flight Management System
GA	General Aviation
GCAS	Ground-Collision Avoidance System

GEO	Geospatial Environment Online
GPS	Global Positioning System
GPWS	Ground Proximity Warning System
IAS	Indicated Airspeed
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
JAA	Joint Aviation Authorities
LiDAR	Light Detection and Ranging
LRFID	Local Radio Frequency Identifier
LSALT	Lowest Safety Altitude
MSL	Mean Sea Level
MTOM	Maximum Take-Off Mass
NAS	National Airspace System
NCO	Non-Commercial Operations
ODM	On-Demand Mobility
PATS	Personal Aerial Transportation System
PAV	Personal Air Vehicle
PPL	Private Pilot License
PPL (H)	Private Pilot License for Helicopters
PPlane	Personal Plane
R&D	Research and Development
S&A	Sense and Avoid

SESAR	Single European Sky ATM Research
SPO	Special Operation
TAWS	Terrain Avoidance and Warning System
TSS	Terminal Sequencing and Spacing
UAM	Urban Air Mobility
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
USS	UAS Service Suppliers
UTM	UAS Traffic Management
VFR	Visual Flight Rules
VISTA	Vehicle Integration, Strategy, and Technology Assessment

1 Introduction

City streets are often a blur of movement: cars, trucks, buses, trams, scooters and bicycles all jostle for space. As traffic jams grow, frustration rises, time is wasted and money lost. To this it is added the world trending phenomena of urbanisation; by 2030, more than 60% of the world's population will be living in cities [8], stretching struggling ground transportation networks even further. Solutions to the urban mobility problem are certainly required.

In this thesis, a possible solution to this problem is proposed and analysed. Such solution is the use of that part of the cities that remains congestion-free: the sky, taking mobility into a third dimension. Adding the airspace to urban transport networks would revolutionise the way in which people live and hence, it is very important to study this topic in order to assess its integration and viability.

Many research and studies have been done on Urban Air Mobility (UAM): the majority of them have focused on evaluating the air vehicle that would be required to carry out this service, some others have studied the social acceptance and market of this new transportation system, and a few have analysed the airspace regulations that would be applied in the case UAM would be integration in cities. Due to the lack of homogeneity between all studies, this thesis summarises and brings all these together with the objective of building a broad and complete picture of the situation and obtaining an understanding of all the aspects that should be considered when talking about the integration of UAM.

As UAM is a system that has an impact on many agents (ground infrastructure, the airspace, the transportation market, the society, the environment, etc.), it is very important to study these as a whole. That way, when judging and making suggestions, these are provided with a better background and considering many more aspects. This thesis proposes some adaptations to what has already been proposed, for example, the air vehicles that could be used, and proposes new methods or paths that could be taken in order to integrate UAM.

However, in order to raise some suggestions, a previous study of these agents is required. For this reason, in this thesis, each chapter analyses individually each one of these and summarises the key aspects that have to be taken into account when evaluating the possible integration of UAM in cities. Chapter 2 looks back at how society and mobility have evolved in the past years to understand whether UAM would actually be a reasonable solution, both for the given urban mobility situation and for the society, whether this one

would be pleased and satisfied with this new transportation mode. Chapter 3 evaluates the type of vehicle that could carry out this service, bearing in mind the mobility needs of the citizens (known from Chapter 2) and ensuring that this vehicle does indeed lead to an improvement of the overcrowded city streets. The main problems and issues related with these vehicles are also discussed in order to set a focus on the main points that should be worked on when designing these vehicles (noise emissions, pollution, etc.) The next two chapters, chapters 4 and 5, present the main challenges and legal frameworks that UAM would encounter during its integration process and during its actual operation. It is essential to understand these two aspects because they determine the starting point of the entire process; it determines the minimum requirements the aerial vehicles should fulfil, in terms of safety, on-board instruments, certifications and limiting parameters (e.g. noise, emissions). They also determine where and when UAM could be operated, and who would be responsible for its correct operation. The thesis presents the trade-off between the characteristics that would present a functional advantage (e.g. integration of on-board instruments to gain full autonomy so that any user can get on board and be transported without the need of a pilot or pilot license) and those requirements that must be fulfilled due to legal or technological limitations (e.g. maximum weight restriction of the vehicle so that it is allowed to fly at low altitudes of the urban airspace. Finally, Chapter 6 takes into consideration all these aspects to propose a possible integration strategy as well as improvements that could be applied to an already-existing model of a UAM aerial vehicle, in order to be more suitable given the proposed strategy and hypothetical integrated model of UAM.

2 The Evolution of Urban Mobility

2.1 The Rise of Cities

Nowadays, 54% of the world's population lives in urban areas, and such percentage is expected to increase over the years [1]. However, as recently as 100 years ago, only 2 out of 10 people lived in a city, and before that, it was even less. How has the world reached such a high degree of urbanisation?

Urbanisation is the process by which more and more people leave the countryside to live in cities [2]. This movement of people initially arises due to the automatisisation (in developed nations) of rural industries, such as agriculture and livestock breeding. As a consequence of this automatisisation, less manpower is required, leading to an increase in the rural unemployment rate. Hoping to find a job, rural dwellers migrate from the countryside to cities. Above that, besides being unemployed, many countrymen lack access to basic facilities such as healthcare, education, entertainment and transport, services which are indeed offered in cities. These attract rural dwellers who seek a secure livelihood and higher standard of living for themselves and their children, fuelling this migration from rural to urban areas.

Nevertheless, the global phenomenon of urbanisation is not the only factor affecting the increasing population in cities. Along with the mass migration to urban areas (people moving in), those who were already born in cities, actual citizens, are not leaving. Today's cities are characterised by high concentrations of economic activity, employment and wealth, encompassing financial, political and cultural centres, as well as social and leisure facilities. Here, people find opportunities and see no reason for them to leave. In fact, from 746 million in 1950, the world's urban population has rapidly grown to 3.9 billion in 2014. Below, in Figure 1, one can clearly identify the increasing trend of urban population across continents; with time, the proportion of rural population (area coloured in orange) decreases as the area in blue, representing the percentage of the urban population, increases.

By further analysing Figure 2.1, it can be appreciated how Europe, represented in the top-left graph, was transformed itself away from being a rural, agricultural community in a slow manner. A similar gradual evolution was experienced by North America (bottom-centre graph) and Oceania (bottom-right). It has to be recalled that more than half of these continents' populations were living in an urban area by 1950. Per contra, more than 80% of the African (top-centre graph) and Asian (top-right) populations inhabited rural areas in 1950. While the pace of urbanisation, i.e. the gradient of each graph, in these two conti-

nents subsequently accelerated, in 2015 a majority of their populations, (59.6 % in the case of Africa and 51.8 % in Asia) continued to live in rural areas. Meanwhile, in 2015, almost three quarters of the European population lived in an urban area, and even higher shares were recorded in Latin America and the Caribbean (bottom-left graph) and North America, 79.8 % and 81.6 % respectively.

In general terms, it can be said that Figure 2.1 illustrates, that, at a global level, it was only during the last decade that the total number of people living in urban areas overtook those living in rural areas. In fact, according to the United Nations, approximately two thirds of the world's population will be living in an urban area by 2050 [3]. With urban areas dealing with big population figures (and expecting even larger), “managing urban areas has become one of the most important development challenges of the 21st Century”, as John Wilmoth¹ said.

With an enormous pressure being exerted on the available resources in cities, these face numerous defiance in meeting the needs of their urban populations' unfettered growth, including the needs for housing, infrastructure, transportation, energy and employment, as well as for basic services, such as education and health care [4]. The main difficulty arises during the process of meeting these needs, as new problems derive, for instance, property prices, poor sanitation, congestion and pollution. Given this situation, the next question that should be asked should be the following: how can the urban populations' requirements be fulfilled without jeopardising the quality of the urban lifestyle?

2.2 Urban Mobility at a Tipping Point

In urban areas, citizens live in the same environment, sharing services, facilities, and for their mobility, they even share the same infrastructure. In some cases, they get to share the same transportation mode, too. In Europe, cities increasingly face problems caused by transport and traffic; urban mobility accounts for 40% of all CO₂ emissions of road transport and up to 70% of other pollutants from transport [5]. Hence, the common challenge to all major cities resides in enhancing mobility while at the same time reducing congestion, accidents and pollution. To be able to do this, cities have to look back at the last past years and see how the citizens' needs on urban mobility have evolved, i.e. analyse the urban mobility demand. By doing this, a trend in the evolution can be identified and thus, a

¹ John Wilmoth, Director of Population Division, a UN Department of Economic and Social Affairs (DESA).

prediction on the mobility future status can be done. This means that cities would be able to adapt themselves more efficiently and effectively, before the mobility change would actually happen.

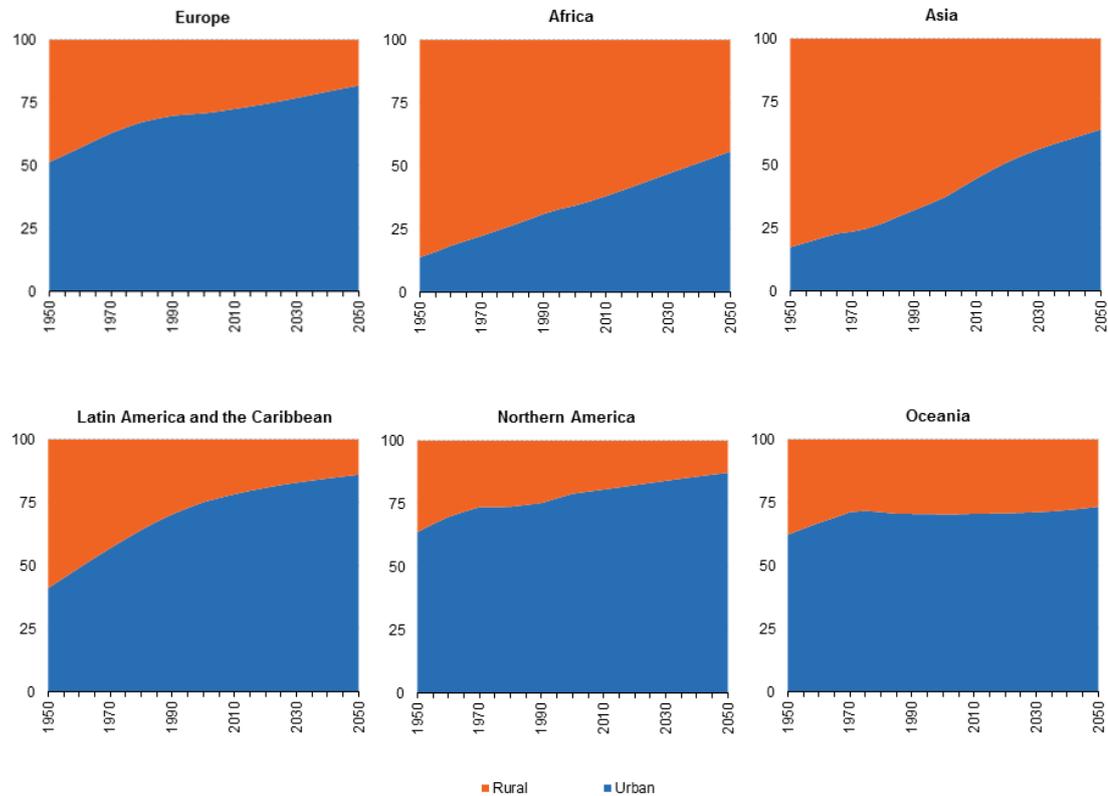


Figure 2.1: Share of urban and rural populations, 1950–2050 (as a proportion of total population). [3]

Early stages of urban growth, around 1950, led to a rapid increase in car ownership and use [6]. The manner in which urban areas adapted themselves to this scenario involved investing in a major urban road building programme and taking measures to maximise vehicle capacity on existing urban streets, supported by large increases in parking provision.

As the levels of car use increased, this transportation mode became less and less practical. Because cars, together with their required infrastructures, took up so much space in the cities, citizens experienced growing traffic congestions, and were exposed to air pollution, rising CO₂ emissions and the increasing risk of traffic accidents.

The solution to these problems was seen in public transport. Urban areas, rather than catering for unlimited vehicle movement, switched the primary objective to cater for growing person movement instead. This enabled road traffic growth to be contained, while increasing overall levels of mobility. This solution not only satisfied the urban mobility demand of the society, but also dealt with the social environmental concern, which was starting to become a common topic within the population around those times [7]. However, despite

the smart approach, another financial investment had to be done in order to adapt the already-existing infrastructures, as cities now had to have an exclusive lane for the public vehicles. With the years, as previously stated, cities have been recognised as centres of economic, social and cultural activities. This change, together with the increasing social environmental awareness and coupled with increasing concerns about public health, has led to a growing interest in providing a higher quality of urban life. As a consequence, cities are working on being more liveable, more sustainable. The way this is being achieved is by, again, reconstructing the ground infrastructures and building footway spaces and cycling lanes.

From this previous overview of the evolution of urban mobility, it can be identified how the ground space is constantly changing, and for that to occur, a high economical investment is required. Beyond that, it can be appreciated that the cities' adaptations always come after the social demand is established. It is perhaps for this reason, that cities, with the rush to supply such demand, the solution is not thought deeply enough, and hence, when a new necessity arises, such solution is no longer valid.

Until now, the following main statements can be asserted:

- Urban population is increasing
- Cities are becoming the centres of economic, social and cultural activities
- A lot of money and time is spent reconstructing the ground space to adapt to the society's demand on urban mobility

From these three statements, it can be assumed that, due to the increase in population and the continuous movement of people all over the planet, the need for mobility will increase. Besides, as most of the world's population will inhabit urban areas, not only will the demand of mobility increase, but more specifically, the urban mobility, meaning cities will have to ensure that both citizens and transportation media will all coexist efficiently, safely and optimally within the same space. In order to be ready to withstand such dense populations and high mobility demand, cities have to adopt some changes and adjust themselves before this revolution actually arrives. This way, the implementation of an urgent and rushed solution to the supply of the society's mobility needs can be avoided, and consequently, public investment can be reduced.

Given such scenario and the three main points above listed, to enable cities anticipate themselves to this revolution, the following question has to be posed: what possible solution is there, that does not further congest transportation on the ground, and still manages to satisfy a growing demanding population in a dynamic and diverse urban environment? People have looked upwards to build skyscrapers and fit more people within the same land surface. They have also looked upwards to construct elevated parks, like The High Line in New York City, to achieve a relaxing and peaceful atmosphere between tall buildings, increasing the quality of urban life. Likewise, this time the solution is above, too: the use of the third dimension, the airspace.

2.3 Urban Air Mobility

Using the airspace as another medium for urban mobility might sound somehow surrealist at first, but looking back at how the cities and urban populations have been developing, it does indeed make sense to make use this third dimension. As previously stated, urbanisation is a dominant trend around the globe and by 2030, more than 60% of the world's population will be living in cities, stretching struggling ground transportation networks even further. Ground infrastructures, i.e. the city streets, hold the entire burden of all urban mobility; cars, trucks, buses, trams, scooters and bicycles, all jostling for space. This leads to traffic jams, traffic accidents, frustration, anxiety, time wasted and money lost. In the EU, traffic congestion currently costs almost €100 billion a year. By 2030, it could be closer to €300 billion. Meanwhile, A drivers lose an average of 42 hours a year in traffic jams [8]. Ironically, the actual purpose of having a wide range of transportation modes, i.e. getting from A to B as quickly as possible, is exactly what jeopardises the mobility. For this reason, continuing to overload the urban roads with the purpose of meeting the urban mobility demand is not the solution. Instead, by focusing the attention on a part of the city that remains congestion-free, the airspace, city streets are alleviated from transportation congestion, becoming safer and cleaner, and thus less stressful for the urban habitants. Like Mathis Thomsen ² says, “adding a third dimension to urban transport networks would revolutionise the way we live”.

International pioneers companies, such as Uber, Airbus and NASA, are already working on this new concept of mobility, and are committed to leading the Urban Air Mobility (UAM) community. Jaiwon Shin ³ states that the convergence of technologies, and new business models enabled by the digital revolution, is making it possible to explore this new way for people to move within the cities. Nevertheless, key challenges still ahead are still to be identified, as well as exploring the research, development and testing requirements needed to address those challenges [9].

Aside to the engineering and technological strains cities and corporations might face during the process of putting urban mobility into the airspace, social challenges will also be encountered, and thus, must be beforehand taken into account. That is, if UAM is not publicly accepted, all of its innovative and revolutionary advantages are irrelevant and pointless. To ensure that the integration of air mobility in cities is worthwhile, avoiding failure and investing rather than wasting money, a progressive development must be planned, implanted and followed. In the case of the European Union, the European Innovative Partnership ⁴ on Smart Cities, has already established a forward plan [10] that consists of 3 main stages:

² Mathias Thomsen, General Manager for Urban Air Mobility at Airbus

³ Jaiwon Shin, NASA's associate administrator for aeronautics research.

⁴ European Innovation Partnerships (EIPs) are European Commission initiatives driven by known challenges, and focusing on societal benefits and a rapid modernisation of the associated sectors and markets.

-
- The first phase focuses on informing about and engaging multi-stakeholders by demonstrating different project approaches for UAM.
 - Once possible investors have been attracted and their attention is called, the second phase develops, qualifies and articulates UAM business and service concepts towards integrated urban mobility solutions as part of a detailed demonstration project proposal.
 - Finally, in the third phase, the demonstration projects are ran and concluded by executing them across cities.

Truth is that citizens are not yet used to vehicles flying above them around the urban spaces, but with time, society is getting more and more familiar with the air travel. Traveling by plane has been standardised and normalised, and nowadays, not only business travellers or wealthy people use the air transport to move around, but also over 54% of international tourists now travel by air [11]. Figure 2 shows the increasing exponential curve that represents the number of passengers carried by air transport every year, from 1970, with 310,441,392 passengers, up until 2016, with 3.696 billion. The familiarisation between the society and aviation is essential for a smooth and fast acceptance, hence integration of air mobility in urban spaces.

The growing use of air transportation is not the only proof of the social assimilation, but also the broad range of types of flights offered: scheduled, regular, charter, private, etc. Users have learnt that air mobility presents many advantages: it is fast, it is safe [13], it is flexible (the customer can chose the traveling package, from “Basic” up to “All included”), and in many occasions, economically affordable [14]. Consequently, society has become more demanding, and expects more from this type of mobility. In fact, aircraft have been so usual, that people now dare to incorporate a sense of the aviation field in their lives, by, for example, buying drones and learning how to build, program and control them. Another way of getting involved in the flying experience, is by sharing a flight with an actual pilot; the platform Wingly connects pilots and passengers, in a similar way than the carpooling system works: when a pilot posts a planned flight, a potential passenger can book the journey [15]. Clearly, a stronger interaction between the air vehicle and the user is being created, an essential factor in the development and integration of air mobility in urban spaces. For this reason it is strongly believed that the revolutionary concept of Urban Air Mobility will be smoothly accepted.

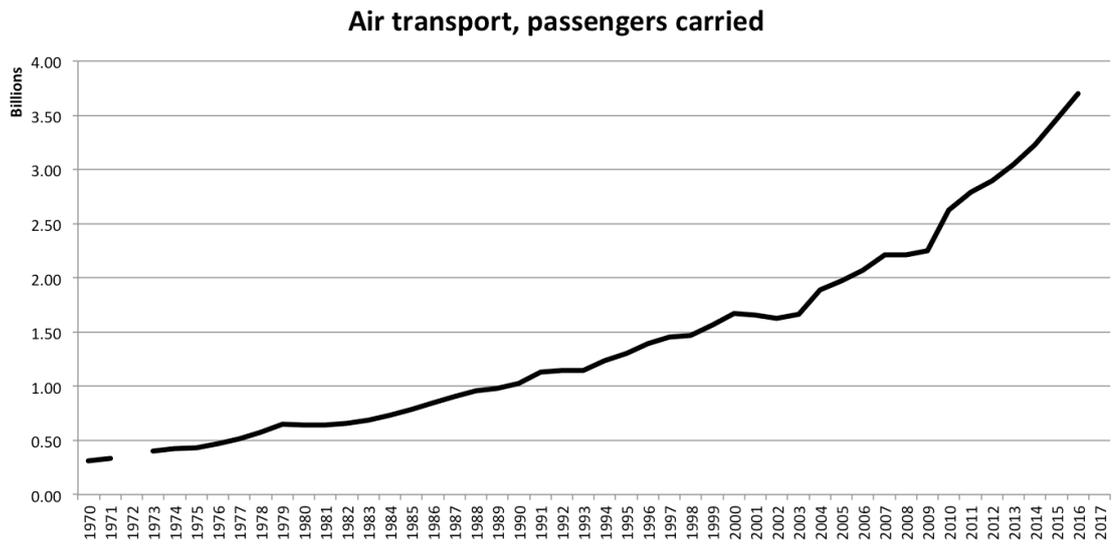


Figure 2.2: Air passengers carried, including domestic and international aircraft passengers of air carriers registered. [12]

3 Personal Air Vehicle (PAV)

In Chapter 2 it was analysed and explained why cities are in such a huge need for a mobility revolution: the urban population is rapidly growing and consequently, urban ground transportation is being pushed to the limits and facing many problems when trying to satisfy the citizens' mobility needs, costing valuable time and money. Given this situation, a solution was suggested: incorporating the third dimension, the airspace to multimodal urban transport networks. After studying the society's behaviour towards the air transportation, it was seen how this possibility is indeed reasonable. The following step is to therefore comprehend how UAM⁵ can be achieved. In order to do this, there are many aspects that need to be deeply studied before actually integrating air mobility in cities. In the case of this chapter, Chapter 3, the vehicle able to satisfy the citizens with UAM is analysed. This vehicle is the so-called Personal Air Vehicle (PAV).

3.1 Introducing the PAV

The term *Personal Air Vehicle* was first used by NASA in 2003 when it established the Personal Air Vehicle Sector Project, as part of the Aeronautics Vehicle Systems Program. This project was part of NASA Vehicle Integration, Strategy, and Technology Assessment (VISTA) office [16]. However, already since 1903, after the Wright brothers achieved a powered flight, there have been many attempts to successfully develop flying cars [44]. Most of them have never met technological success, and the development of those which have, has not gone further than a prototype stage. In fact, the hurdles of designing a successful flying car are enormous, mainly because the design requirements of a ground vehicle are so different of those of an airplane. Therefore, trying to merge the two sets of requirements into a craft have lead to important challenges in the past. By the use of technological advances (composites materials, fly-by-wire control systems or new engines with lower power to weight ratio, for instance) design difficulties are beginning to be overcome and flying cars are nowadays progressing faster than ever. In fact, in the last 10 years, some prototypes have been proved to fly properly [43]. Such is the evolution that today, the "flying car", now known as "PAV", is envisioned as the next step in the natural progression in the history of transportation system innovations [17]. As the automobile improved quality of life and standards of living in the 20th century [18], the PAV are expected to do likewise in the 21st century.

⁵ UAM: Urban Air Mobility

The PAV is not today's General Aviation (GA) aircraft. It is defined as a self-operated aircraft, capable of use and affordable by a large portion of the general public [19]. Besides, the PAV allows for the user to be provided with On-Demand Mobility (ODM). That is, the user is able to select the specifics of a trip, i.e. origin, destination and departure time. As previously mentioned in Section 2.3, the society is each time more demanding when it comes to mobility, and flexibility is a key aspect highly valued. For this reason, the fact that the PAV can satisfy the customers in terms of flexibility and comfort makes it even more suitable for it to be the transportation mode carrying out UAM.

The objective of this aerial vehicle is to dramatically improve individual mobility within the larger transportation environment, by providing a breakthrough in personal air mobility, through dramatic time-savings (by, for example, offering an alternative to congested ground transport systems, as seen in Chapter 2) and increased range. Such ability of personalising air travel through the use of an on-demand, highly distributed air transportation system will provide the degree of freedom and control that citizens enjoy in other aspects of their life, and therefore greatly improve quality of life [19, 20].

The challenge of deriving requirements for revolutionary transportation concepts is a difficult one, due to the fact that future transportation system infrastructure and market economics are inter-related (and uncertain) parts of the equation [20]. Nevertheless, several companies, both large and small, are starting to develop the infrastructure to make UAM a reality (as already mentioned in Section 2.3), by conceptualising the PAV and constructing innovative prototypes. Some examples are Uber, Airbus, Volocopter GmbH ⁶ and eHang ⁷, and the innovative projects these businesses are working on are Uber Elevate [21], CityAirbus [22], Volocopter 2X [23] and EHang 184 [24], respectively. Despite the differences presented by these models between one another, e.g. design, number of passengers and cruising speed (between other specifications), they all share their basic and outline concept of PAV, which NASA initially defined [16]. This one is stated below:

⁶ Volocopter GmbH: a German aircraft manufacturer founded by Alexander Zosel and Stephen Wolf in 2012 [25].

⁷ eHang: a Chinese intelligent aerial vehicles technology & service company founded by Derrick Xiong in 2014 [26].

-
- Seats: less than 5 passengers
 - Cruising speed: 100 – 200 km/h
 - Range: 100 - 200 km
 - Reliable
 - Comfortable
 - Possibility of autonomy
 - Near all-weather capability enabled by Synthetic Vision Systems (SVS) ⁸.
 - Highly fuel-efficient (able to use alternative fuels ⁹).

Provide "door-to-door" transportation solutions, through use of small community airports that are at closer proximities to businesses and residences than large airports, as well as existing helipads and a distributed network of "vertiports" ¹⁰.

3.2 Concept Designs and Approaches

Despite the above definition, the concepts of "PAV" and "UAM" are quite broad and dynamic, allowing aerospace businesses a significant flexibility and freedom when it comes to researching this innovative type of mobility. Each business approaches the case in a different manner: depending on the business' understanding of UAM and the mission concept, such as Rural/Regional or Intra-Urban mission, specific capabilities arise and consequently, to fulfil these, different PAV models are created with different design parameters. Consequently, depending on these parameters, PAVs can be classified according

⁸ Synthetic Vision System (SVS): a computer-mediated reality system for aerial vehicles, which uses 3D to provide pilots/passengers with clear and intuitive means of understanding their flying environment [16].

⁹ Alternative fuels (also known as non-conventional fuels): any materials or substances that can be used as fuels, other than conventional fuels, e.g. biodiesel, hydrogen and electricity.

¹⁰ Vertiport: Vertical Take-Off and Landing (VTOL) hub with multiple take-off and landing pads, as well as charging infrastructure [21].

to 3 main categories: the roadability, take-off and landing capability, and type of propulsion [44]. Such categorisation is represented with a hierarchical chart Figure 3.1.

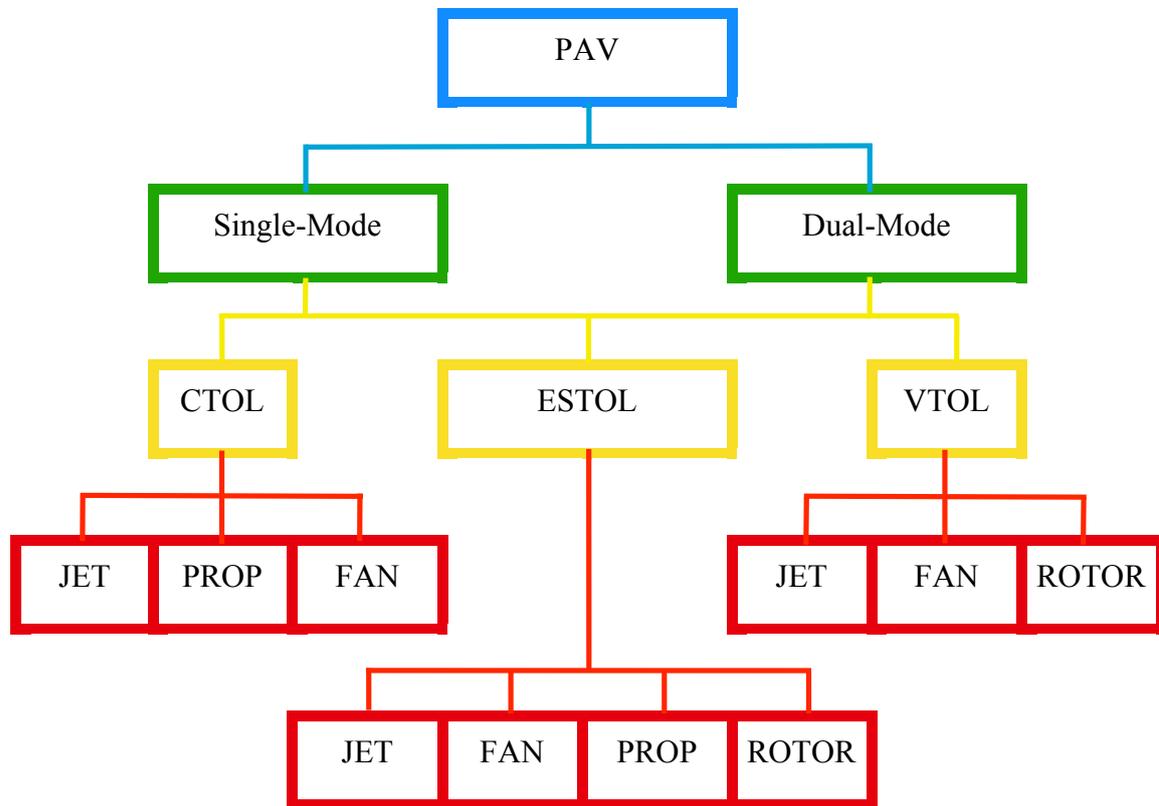


Figure 3.1: PAV Categories. [44]

The first category, roadability (in green), defines whether the PAV is able to operate both on land and in the air (Dual-Mode) or only in the air (Single-Mode). The Single-Mode PAV, because it only needs to be optimised for air travel, the design complexity is significantly reduced, reducing costs and maintenance problem. However, depending on its take-off capability, such a vehicle might require a hub and spoke system, meaning that a substitute transport to and from an airport/runway will be required. Meanwhile, the Dual-Mode configuration is a wholly self-sufficient form of personal transport; in terms of the mission profile, this type of PAV does not need to be substituted for another vehicle at any point in a journey. Yet, this supposes an additional level in the complexity of the design.

The second category, shown in yellow in Figure 3.1, is the take-off and landing capability of the PAV. There are three ways in which the PAV can carry out these operations: conventionally, extremely short and vertically. Conventional Take-Off and Landing (CTOL) require a lower power engine for take-off compared to a similar vehicle with a non-conventional take-off and landing capability. This means that only a small engine is required, thus reducing weight and fuel consumption. However, CTOL designs need runways, constraining the users to a hub and spoke system similar to that of light aircraft. On the other hand, Extremely Short Take-Off and Landing (ESTOL) PAVs (also known under “Super-STOL”, SSTOL) present the same advantages as the CTOLs but, it can operate on considerable shorter runways, thus use up less space. To be able to do this however, technologies such as thrust vectoring and extreme high lift devices have to be incorporated in the vehicle [44], increasing the design complexity and operational costs. Finally, Vertical Take-Off and Landing (VTOL) PAVs, allow for a direct travel, point-to-point, as it negates the need for a runway and thus there is no need for it to be Dual-Mode. The disadvantage of VTOL is the weight penalty incurred due the requirement of a larger engine, greater power and the high fuel consumption during take-off and landing.

The last and third general category under which a PAV can be classified is according to its propulsion, represented in red in Figure 3.1. It can be seen that the two other categories mentioned share the jet and the fan. Jet propulsion is the most efficient form of propulsion for high-speed travel (transonic and supersonic), but at the same time, it is very loud and expensive (in comparison to the other propulsion system described in Figure 3.1: fan, rotor and propeller). An expensive propulsion system would significantly reduce the affordability of the PAV, and the high noise emission would constrain it from operating near residential and urban areas. In case of the fan, it is more efficient than jet propulsion at subsonic speeds and for VTOL [44]. Besides, it is significantly less noisy than jet propulsion, meaning that vehicle can operate near residential and urban areas. The key problem with the fan is safety, due to its dangerous rotating components.

Meanwhile, the propeller, which is quite similar to the fan, is also less noisy and presents dangerous aspects due to rotating components. However, the propeller limits the vehicles capability to CTOL and ESTOL, i.e. it requires a runway, as the propeller generates thrust, but not lift. Per contra, rotor propulsion is the most effective form of propulsion for VTOL. Nevertheless, rotors limit the ability to cruise at high forward speed, because they are limited to operate below supersonic tips speeds [44]. Some designs incorporate a fan or a propeller for forward propulsion and use rotor blades for VTOL only. Yet, rotors tend to produce considerable drag when rotating during high-speed forward flight. Above that, rotors are vulnerable to collision and damage especially when the vehicle is manoeuvring

on or close to the ground. This compromises the airworthiness of the vehicle and raises questions as to the safety and insurance of such a vehicle.

3.3 Examples of Modern PAVs

This section shows how this categorisation is been applied on different PAV designs, which have been proposed these days. Although these examples share some characteristics, they are still all different from one another, emphasising the point stated before: because each business approaches UAM differently, the PAVs mission is consequently differently defined, leading to different technological parameters. Figures 3.2, 3.3, 3.5, 3.6 show this diversity, and also provide a better understanding of how this innovative transportation medium can look like.

The first example is the PAV model designed by Uber, the eCRM-001, which was announced in November 2007 and belongs to the air mobility program Uber Elevate. Throughout this program, Uber's objective is to implement an UAM ridesharing network in cities [29], and for that, they have designed an Electric Vertical Take-Off and Landing (eVTOL) aircraft, equipped with co-rotating propellers and energy-dense batteries¹¹. In section 3.2 it is mentioned that propellers are not used for VTOL PAVs, but the eCRM-001 has the propellers coupled with a vertical thrusting component, the electric batteries, enabling it to take-off and land vertically, tilting its propellers to transition between vertical and forward flight. Uber Elevate eCRM-001 can be appreciated in Figure 3.2.

Meanwhile, NASA is focusing on a new technology frontier: Distributed Electric Propulsion (DEP). They believe that with DEP, ultra-high efficiency, low carbon emissions, low community noise and low operating costs will be enabled [31], meaning that by creating an experimental PAV with this characteristics, UAM will be easily integrated and socially accepted. DEP allows for the removal of engines, which means that a significant source of noise is removed; electric motors are far quieter than piston or turbine engines because they do not need to ingest and expel large volumes of air though hydrocarbon combustion. This technology has been integrated in NASA's PAV model, called NASA X-57 Maxwell, and it consists of 14 electric motors driving propellers, which are mounted on the wing leading edges. This can be seen in Figure 3.3. Thanks to the distributed propulsion, the size of the aeroplane engines can be reduced. Also, electric motors are substantially smaller and

¹¹ Energy-dense battery: battery that stores a large amount of energy in relation to its volume.

lighter than jet engines of equivalent power [32], meaning that both the weight and the size of the aircraft can be reduced. A lower weight demands a less powerful propulsive system (reducing complexity and costs), and a small aircraft requires smaller infrastructures for it to take-off, land and be stored. This also reduces its operating costs and facilitates the integration within the urban airspace.



Figure 3.2: Uber Elevate eCRM-001 model. [27]

These two previous models, eCRM-001 and X-57 Maxell, have an “airliner-alike” design. This seems pretty reasonable, because it is a design, which society is comfortable with, and that means that in the case of using one these models when integrating UAM, social acceptance would be smoothed. As seen in Chapter 2, social acceptance plays a key role in the mobility market; when launching a new concept of transportation, it does not only matter how technically revolutionary it is, if it is not welcomed by the potential users. Therefore, according to theory, citizens would feel safer and more relaxed if they had to interact with “small aeroplanes” flying around the urban airspace.

Nevertheless, the UAVs ¹² (commonly known as “drones”) and UASs ¹³ are rapidly growing in popularity, both in terms of recreational (e.g. photography) and non-recreational (e.g. track and map wild fires) purposes, as it can be appreciated in Figure 3.4. Those who are fans of new technologies are keen to learn more about them, and some of them, even dare to build and program them. This increasing awareness and understanding of the drone technology has enabled the governments to take proactive measures to ensure safety and reliability, standardising the UAV industry. Likewise this has pushed the drone market, making it more accessible for anyone curious about this gadget. In fact, nowadays, one can get a Mini Drone for less than 20€ via Amazon. Indeed, the UAS market shows a positive outlook with strong industry growth and trends. This growing popularity can be seen in Figure 3.4, where the revenues from small UAS (sUAS) have been recorded from 2014 until 2017, and predicted for 2018 and 2019. Each year has been divided between sUAS used for military, commercial or recreational (hobby) purposes. Clearly, the commercial shows the fastest increasing trend, but hobby drones show an increase too. Yet, sUAS employed for military reasons generate constant revenue.



Figure 3.3: NASA X-57 Maxwell. [28]

¹² UAV: Unmanned Aerial Vehicle.

¹³ UAS: Unmanned Aerial System.

Companies involved in the aerospace field have noticed this familiarisation, and instead of scaling down a commercial aeroplane, they have inspired themselves in UAVs when designing their PAV model. This is the case of the German firm Volocopter, pioneer in urban taxi development. Their PAVs, known as “Volocopters”, are based on drone technology and scaled up to carry two people, with eVTOL. This model is extremely flexible and permits piloted, remote controlled, and fully autonomous flight [33]. The company focuses on developing their aircraft specifically for inner city missions, meaning that, when designing the PAV as well as the infrastructures required by both, this vehicle and the UAM program, Volocopter has considered beforehand the evolution experienced by urban areas: growing populations, cities becoming the centre of socio-economic centres, high social expenditure on urban infrastructures (these have been explained in Section 2.2). Their vision integrates air taxis into existing transportation systems and provides additional mobility for up to 10,000 passengers per day with a single point-to-point connection [33]; as Volocopter’s CEO Florian Reuter said, “we are here to develop the entire ecosystem” of today’s innovative mobility concept.

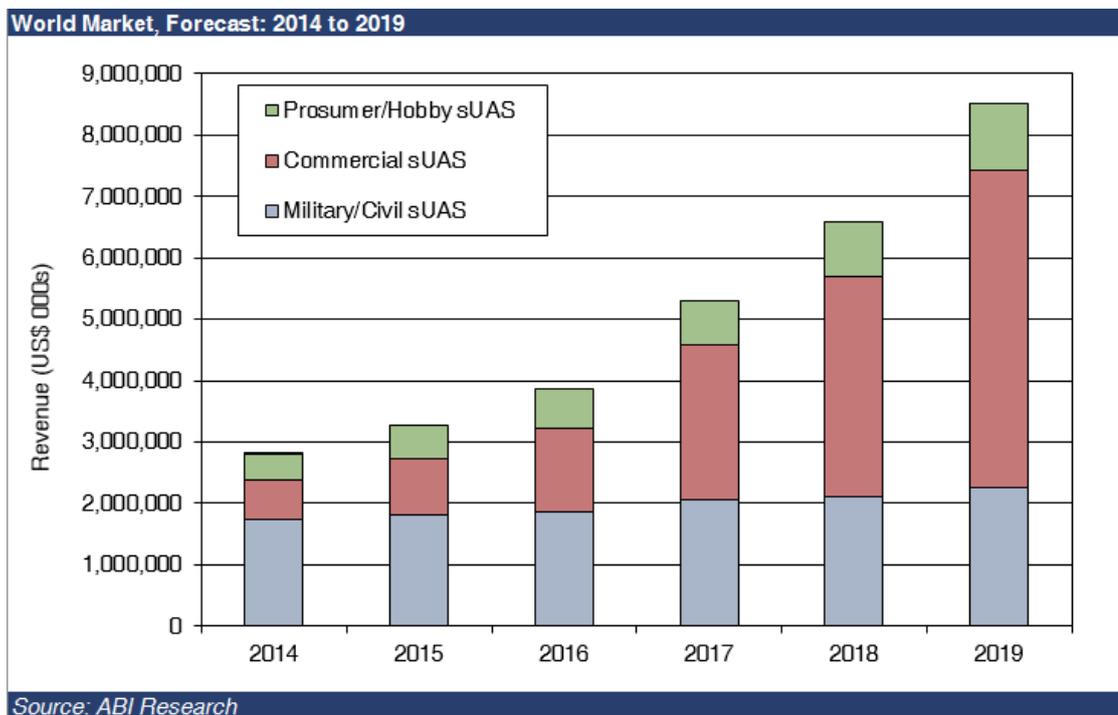


Figure 3.4: Total sUAS Revenue – World Market, Forecast: 2014 to 2019. [30]

The firm's last and most innovative model, the Volocopter 2X, can be appreciated in Figure 3.5. It is classified as a rotary wing aircraft and has 18 rotors. Hence, this PAV is classified as a multicopter¹⁴. A simple joystick can carry out the control of these rotors. Such a significant amount of rotors are required for safety reasons, as 18 rotors ensure a high redundancy, and also to improve the vehicle's performance. That is, because the Volocopter 2X does not use wing-borne flight, i.e. it is not transported by wings but by rotors and batteries, in order to increase its efficiency, a significant amount of rotors are required. Besides, by mounting 18 small rotors, the Volocopter 2X still benefits from the rotors ability to produce efficiently enough power for vertical take-off, whilst maintaining low perceived noise levels (in comparison with a similar aircraft propelled by less, but larger rotors). As Uber's model eCRM-001, the Volocopter 2X is also an eVTOL PAV; companies opt for electric propulsion designs because they have no operational emissions, and as PAVs represent a potential new form of urban transportation, they should clearly be ecologically responsible and sustainable. The Volocopter 2X, described as a "light-sport"¹⁵ aircraft, also achieves weight reduction by using fibre composites for the composition of its structure, which is designed under the principle of lightweight construction [34]. That is, the shape of the Volocopter 2X's structure is determined through an optimisations process to efficiently carry the loads using the lowest possible amount of material. Reducing the mass of the PAV reduces the power required and thus also the vehicle's energy consumption and ecological impact over the usage phase. This model is the world's first manned, fully electric VTOL.

An additional example of a PAV design being influenced by the drones' technology is that one created by the Chinese firm eHang: EHang 184. The EHang 184 is an Autonomous Aerial Vehicle (AAV), which in general terms means that it is a manned version of a traditional UAV. It provides means of personal transportation for a single passenger weighing not more than 100 kilograms, while flying at low altitude (500 m AGL¹⁶). Its name comes defined from its design description: "*one* passenger, *eight* propellers, and *four* arms" [37]. These characteristics can be identified in the following figure, Figure 3.6. The main advantage of placing 8 rotors on four arms is that the manoeuvrability and agility of a quad-

¹⁴ Multicopter: small rotorcraft with more than two rotors.

¹⁵ Light-sport aircraft: simple, low-performance and -energy aircraft that are limited to 600 kilograms maximum take-off weight (for aircraft not intended for operation on water) [35].

¹⁶ AGL: Above Ground Level

copter¹⁷ are combined with the redundancy of an octocopter¹⁸. Like the other examples seen, the EHang 184 is also an only-electric VTOL air vehicle, designed to be a 100% with green technology. This means that this multi-rotor PAV, is propelled by rotors driven by electric motors, which converse the electrical energy into mechanical energy to generate drive torque (something that directly affects the efficiency of the propeller).



Figure 3.5: Volocopter 2X. [23]

3.4 The PAV Market

Despite existing many approaches and proposals of this aerial vehicle, it may occur that none of them fully satisfy the mobility needs of an actual customer. This is simply due to the fact that there are multiple variables that go into defining this new product, and as seen before in Section 3.2, there are numerous and diverse conceptual designs. Beyond that, the future transportation system and market economics are inter-related and uncertain parameters, making it even harder to derive a certain and homogeneous definition, and thus design, of the PAV.

¹⁷ Quadcopter: multi-rotor rotorcraft lifted and propelled by four rotors.

¹⁸ Octocopter: multi-rotor rotorcraft lifted and propelled by eight rotors.



Figure 3.6: EHang 184. [24]

To capture a significant portion of the market, i.e. to satisfy as much mobility demand as possible, it is necessary to conduct a more detailed study of the market behaviour using key variables that define the characteristics of a PAV (introduced in the earlier sections of this chapter). In other words, now that the general concept of the PAV has been discussed, it is necessary to look at the macroscopic picture of this transportation medium.

There are three main systems that interact to impact the marketability of a product [41, 42]:

1. The consumer/passenger
2. The service providers, manufacturers and regulatory agencies.
3. The researchers and developers.

The consumer/traveller system deals with the fact that the consumers' motivation to use a form of transport is to complete their trips safely, with less travel time and money spent. However, the term "customer" is very broad and can refer to anyone, from a business traveller flying on a moment's notice to a person visiting family or friends on a long-planned vacation. The various features that can characterise the customer and thus make the travelling public diverse are shown in Figure 3.7. The differences in these characteristics behind the individual travellers drive them towards specific transportation options. This is why, it is so important to perform a detailed and deep study society, to be able to

understand what characteristics and mission concept the PAV should have, in order to satisfy as much customers as possible.

Meanwhile, in the second system, the regulatory agencies' primary focus on maximizing safety and security while reducing costs. Service providers and manufacturers' primary objectives are to maximise profit by meeting the consumer's needs. That is, by understanding the customers' expectations after a social study and market research, service providers and manufacturers design a product, in this case the PAV, which meets as much expectations as possible. If customers are satisfied, they repeat the experience and make use of the service more often; usage repeatability and thus loyalty is obtained, leading to a constant profit. However, each user is different to the other, ergo each one has a unique set of demands and expectations. For this reason, designing a product that suits every customer's profile is very difficult. Analogously, the same occurs with UAM: each passenger will want and expect something different from the PAV and from this transportation mode, and thus, designing a system and a vehicle that pleases everyone is indeed a big challenge.

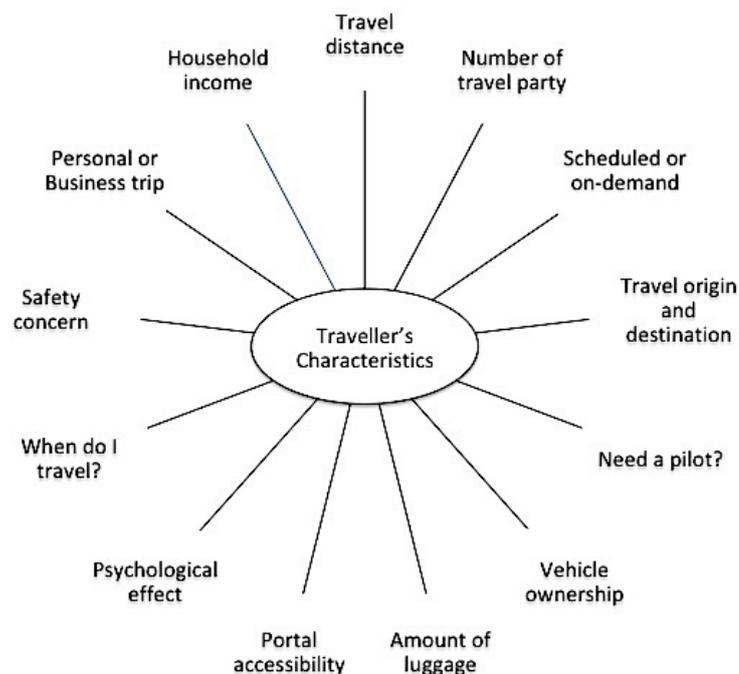


Figure 3.7: Variables that influence a consumer's motivation. [41]

Finally, the third system, in which researchers and developers, with the input of all the data and constraining factors from the other two systems, the researchers and developers make critical decisions to formulate a conceptual design and eventually a final product [41]. That is, knowing what satisfy the majority of the potential customers, but bearing in mind the technological (such as propulsion and battery efficiency) as well as the legal limitations (for example noise emissions or air pollution), researchers and developers weigh out all aspects and consider all trade-offs in order to come up with the most optimum design with given characteristics. These are represented in Figure 3.8.

It is reasonable to expect that both diagrams, Figures 3.7 and 3.8, actually have common characteristics, as the PAV design (“Vehicle’s Characteristics”) is highly influenced by the requirements of the travellers (“Traveller’s Characteristics”). For example, the traveller wants this vehicle to be accessible (“Portal accessibility”). Knowing this, researches and developers look at the types of access portal there, trying to figure out which type (or types) will be the most suitable.

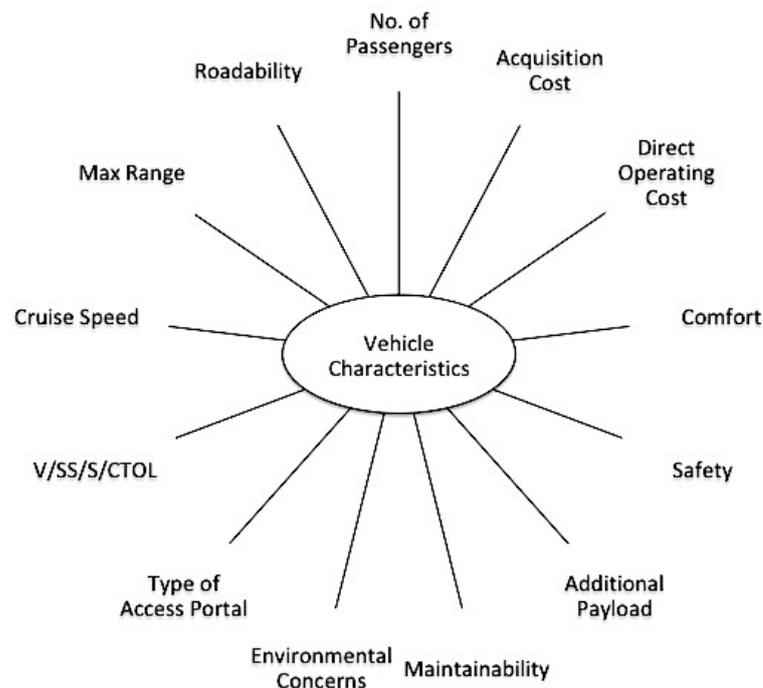


Figure 3.8: Research and development parameters that influence the PAV design. [41]

In real life, such parameters have to be considered in order to obtain an optimum design of the PAV and ensure that the money and time spent on the development are an investment and not a waste. In other words, it is not enough to study already-proposed models, compare them and choose one to carry out the program of UAM, but a deep analysis and evaluation of the market, environment and technology status is essential.

From Chapter 2 it has been seen that the enlarging population together with the urbanisation occurring all around the world, urban spaces are experiencing not only a demographic growth, but also an economical one. This, within others, has a transportation impact, as more and more people have to get displaced. Nevertheless, despite the ultimate goal of mobility being the transportation of passengers from a point A to a point B, the manner and mode in which this is done is very important, specially nowadays, where society expects more from transportation: comfort, price affordable, accessible, safe, clean, etc. For this reason, governments, city halls and business involved in the mobility industry make huge investments on understanding and predicting the social expectations. Hence, the PAVs market research starts off with the “Passenger system” and from it, works up towards the other systems. Yet, the design of “the” PAV, i.e. the PAV which guarantees maximum performance, maximum customer satisfaction and maximum sustainability is to be discovered.

Despite the big interest and actual progress that designing the ideal PAV would actually mean, this one is not the objective of this thesis. This thesis studies the possible integration of UAM, and for that, it looks at the possible characteristics and features that the PAV could have in order to carry out the equivalent function of a car, but in the air transportation. For this reason, this chapter is dedicated exclusively to the PAV and the research behind its creation. Having understood how a PAV can be characterised and what aspects have to be considered when designing it, i.e. an evaluation of the PAV at a microscopic level, the next step is to zoom out and perform a macroscopic evaluation, to study how this vehicle is integrated in the airspace and actually operated. Such macroscopic study is carried out in the next chapter, Chapter 4.

To understand how external agents, such as airspace management and weather, affect the PAV and its integration, a reference PAV is chosen in this thesis. By using a reference PAV, actual examples can be provided and thus a better understanding of the implementation and operation of PAVs can be obtained. The chosen model is the Volocopter 2X, and the arguments behind this decision are exposed in Section 3.5.

3.5 Volocopter 2X

In Chapter 2, by studying the evolution of Urban Mobility, it has been possible to identify the problems with modern travel; due to the rapid growth of cities, the demand on urban mobility has increased too. To satisfy this demand, public money is being spent on ground transportation media and infrastructures, saturating the urban environment, causing air pollution, traffic jams, accidents, etc. Given this situation, it is concluded that the optimisation of urban spaces used up for mobility purposes is essential, as cities have to fit in many people and these need to move around, conclusion which calls in the use of the third dimension: the airspace.

As a VTOL aircraft requires a smaller infrastructure than a runway, and thus improves the optimisation of the urban space, the model chosen has to take-off and land vertically, to facilitate the future integration of Air Mobility in cities (this will be later discussed in Chapter 6). Also, as previously seen, because the awareness and usability of UASs are rapidly growing, they are gaining significant importance in the airspace, governments and aviation agencies are deeply studying this technology, looking for possible manners of integration, expanded operation together with homogeneous and normalised regulations. For this reason, PAVs inspired by the functionality and design of UAS might benefit themselves of this situation. From Section 3.3 it is known that the Volocopter 2X is one example of a PAV which is VTOL and its design parts from the technology behind UAS. Besides, it is the world's first-manned, fully electric VTOL multicopter, meaning that it has already been introduced to, at least, a fraction of society. Working with a reference PAV with which the reader can be familiar, or can rapidly find information about it, eases the understanding of the topic, opposite to working with a more "abstract" concept of the PAV.

Given that both the Volocopter 2X and the EHang 184 are both VTOL aircraft and both their design is inspired by the UAS technology other influence, one other factor that is taken into account in order to ensure the decision. Such factor is the time in operation and the series of improvements these models have been submitted to. In the case of the Volocopter 2X, it must be stated that it is not a brand new model, but a consequent evolution of the VC200 prototype [36]. The Volocopter VC200 made its first unmanned flight in November 2013, and the first manned flight occurred March 30, 2016 [37]. As said, the Volocopter 2X is a refined version of the VC200, with a limited number of pre-production prototypes now under development for future sale. According to Volocopter, the Volocopter 2X is the world's first 2-seat electric VTOL aircraft. This shows that, besides the firm's experience, this PAV model has been long under analysis and study, being under

constant evolution and further progressing technically and aesthetically. For example, Volocopter has applied changes on their vehicle's fuselage and rotor section; the raised multi-copter assembly, has allowed for the Volocopter 2X to provide with a larger cabin. This one has also undergone some refinements, so that the experience for the passenger is actually more pleasant. Its actual structure has been more streamlined to achieve a more elegant appearance. Besides, to improve maintainability and operation, the batteries have been improved so that they can be quickly changed between journeys. The improvements are such that actually, the German company has shown repeatedly that Volocopters fly safely, last in Dubai and Las Vegas [33]. On the other hand, the Chinese company introduced the concept (not the prototype) of the EHang 184 in January 2016 and in February 2017 multiple adaptive tests were performed on the vehicle. That is, the EHang 184 is the first generation of PAVs within the creator company and thus disposes of less experience. This also means that when it comes to research, available resources and published information, i.e. bibliography, there is much less for one to gather, read and investigate. Because this thesis is based on deep research and data synthesis, it is essential to be able to collect as much knowledge material as possible. Hence, the Volocopter 2X is a suitable prototype.

Safety is indeed a key factor when deciding the design specifications of the PAV, as not only it facilitates airspaces integration, but also it transmits confidence and trust to the user, who will essentially only dare to fly if he/she perceives the PAV as a safe and stable vehicle. As a consequence, the Volocopter 2X is already equipped with more than 100 microprocessors designed to monitor turbulence, wind and other factors and also to keep the aircraft in the air during multiple failures, i.e. redundancy. That is, these microprocessors automatically ensure stability and control of the multicopter, as they permit this air vehicle to perform certain manoeuvres automatically. These are automatic attitude control, automatic altitude control, automatic position hold (crosswinds and turbulence are automatically compensated) and automatic landing hold (a gently touchdown is performed upon the pilot's command). The way in which these are performed is via the fly-by-light control system. The fly-by-light control system uses optical fibre and optical sensors, benefiting from immunity to electromagnetic interference (EMI) and HIRF¹⁹, a large data bandwidth, as fibre optics support enormous data transmission speeds, and light weight. Ensuring that the Volocopter flies and manoeuvres safely and smoothly, emphasises how Volocopter 2X does indeed pursue safety as well as the passenger satisfaction.

¹⁹ HIRF: High Intensity Radiated Field.

Moreover, it must be mentioned the fact that last 17th April 2018, Volocopter presented its air taxi infrastructure for cities, defining what is necessary to operate and scale an air taxi service into a full network system spanning over cities [33]. In other words, Volocopter is not only focusing on the vehicle itself, but on all the other technical and operational aspects that have to be considered during the integration process of UAM. As this thesis also evaluates the implementation of this new mobility concept, working with a PAV prototype, which is already being tested to be circulating around urban spaces, amounts to a considerable step forward.

Recalling Figure 3.8, it is of considerable significance to into the Volocopter 2X's design specifications with further details so that most of the Research and Development (R&D) parameters that influence the PAV design are specified. This aerial VTOL vehicle features 18 fixed-pitch propellers, each powered by its own electric motor, and all arranged in a circular symmetrical pattern on a composite wheel mounted above the cabin. Such propellers are powered by DC electric motors, which are powered by nine independent, quick-change lithium ion batteries, each one powering two motors. These batteries can be charged in 120 minutes normally, or 40 minutes on quick-charge from the municipal power supply, and use active air-cooling. The entire propeller system can be dismantled for storage or ground transport. When it comes to the accommodation, it consists of two leather seats in side-by-side configuration²⁰ (see Figure 3.9) in an enclosed cockpit with a quiet vibration-proof windshield, and it uses fixed skid landing gear, both for landing and take-off. These save weight and cost, as skid landing gears are simpler than retractable landing gears. The controls are a triple-redundant²¹ primary flight control unit, plus a backup flight control unit and a joystick control. The stabilization system employs gyroscopes, acceleration sensors, magnetic field measurement sensors and manometers. In addition, all communication networks are connected via optical fibres, i.e. "fly-by-light"²². Also on board, there is an emergency parachute. [All these data are obtained from the document "Design

²⁰ Side-by-side configuration: seating arrangement in which pilot and co-pilot are seated next to one another.

²¹ Triple-redundant (flight control system): a system which has three sub components, all three of which must fail before the system fails.

²² Fly-by-light: system that replaces the conventional manual flight controls of an aircraft with an electric interface.

Specifications of the Volocopter 2X²³, published by e-volo GmbH 23 (also known as Volocopter); reference 34].

Regarding its structure, this PAV is made out of fibre composites and it features a lightweight constructed structure. The geometry of lightweight construction permits a high loading capacity despite a maximum weight reduction. Thus, this type of construction offers enormous potential for weight and energy savings. The dimensions are presented in Table 3.1.



Figure 3.9: Interior of Volocopter 2X's cockpit. [33]

Furthermore, the performance of the Volocopter 2X also has to be presented, so that it can be later considered when studying the vehicle's limitations (Chapter 4), the airspace airworthiness regulations and certifications (Chapter 5), and the actual integration of air mobility in urban spaces (Chapter 6). The performance parameters are likewise tabulated in Table 3.2.

²³ e-volo GmbH: the German company Volocopter was known as “e-volo GmbH” until July 2017 [37].

Structure	
Overall height	2.15 m
Diameter of the rotor rim incl. propellers	9.15 m
Diameter of the rotor rim excl. propellers	7.35 m
Diameter of a single propeller	1.80 m
Cockpit (length / width / height)	3.20 m / 1.25 m / 1.21 m
Skids (length / width)	3.02 m / 2.06 m

Table 3.1: *Structural dimensions of the Volocopter 2X. [34]*

When it comes to the economic aspects of the Volocopter 2X, the company has not made any public official statement of how much it can cost to make use of this service. According to the Design Specifications brochure, the estimated selling price is available upon request. Nevertheless, it the Volocopter is described as “cost effective”, as fuel is replaced by economic (and increasingly sustainably generated) electricity. On top of this, requirements for maintenance, repair and overhaul are reduced to a minimum through the avoidance of complex mechanical components.

If the provided data is compared with the “checklist” Figure 3.6 consists of, information can be synthesized, like shown in Table 3.3. It is important to have this sort of information all gathered and organised, especially for the coming sections of the thesis, in which the limitations and barriers of the PAV will be analysed.

Performance	
Max. Take-off mass (MTOM)	450 kg
Max. Payload ²⁴	160 kg
Operating Weight Empty (OWE)	290 kg
Max. Range (at MTOM)	27 km at an optimal “range” cruise speed of 70 km/h
Max. Airspeed (limited time)	100 km/h
Altitude (service ceiling)	≥ 2,000 m AMSL ²⁵
Altitude (hovering)	≥ 1,650 m AMSL
Noise level	~ 65 dB(A) ²⁶ at 75 m

Table 3.2: Performance parameters of the Volocopter 2X. [34]

²⁴ Payload: the carrying capacity of an aircraft, usually measured in terms of weight.

²⁵ AMSL: Above Mean Sea Level

²⁶ dB(A): A-weighted decibels; an expression of the relative loudness of sounds in air as perceived by the human ear.

Volocopter 2X R&D parameters	
No. of Passengers	2
Acquisitions Cost	Available upon request
Direct Operating Cost	Available upon request
Comfort	Simple joystick; autonomous; cockpit design
Safety	Redundancy; “fly-by-light”; emergency parachute
Additional Payload	-
Maintainability	Reduced; carried in Volo-Hubs ²⁷
Environmental Concerns	Emissions, noise levels
Type of Access Portal	-
V/SS/S/CTOL	VTOL
Cruise Speed	100 km/h
Max. Range	27 km at an optimal “range” cruise speed of 70 km/h
Roadability ²⁸	Non-roadable; features skid landing gear

Table 3.3: *Synthesis of the Volocopter 2X’s design specifications and the R&D parameters.*

²⁷ Volo-Hub: element of the infrastructure necessary to operate Volocopter’s air taxi service; it resembles cable cart stations [33].

²⁸ Roadability: the ability of a vehicle to remain stable and hold the road whilst being driven (according to the Oxford dictionary).

4 Socio-Economic and Technological Challenges

“Designing the air vehicle is only a relative small part of overcoming the challenges.” [57].

Until now it has been discussed how the PAV presents a possible solution to the current urban mobility situation given in cities due to urbanisation, between other reasons (these are further explained in Chapter 2).

However, despite the many advantages presented by this transportation medium, technical limitations must be considered, as well as other barriers such as acceptance by society and market share success. More details about these last are given in Section 3.4, when evaluating the market of the PAVs. Besides these issues, and many others, such as safety, environmental issues and noise disturbance, another aspect to be paid attention to is the regulatory framework in which the PAVs are expected to operate, as this one co-determines how high the access barriers for the users be [45]. Chapter 5 further studies the legal framework of the PAVs by discussing the certifications and regulations this UAM vehicle is entitled to. One other major challenge is the integration of the PAVs into the existing ground transportation but also into the existing air transportation system [45]. Aspects and questions regarding the integration of UAM and thus the Personal Aerial Transportation System, also known as PATS, which includes both the vehicle together with its corresponding infrastructure, are examined throughout Chapter 6.

Meanwhile, the PAV’s limitations and barriers are analysed in this chapter. Chapter 4 not only presents the restrictions regarding technical feasibility of such vehicles, but it detects the most important concerns which surround a successful and easy implementation of PAVs. Therefore, this chapter gives an overview of the identified issues and tries to picture their relevance and “problem potential”. Nevertheless, given that the concepts of UAM and PAV are at an early stage and nowadays only being approached and slightly tackled in real life, the number of issues found is considerable and consequently, not all of them are described in detail at this stage.

According to NASA [19], the major barriers presented by the concept of the PAV, i.e. the vehicle, are the following:

-
1. Poor safety (~6x worse than cars, ~110x worse than airlines).
 2. Single engine aircraft have poor perceived safety with a lack of redundancy across primary power.
 3. Low trip reliability due to weather, mechanical, pilot limitations.
 4. Communities object to high noise and limited community benefit.
 5. Poor emissions do not promote sustainable or scalable operation, i.e. environmental concern
 6. High vehicle cost due to expensive components and materials.
 7. High operating cost due to poor efficiency, high fuel cost, poor reliability and high maintenance, as well as small market and low utilisation.
 8. Low Ease-of Use due to high initial and recurring training and inflight workload discourage non-enthusiasts.
 9. Uncomfortable & fatiguing ride quality due to low wing loading.

These above can therefore be classified into three main categories depending on the type of concern they belong to: Safety (points 1, 2 and 3), Environment (points 4 and 5), and Technical and Operational Limitations (the four last points, i.e. 6, 7, 8, 9). Given this classification, each category is below further discussed, but given the fact that whenever the idea of PAVs (or flying cars) is presented and discussed, many questions regarding the vehicle's safety are socially expressed [45], this is first aspect to be reviewed.

4.1 Safety

As commented above, one major issue that is often dominating the discussions and comes first is the safety issue. Such social awareness and concern about the safety and reliability of the PAVs are fed by numerous news referring to helicopter accidents or gyrocopter²⁹ crashes worldwide and their corresponding frightening pictures [45]. For example, the

²⁹ Gyrocopter: an aircraft that shares common features with airplanes and helicopters. It is a rotary-wing aircraft that is driven forward by a conventional propeller, i.e. thrust is provided [47].

gyrocopter crash that took place in May 2011, in Awanui, New Zealand [46]. In contrast to other modes of ground transportation where an engine failure or fuel shortage often leads to minor incidents this is rarely true for aviation. The fact that air vehicles cannot just stop on the next emergency lane if a technical problem occurs, as there are hundreds or thousands of meters between them and the ground, makes safety a very sensitive topic. This is also confirmed by the results of the PPlane³⁰ Delphi Study³¹ where those who were questioned, were asked to assess the importance (from 1 least important to 5 most important) of potential attributes of a future PAV, and from 141 responses, “safety during flight” was assigned with the highest importance, i.e. with a value of 5 [48].

The safety issue is complex and has many faces; there can be internal and external safety hazards [45]. Internal safety hazards address those hazards related with the PAV itself (for example, mechanical failures) and its control system (including on-board sensor systems, within others). It should be pointed the fact that the control unit could be a human, meaning its associated human errors (tiredness, non-attention, misinterpretation etc.) should also be considered, or a technical system. External hazards relate to weather conditions, collisions with other objects in the air (bird strikes, air vehicles) or with ground objects [45].

Besides this differentiation, safety is far broader and it includes the safety of users of PAVs, i.e. the passengers on board, and the people on ground. Regarding on-board safety, some possible problems envisioned are misuse by terrorists, laser attacks, computer hacking into the system, hijacking and danger through PAV parts dropping of one PAV down to another one. Additionally, the problem of induced fire due to a PAV crashing into buildings can also be raised [50]. Despite the unlikelihood of this last scenario, even the worst and most drastic cases have to be considered in order to be able to design the system as safe as possible. Consequently, not only the PAV is being analysed, but the entire system, the PATS, as previously mentioned. Consequently, limitations and barriers about the infrastructure required by this aerial vehicle are also to be taken into consideration, like for example, secure landing spots for emergency cases that could potentially be a handicap for PAV operations in cities, or problems with aerodynamics during landing at places where buildings around could embrace the air flow were considered [50]. As the scenario of emergency cases has been pointed out, a distinction has to be made between an emergency

³⁰ PPlane: Personal Plane

³¹ Delphi Study: a technique of obtaining a collective view from individuals about issues where there is no or little definite evidence and where opinion is important [49].

situation for the person inside because of medical reasons and a system failure (loss of power, computer malfunction, etc.).

Moreover, a major challenge is surely the weather situation and how the PAV would be able to cope with strong winds, snow, icing and heavy rain.

4.1.1 Weather

Although aircraft flying under IFR ³² have a clearly lower dependency on weather conditions, they still are affected by snow events, freezing rain or other hazards, and airport closures. Delays in connection with unfavourable weather do even occur in the commercial IFR sector. Consequently, for smaller air- and rotorcrafts with a lower level of instrument equipment, even greater restrictions in terms of weather can be expected. This means that, safety is not the only aspect affected by weather, but also the users' satisfaction. For this reason, beyond being safe and reliable, the PAV has to guarantee a maximum "usability over the year" so that the payback period is as short as possible. That is, by ensuring that the PAV can perform the majority of the operations, which includes being able to operate given any climatological condition, not only makes users satisfied with this service, but also generates a positive cash flow ³³ for the business, shortening the time period required to recover the cost of the investment.

With the objective of achieving maximum usability while obtaining as much reliability and safety as possible, the Volocopter 2X operates autonomously, as stated in Table 3.3. The Volocopter 2X can operate under a flight status called Autonomous Flight Rules, abbreviated as AFR. Being equipped with AFR implies that when weather conditions are terrible, visibility is negligible and the PAV control is difficult, the Volocopter 2X is able to "self-separate", maintaining safe and legal distances between itself and all other aircraft, objects and terrain [51]. This is done with the aid of flight plans and aircraft performance data stored in the Flight Management System (FMS) [52], along with the pilot using on-board systems and traffic information.

³² IFR: Instrument Flight Rules, also known as Blind Flying.

³³ Cash flow: Incomings and outgoings of cash, representing the operating activities of an organization. It is positive if the closing balance (amount of cash at the end of the period) is higher than the opening balance.

Likewise, in Chapter 3 it is specified that the Volocopter 2X has VTOL abilities and is a lightweight aircraft. These two characteristics must be taken in special consideration when designing the security and safety measurements of the PAV against all (or most) meteorological phenomena. For example, two meteorological phenomena, which are a big threat for VTOL lightweight PAVs, are surface winds (including gusts³⁴) or turbulences. Note that turbulence can be both atmospheric and induced by the PAV [53]. These can interfere with one another during the vertical take-off and landing, decreasing the stabilisation of the vehicle and thus, increasing the risk of accident and failure. Obviously, the PAV should be prepared and fully equipped to withstand any type of weather, but reinforcements have to be done for those cases in which the PAV is really endangered due to its characteristics.

Another criteria which is seen as critical for a safe flight performance, and which is also an issue in the Volocopter 2X, is the absence of de-icing conditions, the forming of ice on the exterior of the vehicle, i.e. airframe icing, or build-up of ice on the induction system [45]. Induction system icing is a type of icing that occurs with both piston and jet engines, and it is a big concern because it always lowers engine performance and can even reduce intake flow below that necessary for the engine to operate [55]. However, in the case of the Volocopter 2X, as this reference PAV is purely electric, there is no combustion and thus no fuel induction, but still, there is a type of induction does affect its 18 rotors. This one is called *impact ice*, and it is formed by the impact of moist air at temperatures between -10°C and 0°C on air scoops [56]. Figure 4.1 shows the geometry of a rotor belonging to the Volocopter 2X. This one has holes to enable the circulation of air and thus prevent overheating. Nevertheless, these apertures present a high probability for potential impact ice to be built.

Icing is not only a topic on cold and wet days, but might also occur on warmer days with a high humidity. Therefore, it is seen as an important issue to be addressed. In the case of the Volocopter 2X, it has to carefully evaluate the de-icing system, as this one determines the usability and operability, but might jeopardise the simple complexity disposed by the vehicle's propulsion system (such simplicity can be appreciated in Figure 4.1); nowadays, a number of de-icing and anti-icing devices are on the market with the aim of expanding operability [45]. These ones are also beneficial in a number of other conditions such as sand, dust, salt, snow, and heavy rain. However, the icing issue seems to be quite difficult to cope with, as even aircraft with an approval to fly into known icing conditions are not

³⁴ Gust: rapid fluctuations in wind speed with a variation of 10 knots or more between peaks and lulls [54].

advised to really do this [58]. This means that if it is complicated for aircraft with experience, it is even harder for the modern and not-yet-integrated PAV to obtain the de-icing ability.



Figure 4.1: Exterior view of a Volocopter 2X rotor. [57]

Another barrier to safety, in terms of weather, that PAVs are limited to, and thus also affects its usability, is the case of a thunderstorm. Thunderstorms can lead to unfavourable conditions such as turbulences, the potential of lightning strikes, and hail stones. As specified in Chapter 3, the Volocopter 2X disposes of a redundant stabilisation system, but as it is built out of a lightweight structure, this might actually threaten the stabilisation by being unable to withstand the strong and sudden wind forces. On the other hand, the fibre composites that form its structure reduce the possibilities of impact by lightning strike.

Ideally, in order to get a first impression about how tricky it might be to obtain for the PAV the previously mentioned “usability over the year”, at least, a weather analysis should be conducted. Notwithstanding, this thesis’ analysis does not focus on weather, nor does this chapter. For this reason, the results from a weather analysis have been below stated to proof and emphasise the importance and relevance of the weather conditions when it comes to the safety parameters in the design of the PAV. Such weather analysis was carried out by the European Union, for a program called “myCopter”, in which technologies for Personal Aerial Transportation Systems were researched [59], and it consisted of measuring how many days of a given year a flight from A to B (a 30 km distance) in the region

of Frankfurt, Germany, would have been possible at certain times of the day [45]. The conclusion was the following:

“Although this analysis was only looking at one certain area in one year, it illustrates that the dependency on weather conditions is quite high, and that the topic of how to expand the operability of the PAV into challenging weather conditions will have to be considered further.” [45].

4.1.2 Induced Errors

Next to the influence of weather conditions on flight safety, a number of technical and human induced errors can lead to accidents or unsafe situations in aviation, and hence in UAM. The annually issued statistics of EASA³⁵ give an overview of accident numbers and fatalities in different aircraft categories of aircraft (registered by the EASA Member States), but as the reference PAV in this paper, with VTOL abilities, is a rotorcraft, the helicopter aircraft category seems to be most related. Table 4.1 displays a segment of the statistics published by EASA, showing only the numbers recorded for the aircraft category of the helicopter. It is to be noted the fact that this category is composed of several subcategories; it comprises helicopters dedicated to Commercial Air Transport (CAT) operations as well as those dedicated to Non-Commercial Operations with other-than-complex aircraft (NCO). At the same time, CAT Helicopters include Offshore, Special Operation (SPO) and others.

Despite the great utility of these recorded data in real life, this chapter focuses on the reasons for accidents to occur rather than pure accident numbers. The EASA uses so-called “accident categories” as a tool to cluster and classify the reasons leading the accidents. EASA’s Annual Safety Review of 2017 reports that the top identified safety issues are, regarding operational issues: flight planning and preparation, intentional low flying, airborne separation³⁶ and handling of technical failures. Besides, the safety issues regarding human factors are: perception and situational awareness, decision-making and planning, and experience, training and competence of individuals [61]. It has to be taken in mind that, as said, these safety issues correspond to the helicopter and not to the PAV. In general terms, the helicopters analysed have a higher Maximum Take-off Mass (MTOM) than this thesis’ reference PAV, the Volocopter 2X. According to EASA’s publication, the helicop-

³⁵ EASA: European Aviation Safety Agency.

³⁶ Airborne separation: separation that takes place in the air, in flight.

ters have a maximum MTOM of 2250 kg [61], whereas the Volocopter 2X has a maximum MTOM of 450 kg. Besides this difference, the Volocopter 2X and the helicopters also distinguish from each other the arrangement and number of rotors. Nevertheless, EASA’s reviews on helicopters give an overview of the variety of safety issues relating to operations and with the accident categories.

Aircraft category	Fatal Accidents 2016	Fatal Accidents Annual 10 Year Mean	Fatalities 2016	Fatalities Annual 10 Year Mean	Fatalities Annual 10 Year Median
Helicopter	12	16.4	32	30.7	26.5

Table 4.1: Overview of fatal accidents and fatalities 2016 vs. 10-year average (2006-2015). [61]

Furthermore, one other type of induced error that could be experienced is that one due to overloading or unbalanced loading. Such issue is especially relevant for very light PAVs [45], meaning that it could affect the reference PAV. If the vehicle is overloaded (exceeding the allowed payload limit) or does exceed the allowed centre of gravity, this can lead to tilt, changes in its control behaviour, and performance during hovering, take-off, climb, autorotation, and landing [62]. However, in the case of the Volocopter 2X, as it disposes of an autonomous system, there is no option for user input (something that could lead to a critical solution), meaning that the human errors are eliminated.

4.1.3 Cyber-Security

When introducing the topic of safety, some possible problems the PAV could face and endanger the on-board passenger’s safety have been stated, like, for example, hijacking, laser attacks and computer hacking in to the system. These potential scenarios have to be taken into consideration too so that the PAV is technically equipped to avoid these problems in most, if all, occasions.

Due to the rise in number and significant of Unmanned Aerial Vehicles (UAVs) / Systems (UASs), and the same time, the development of technology and computer sciences, the

Governments are insisting on the cyber-protection and pressuring aviation bodies, such as the FAA ³⁷, so that they create laws and demand safety requirements for aerial vehicles [73]. Governments want to ensure that there are defined and valid spectrum requirements, frequency models and analysis for UAS communications [73] so that cyber-attacks can be diminished, and in the case of hijacking, the aircraft system can be accessed and controlled from ground. The testing is very severe because [73], not only the UAS (or other types of aircraft), have to ensure that they comply with the demanded safety requirements, but also, that they do not present any illegal quality that allows the vehicle to have access to private (or secret) properties of the Governments, for example, being able to be avoided by or hidden from a radar. In other words, Governments have to ensure that the general public can pilot UAS safely, and that there are neither terrorists nor criminals flying a UAS with a bad purpose.

Despite this focus being on UAVs / UASs, it is very relevant in the topic of UAM because the purpose of PAVs, at least in the case of the Volocopter 2X, is for them to fly around the urban environment, interacting with the urban infrastructures. This includes tall buildings as well as signals and radio frequencies emitted by other sources. For this reason, the comparison between UASs and PAVs is appropriate. By understanding how UASs are restricted and the barriers they experience due to the cyber-security measures demanded, companies involved in the production of PAVs can design their vehicle accordingly.

The first thing to be understood are the security vulnerabilities the PATS might suffer as a consequence of operating in the complex and congested urban airspace. It has to be taken into consideration that not only the PAV might be cyber-attacked, or hijacked, but also its infrastructure. The parking, storing and VTOL spaces have to guarantee that the access control is secured, and perimeter intrusion systems installed. This means that not only are the PAV, as in vehicles, limited by security measures, but also their corresponding infrastructure. Later in this chapter, the topic about the infrastructure is further discussed.

The security challenges of UAM in terms of technology are the following [73]:

³⁷ FAA: Federal Aviation Administration.

-
- Spoof Attack-Sensor:
 - Sensor attacks utilise the same physical channels as the targeted sensor in most cases, which can disrupt or manipulate the sensor readings.
 - Flash Light LiDAR ³⁸ Comprises:
 - Attackers use this to record legit pulses (pulses that are not encoded or encrypted) and to build up a 3-D picture of the vehicle's surroundings.
 - Acoustic Attack on Accelerometers ³⁹ Sensors:
 - Acoustic interference can displace the sensing mass enough to spoof false acceleration signals.
 - Acoustic Attack on Gyroscopes ⁴⁰ :
 - This kind of attack aims to generate ultrasonic noises and cause continuing vibration of the membrane on the sensor, which make the measurements impossible.

Knowing these common threats to UAM (inspired by those experienced by the UASs industry) gives the engineers and technicians a reference starting point: they are restricted to design a safety system that protects the vehicle from all these attacks at every occasion (or most of them). However, this is only a minimum requirement, as the safety system must also comply with the other safety aspects mentioned previously.

4.2 Environment

In the field of environmental issues the uncertainty about energy consumption and emissions is noticeable; especially the issues of noise and visual disturbance seem to be key ones that come up whenever people are confronted with the idea of PAVs flying around in

³⁸ LiDAR: Light Detection and Ranging.

³⁹ Accelerometer: an inertial navigation system that measures the acceleration of a body in its own instantaneous rest frame.

⁴⁰ Gyroscope: instrument that measures the device's angular velocity along 3 orthogonal axes.

higher counts in a city environment [45]. Such disturbances are, besides negative effect that the PAVs can cause, very obvious to people, and consequently, they are strongly linked to social acceptance. Beyond that, assuming that PAVs can use most of the airspace, people cannot escape from the noise and the visual disturbance caused by the aerial vehicle by leaving far away from major streets, in contrast to the adverse effects of cars; cars are bound to visible infrastructure on the ground, and these reduce significantly when the urban nucleus is avoided. Additional concerns to be considered are also power sources and energy storage for powering the PAV. Unfortunately, the option of possibility of new health risks due to dispersed dust during take-off and landing has to be taken into account too.

Recalling Figure 2.2 it can be reminded that air traffic has increased considerably since the 1970s and contributes between 2 and 3% to the total annual anthropogenic⁴¹ carbon dioxide emissions. The greenhouse gas emissions are of special concern because they are ascribed to have an enhanced global warming effect due to their place of formation at high altitudes [45, 63].

Regarding the environmental concerns, this thesis makes an emphasis on two of the above ecological impacts: energy consumption and noise emissions, which is already a big topic for operator of airports and manufacturers.

4.2.1 Energy Consumption

It has been previously stated that one major topic contributing to the environmental input and to public acceptance or compliance with political goals in the field of greenhouse gas reductions will certainly be the question of how much energy the PAV will consume. Of course, no exact number can be stated, as like cars, the energy consumption depends on the individual PAV being analysed. Nevertheless, it can be said that in general terms, most concepts and designs of PAVs aim at a simple and light structure powered electrically.

Electric motors avoid non-essential structures and thus, allow for a weight reduction of the PAV. This means that the power required propelling and/or lifting the vehicle decreases too. Besides, what makes electric motors also an attractive prospect (especially for urban mobility) is the lack of emissions and powertrain noise (compared with traditional combustion engines). However there are some limitations to this. At the heart of the issue is the

⁴¹ Anthropogenic: caused by humans or their activities.

consideration of on-board batteries for energy storage and the use of electric motors to drive rotor-based propulsion systems [73].

The major drawback of electric powertrains is their reduced specific energy density. Aviation fuels such as avgas⁴² or Jet A-1 store approximately 12,500 Wh/kg⁴³, where current lithium ion batteries store approximately 150-250 Wh/kg [73]. Besides this limitation, another challenge faced by electric PAVs, like the case of the Volocopter 2X which also uses lithium ion batteries, is the ageing suffered by batteries. Batteries are not only time or calendar dependent, but they are also dependent upon the number of charge-discharge cycles that they have undergone. Such ageing is affected by temperature: overheating or overcharging causes the battery to degrade faster than it normally would [74]. This means that the PAV must dispose of an efficient and sufficient cooling system in order to avoid a quick discharge of the battery.

Related to Section 4.1.1, the energy consumed by electric systems is also limited to its charging ability in cold scenarios. In the case of lithium ion batteries, these do not dispose of a possible rapid charge at freezing temperatures, i.e. below 0°C [75]. This means that the range of the PAV is limited to the weather conditions due to the fact that the durability of the batteries is temperature-dependent.

When designing the PAV and determining its power supply (and thus, its energy consumption), it is useful if not indispensable to carry out an energy consumption analysis. This way, not only the durability and consequently the range of the vehicle is determined, but also, the determination of how the batteries of the PAV will be charged will be specified. There are two practical methods for analysing the energy consumption of a vehicle: direct measurements or by developing a mathematical representation (model) of the vehicle. The benefit of direct measurements is that they provide accurate energy consumption information. The downside is that a direct measurement only provides information on the driving condition of the vehicle during the measurement. For analysing multiple driving scenarios, modelling and simulations are typically used because of their versatility. For achieving versatility and accuracy, the developed models can be validated and calibrated with direct measurements [76]. Nevertheless, the aim of this paper is not to carry an energy

⁴² Avgas: Aviation Gasoline; the most commonly used fuel for piston engines.

⁴³ Wh/kg: Watt-hour per kilogram; a unit of specific energy commonly used to measure the density of energy in batteries.

consumption analysis for the PAV but to state how this one is limited to the capacity of its power source.

4.2.2 Noise

Noise pollution is of major concern of citizens all around the world, from the European Union, to Japan all around until the United States [64]. In fact, in the Green Paper on Future Noise, the European Commission states that environmental noise is one of the main environmental problems of Europe [65]. Older data from the EU estimate that around 20% of the Union's population (around 80 million people) are exposed to noise levels that are considered to be harmful in terms of health issues, leading to annoyance, sleep disruption, and more [65]. Although individual noise levels of cars, trucks, and aircraft are decreasing, this success is offset by traffic growth on the ground and in the air, as commented before in Chapter 2. Figure 4.2 shows the increasing trend of noise disturbance from different transport media.

Additionally, air traffic noise is one of the main sources of noise annoyance, as confirmed by survey data from the Netherlands, which the European Commission Working Group on Health and Socio-Economic Aspects mention in their position paper on night-time noise. The survey (carried out in 1998 and 2003) asked people to what extent their sleep was disturbed by noise from different sources, and the result was that air traffic ranked third behind road traffic and neighbours' noise [66]. This can be appreciated in Figure 4.2 too, where the graph corresponding to the noise generated by air traffic (Graph (a)) presents higher values than those representing road and rail traffic. More specifically, for road and rail noise, the percentage of the population estimated to be highly sleep disturbed is approximately 2% for L_{night} levels of 40 dB, whereas for aircraft noise, 10% of the population is estimated to be highly sleep disturbed for the same noise level.

As already indicated noise exposure is thought to have several negative effects on health and the overall well-being, such as sleep disturbance, indirect effects on mental illness, physiological and performance effects [45]. While the effects on health are not always easy to detect and often build up subtly over time, noise has also a more direct effect on people by disturbing them in their present activities, be it a conversation, watching television, or trying to find relief from work stress at home. Noise can be loud and obtrusive or also very vague. What seems to be a common character of noise is that it is unwanted, uncontrolled and unpredictable [68]. Generally, noise could be defined as being the “negative evaluation of sounds that are judged to be disruptive and intrusive” [68].

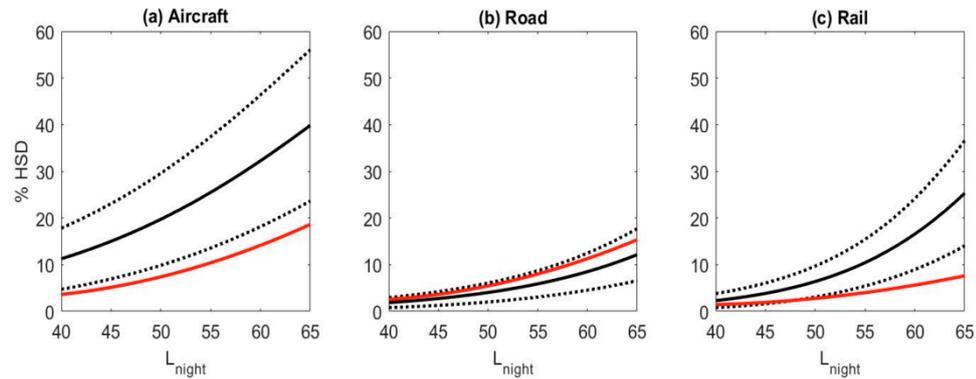


Figure 4.2: Percentage of Highly Sleep Disturbed (HSD) based on responses to questions on awakenings, difficulty falling asleep, and sleep disturbance for aircraft (a), road (b), and rail (c) noise.

Legend: black dashed lines: 95% Confidence Intervals; black bold lines: mean; red bold lines: recorded sample data. [68]

For this reason, the noise emissions of PAVs (and its impacts), is an important issue throughout the entire design and integration process. A first impression is that this issue is difficult to address both in terms of an overall accepted strategy for measuring or mapping noise emissions and in terms of an evaluation of the individual level of noise perception and annoyance. Besides that, the measuring and categorization of aircraft noise is diverse in terms of the indices used. Because the noise indices in regulations to aircraft noise are significantly numerous, it is extremely difficult to compare noise reception limits; the opposite occurs in the cases of road and rail noise, their measuring is far way less complex. In fact, two approaches seem to coexist when it comes to the control of aircraft noise emission: some countries use the L_{Aeq} ⁴⁴ (in the United Kingdom, Germany and Sweden, for example), and other use indices which consider both the number of aircraft movements and the peak sound level of each over-flight with different weightings for the different periods during the day [66]. In most cases, two periods are used: daytime (6.00 a.m. - 10.00 p.m.) and night-time (10.00 p.m. - 6.00 a.m.).

⁴⁴ L_{Aeq} : sound level in decibels equivalent to the total A-weighted sound energy measured over a stated period of time.

The lack of unification complicates the analysis of the Volocopter 2X's noise level. In the case of this reference PAV, it is specified in Table 3.2 that it emits around 65 dB(A) at 75 m, which is as quiet as the smallest helicopter within 500 metres distance. Mathematically speaking, that is a reduction factor of 7 [23]. This is achieved by acoustically operating all 18 rotors within a narrow frequency band, so they appear to the human ear to be only twice as loud as one single rotor [23]. Because it is a purely electric vehicle, it is thought to have highly reduced noise levels, but still, given the complex categorization and subjective perception for aircraft noise, such 75 dB(A) cannot be certainly classified as a reasonable noise level or excessive. In fact, for a noise level to be considered as acceptable to communities, it is required for it to be more on the order of 55 dB(A) [17]. This can be extrapolated to the cases in which businesses are developing a new design for a PAV, and are limited to a certain noise emission. However, due to the lack of homogenous regulations and the unpredictability of noise, there is no specific regulated value they can stick to. Of course, the PAV should be as little noise as possible, but again, there has to be a law that states how much is "as little as possible". This is a today's problem, as UAM is just a concept and proposal, but has not yet been integrated in urban spaces, and thus, specific regulations have not been established. Certainly, in a future, for the PAV operation there will be noise standards to be respected although these thresholds could be different in the single countries and could also differ depending on settlement structure and time of the day.

Finally, an emphasis has to be made on the fact that air traffic noise, despite technological improvements, will remain a sensitive issue especially if a significant number of flight operations is expected to occur, which is the assumption done in this thesis on grounds of the conclusions obtained in Chapter 2, after analysing the evolution of both society and mobility. This means that even if individual noise signatures of the PAVs were decreasing, the general trend of increased ground and air traffic, makes it very likely that this topic will remain of high priority.

4.2.3 Further Environmental Aspects

Further issues concerning environmental impact and sustainability of future PAVs could be the issue of bird strikes or general irritations of the fauna, toxic substance emissions independently from global warming potential, and also the visual impacts on the sky. The creation of take-off and landing sites as well as the provision of parking space would have to compete with other uses especially precarious in the already crowded inner city areas where also the visual impression of new built ground infrastructure could become a topic of concern.

Lastly, the question of social segregation and reasonableness is also to be asked because the PAVs seem to be, at least at the beginning, a technology which will not be affordable and accessible for all parts of the society, but negative effects (noise, local emissions, climate change) will have to be carried by all [45]. The socioeconomic restrictions experienced by the PAV, and the PAV system, i.e. PATS⁴⁵, are further discussed in the following section, Section 4.3.

4.3 Technical and Operational Limitations

There is of course also a technical component when talking about the limitations, and a challenge to be met in order to create a PAV, but the overall challenge to create a personal air vehicle itself seems mostly overcome with a number of PAVs already on the market, and small helicopters and, especially, gyrocopters existent all over the world [45]. The current situation of what the PAV market looks like and a simple market analysis was done in the prior chapter, in Section 3.4. Here it was discussed the complexity of operation aspect of the PAV, and how difficult it actually is to design a successful PAV, from technical to profitable characteristics. That is, a lot of challenges regarding their production in higher quantities, to a lower price, with a simple manageability and a high level of safety and automation remain.

In Chapter 2 it was discussed that due to the increase in the world's population and specially the urban population, the demand of urban mobility is increasing vastly, together with the exquisiteness of the users, and the numerous requirements asked by these. Consequently, in order to satisfy this demand and be able to offer UAM to a significant percentage of the citizens, it is essential that the production of PAV is, as said, in high quantities and relatively cheap. In fact, the Volocopter 2X was launched as a series production version by e-volo GmbH⁴⁶ in April 2017 [69]. The German company was, by that time, planning to certify the Volocopter 2X in 2018 under a new German Ultra-light category being created for that same year and the goal was to sell this PAV the year after, i.e. 2019. However, at this current times, July 2018, the Volocopter has not yet been certified, which also means its sale will be delayed [69]. This emphasizes the previous statement: how complicated it

⁴⁵ PATS: Personal Aerial Transportation System.

⁴⁶ e-volo GmbH: the German company Volocopter was known as "e-volo GmbH" until July 2017 [37].

actually is to launch this vehicle, and once launched, to achieve a high (and affordable) production.

Operational barriers also affect the passengers. That is, it is not enough for a company involved in the design and production of PAVs to build such vehicle in series, but the economic effort (or investment) the user has to make must also be considered. Nowadays, to the general costs concerning PAVs from the passengers' point of view, no detailed investigation has been seen as meaningful [45]. What certainly can be stated is, that actual pilot training is more expensive than a car driving license, especially, if one considers PPLs⁴⁷ (the costs for a PPL (H)⁴⁸ start from \$ 28,750 (almost 25,000 €) [70]. On the other hand, ultra-light licences are comparably cheap, with costs of around 5,000 € [71]. Regarding the Volocopter 2X, is granted a certification for manned flights, meaning that the pilot does indeed need a licence. This increases the cost of its operability. Notwithstanding, it is designed for it to be an ultra-light vehicle (although this certification has not yet been obtained), which, as explained, does not require such an expensive training.

On top of this come costs for maintenance, repairs of the PAV, fuel, keeping the “pilot certification”, and more. According to the German company Volocopter, their vehicle is cost effective by setting new benchmarks not only in terms of reliability and simplicity, but also where cost effective is concerned; fuel is replaced by economic electricity and when it comes to maintenance, repair and overhaul, these are reduced to a minimum through the avoidance of complex mechanical components [23].

4.3.1 Automation and Autonomy

As commented, technical, economical and operational barriers are experiences by the vehicle as well as the user. Furthermore, one key aspect is the relationship between the human user and the PAV or its internal system. The degree of autonomy of the system is very important for the overall design and management of the whole personal air transportation system and has also far reaching consequences on training requirements. Autonomy is the ability of a system to make decisions and then follow these decisions [45]. It is important to not be confused with the similar term automation; this term describes a system that does exactly what it is programmed to do and it is not open for decisions while it is executing the pre-programmed actions [45]. This means that the level of automation is of

⁴⁷ PPL: Private Pilot License.

⁴⁸ PPL (H): Private Pilot License for Helicopters.

crucial relevance for the socio-economical assessment since the user/driver/pilot is directly affected. In fact, without assuming an autonomous system, it is very difficult to envision anyone but a trained pilot flying these aerial vehicles.

Although it might seem obvious to equip all the designs of PAVs with autonomy, the all the cases must be analysed, both operational and technical, and all situations weighed. This leads to a scaling of the level of automation, from no automation, semi-automation to full automation (or autonomous control) [45]. In terms of the technical parameters, automation is a PAV barrier as it affects the vehicle's weight, since the sensors, actuators, and the control systems add to the overall weight of the PAV as well as to the additional power supplies needed to run them. Regarding the impact of automation on the operational aspects, the skills and trainings necessary by the pilot are affected; the first level of automation (no automation) requires a full pilot license, the second one refers to a much less complex and costly car driving licence, and the third one, full automation, takes the human passenger on board without having any additional skills [45]. Applying this classification to the Volocopter 2X, it can be said that this vehicle presents a third level of automation, i.e. it is equipped with an autonomous system. As mentioned in Section 4.1.1, the Volocopter 2X operates under the flight status Autonomous Flight Rules (AFR), and therefore, its operation only requires a short introduction. Despite its fully automation, it still requires a licensed driver, i.e. pilot, but its control and manageability is described as simple "using a single joystick and the highest degree of reliability". In fact, even if the pilot lets go of the joystick, the Volocopter 2X retains its prevailing position fully automatically, and even better, "in areas in which autonomous operations are possible, it can simply fly on its own" [23].

At the same time, this is highly linked to a limitation evaluated before: safety, and this one is related to social acceptance; the fully autonomous mode seems to be the only one thinkable in emergency situations such as thunderstorms or heavy rain. This means that, the level of autonomy is, therefore, a trade-off between the technical and the socio-economical, i.e. operational, characteristics of the PAV.

4.3.2 Infrastructure required by the PAVs

Above the limitations experienced during the process of designing the PAV so that it flies and carries passengers, the case in which these are stationed must be studied too. As evaluated in Chapter 2, cities are growing rapidly and the optimal and efficient use of urban space is essential. As a consequence, the issue regarding parking and storing possibilities seems quite complex, especially in already-congested inner city areas [72]. This does

indeed limit the PAV because it determines its design, purpose and therefore, target market; the question of where to park the PAV requires an evaluation of the current urban space, whether the PAV fits into a current automobile urban infrastructure. In the case of the Volocopter 2X, from Table 3.1 its sizes can be recalled, and it can be deduced that it is way too big compared to a conventional car, being unable to fit into a parking spot. Given this situation (in which the design was thought before considering the limited urban space), an alternative has to be considered: the construction of parking lots exclusively for, in this case, the Volocopter 2X. As the available urban space determines the size of this parking, the units of Volocopter 2X being stored there are limited too.

Additionally, another way in which the design of PAVs is restricted is the take-off and landing sites that they require. If the purpose of the PAV is to operate around urban areas, and satisfy the increasing social demand on urban mobility, it must be able to take-off and land in the urban space too. This way, it is handy for the users and avoids them from displacing outside the city centre. By willing to fulfil this requirement, and therefore forcing its landing and take-off sites to be located within the urban space, the vehicle is technically limited to a certain size, power and noise, barriers which have been previously commented.

When it comes to the infrastructure required for the operation of the PAV, another aspect has to be studied: safety. The safety and protection of the infrastructure has already been introduced in Section 4.1.3, when evaluating the possible external threats to PATS. As said, parking areas as well as VTOL spots must ensure that the access to them is controlled, just as it occurs with parking spaces for ground vehicles: they either have a guard supervising the parking during the entire day, or security alarms when these ones are closed or out of service.

Although it might seem obvious, the safety measurements installed in the infrastructures must be considered too because they come along with an economic budget, which results in an economic limitation for a business. Together with that, another question is raised, whether the user of the UAM service will have to pay for this parking or not. And again, one other interconnection between different parameters of the UAM is brought up: public acceptance.

5 Laws and Regulations

Chapter 3 gives an overview of how the concept of Personal Air Vehicle, the suggested solution to the urban mobility and social situation described in Chapter 2, is being approached. Despite the suitability of this vehicle, the vehicle itself in the microscopic scenario presents certain limitations and challenges, which have to be considered when designing and developing it. Such barriers and restrictions, both external to the vehicle and technical within the vehicle's system, are discussed in Chapter 4.

However, the analysis goes beyond the understanding of the PAV, beyond understanding its purpose and its functionality. It is essential and critical to comprehend how the individual PAV interacts with the larger system; even if solutions to those limitations described in Chapter 4 exist, the realisation of Urban Air Mobility with a high number of PAVs, and the corresponding PATSs, operating in an urban environment strongly depends on the legal framework.

This chapter focuses on such regulatory framework in which the PAVs are expected to operate. That is, Chapter 5 explains the laws and regulations that determine how, where and when can PAVs fly. These could also be considered as limitations and barriers experienced by the PAV, as the design of the legal framework also co-determines how high the access barrier for the users and businesses in this sector will be. The main difference between the legal limitations and those evaluated in Chapter 4 is that the barriers in Chapter 4 exist within the vehicle and its system. That is, the limitations presented in the micro-level of the PAV. Meanwhile, the laws and regulations discussed in this chapter are limitations in the macro-level, rules which have been imposed by legal entities that PAVs, PATS and companies working in the UAM industry have to follow.

It has to be clarified that, although in this thesis the limitations experienced in the micro-level and the macro-level are explained in different chapters, they are strongly interconnected and both play a significant role for the other.

5.1 Certification

The aspect that is seen as a major hurdle, both for developers of the PAVs and for people who want to fly/use them, is the issue of getting certification for the vehicle and the licence required to fly the vehicle in a given country and environment [45]. The question of certifi-

cation is also raised in the previous chapter when evaluating the level of automation installed in the PAV. As it has been stressed before, and it becomes more and more apparent, most questions and issues are related to each other, and changing one assumption about the PAV abilities, level of autonomy or system architecture, creates changes in many of the other fields.

To clarify this last statement, the following applied example can be helpful: if the level of autonomy is not very pronounced, that is, the final decision in critical situations is taken by the user, conventional insurance schemes might work. If it is assumed, however, a full autonomous system with a human passenger on board playing the role of pure “cargo”, then the situation looks very different and will probably constitute an unsolved problem for the insurance industry. In other words, changing, for example, the degree of autonomy does not affect the vehicle’s design nor the user’s flying knowledge only, but also external agents, such as the insurance companies.

Auto insurance companies make money through a combination of managed risk and the strategic use of money. This risk is highly dependent on the driver, i.e. human error. Therefore, if vehicles get automatized, such risk will decrease and insurance companies will be able to charge less for their policies. The same will occur for the UAM industry: if the PAVs carrying out this service are fully-autonomous, the human error will drop vastly, or even will be inexistent, and therefore the insurance companies will not be able to establish high prices. This is indeed an advantage for the customer, who will be face a lower investment. However, in the case PAVs are autonomous, PAV manufacturers will be the responsible for the entire safety, integrity and security of the vehicle and its passengers, meaning that they will have to pay a significant amount to be able to operate.

The given example brings up the topic related with responsibility and insurance and besides these aspects, a related issue to be considered too is the question regarding the time periods people are allowed to fly PAVs and which parts of the airspace are open to them.

5.1.1 Vehicle Certification

The timescale of the Volocopter 2X, according to Volocopter, is short-term and it is assumed to be seen flying around the cities of Dubai and North America [33]. Unfortunately, things are not turning out as planned by the German company and the launching process is suffering a delay. This comes along with the entire industry of UAM and PAV, as it is still being analysed and studied, and thus, its timescale is rather long-term and expected to emerge in a few years time, perhaps even decades [45]. Therefore, the certification categories and procedures existing today might have changed and new ones might be in place.

This is an actual problem because PAV manufacturers will spend a long period of time analysing the certification requirements of the category they are aiming at to ensure that they fulfil them, which will also lead to a higher economical investment during the production process and during the certification process. If the categories themselves or the categories' requirements change, it might occur that the certification obtained by the PAVs will no longer be valid, meaning they would not be able to operate.

This is the case of the European Light Aircraft (ELA), a certification for Light Sport Aircraft (LSA) issued in August 2012 by the Commission Regulation with the aim to simplify and lighten the regulatory regime for aircraft and related products [78]. Those LSA which correspond with the description given in ELA, if they do not have the ELA certificate, they are not able to fly despite having the old EASA certification "SLA Permit to Fly (PtF)" [78]. Consequently, airlines, companies or pilots owning these kinds of aircraft, will have to spend time and money in acquiring the new certification. With this example it is proven how risky it is to actually construct a PAV nowadays when the PAV certification and regulation system is not consolidated.

Notwithstanding, the existing rules give a feeling in which legal framework PAVs will be integrated and, despite the new regulations that might appear in a future, PAVs will certainly have to cope with today's existing aircraft categories and airspace divisions. A company that has thought beforehand about this situation of interaction is Terrafugia⁴⁹. In Terrafugia they are developing a roadable aircraft called "Transition" and a flying car called "TF-X" [79], and their goals have been specified in terms of street and air certification for their vehicles. Meanwhile, the team is also reporting on the difficulties they experience to fit into the existing system [80].

Before the PAV (or any other newly developed aircraft model) may enter into operation, it must obtain a type certificate from the responsible aviation regulatory authority. Such certificate testifies that the type of aircraft meets the safety requirements set by the European Union [81]. The organisation responsible for the certification of aircraft in the European Union and for some European non-EU Countries (i.e. a total of 32 Member States) is EASA (already mentioned in this thesis). This agency was officially established in 2002 and took over the airworthiness functions of the former JAA⁵⁰ [82].

⁴⁹ Terrafugia: a Chinese-owned corporation, based in Woburn, Massachusetts, United States [79].

⁵⁰ JAA: Joint Aviation Authorities; established in 1970.

Yet, it must be taken into account the fact that some aircraft do not fall under the responsibility of the EASA and these exceptions are listed in the Annex II of their Basic Regulation from 2008 [83]. These have to be considered because they can be relevant to an approach of the PAV being designed by a business. By analysing Annex II, it can be seen that in the field of ultra-light air vehicles, Europe has no harmonised legislation so far [45]. On the other hand, in the case of, for example, a heavier Unmanned Aerial Vehicle (UAV) with human cargo, the responsible would be EASA [84].

In the case of the United States, the Federal Aviation Administration (FAA) regulates aviation operations within the United States Airspace, known as the National Airspace System (NAS).

5.1.2 User Certification

Another issue concerning the implementation of PAVs is whether there are laws and/or regulations demanding minimum requirements regarding the qualifications and aviation knowledge of the passengers, if so pilots. It seems coherent to believe that users should indeed be somehow qualified if the abilities needed to pilot current air vehicles are considered; pilots need to manage all the navigation and separation tasks. Above that, the requirements are not only high in terms of knowledge and training, but it is also very expensive and time consuming to take and to keep a pilot licence, as commented before in Chapter 4. Consequently, the figures for driver licenses are far higher than for private pilot licenses (PPL) [45].

In order to make it more affordable, and hence attractive, the aim of most companies involved in the industry of UAM and production of PAVs is to minimise the training requirements for the user by both improving the handling characteristics of the vehicle, and by achieving as much automation as possible within the PAV system; the more autonomous the vehicle, the less aeronautically-skilled the user can be. Ergo, the requirements for the pilot training depend on the automation level of the PAV. However, the higher the degree of automation, the greater the weight of the vehicle, as more computers and microprocessors are required. This characteristic jeopardises those companies, which aim at designing an ultra-light PAV, as the ultra-light licenses have lower requirements in terms of minimum flight training hours, frequency of repetition of medical certificates and validity and thus can be more appealing to potential clients.

In the US, the FAA allows one-seat ultra-light vehicles to be flown without any pilot licence, as long as the driver obeys a few specifications: do not fly faster than 55 knots

(around 100 km/h), have no more than around 19 litres of fuel on board, and do not exceed 254 pounds (around 115 kg) of Empty Weight limit [110].

The Federal Aviation Regulations (FARs) applied by the FAA contain rules for the certification of pilots, certification of aircraft, etc. [73]. Because the reference PAV in this paper is a VTOL vehicle (and assuming that in the future, all PAVs will count with this characteristic for the sake of urban space optimisation), only the FARs applicable for the certification of pilots that will be operating VTOL aircraft (classified as powered lift by the FAA) are listed below [73, 85]:

- Part ⁵¹ 61: Certification of pilots, flight instructors and ground instructors.
- Part 67: Medical standards and certification.
- Part 135: Operating requirements of commuter and on demand operations.
- Part 141: Pilot Schools.
- Part 143: Training Centres

Most pilots, who are not pursuing a career as a professional pilot, take the route of Part 61, which is flexible and allows tailoring the lessons and skill learning sequence. Nevertheless, the most relevant Part when it comes to the PAV is Part 135, because urban VTOL operations fall under the commuter and on demand operations category [73, 85]. Pilots operating under this Part are required to have a flight experience of 500 hours when flying in Visual Flight Rules (VFR) ⁵² conditions, and in the case of Instrument Flight Rules (IFR) ⁵³ conditions, pilots must have 1,200 hours of flight experience [73, 85]. Part 135 also states flight time limitations and requirements for unscheduled operations [73], and these must be taken into consideration when projecting the future need for pilots.

⁵¹ Note: the FAA regulations are prescribed in the FARs, which are contained in the Code of Federal Regulations (CFR). FARs are sections within the CFR and they are referred as *parts* [73].

⁵² VFR: set of rules created by the FAA for flight in Visual Meteorological Conditions (VMC) [86], i.e. the pilot is able to see where the aircraft is flying.

⁵³ IFR: the set of rules that govern aircraft that fly in Instrument Meteorological Conditions (IMC), below the minimums prescribed for flight under VFR [86], i.e. the pilot is not able to see due to weather conditions.

Furthermore, it is also important to analyse not only the requirements needed for a passenger/pilot of a PAV, but also at the availability and disposability of those who would actually want to fly this vehicle. In the case that PAVs do indeed require certified pilots, it seems reasonable to believe that people already disposing of a pilot licence will be willing to fly a PAV before those who still have to get a licence. However, this brings up the following question whether already-certified pilots will actually want to try this new aerial vehicle or will rather stay in their corresponding aircraft category.

Given the job environment today, only a 2% of Airline Pilots are currently unemployed [87]. This is a very low unemployment rate compared to the rest of the economy and thus, an indicator of labour supply shortage. Different sectors of commercial aviation are experiencing this shortage at different degrees; major airlines have not been affected yet, whereas regional and small carriers (corresponding to Parts 121 and 135) are suffering a shortage of pilots caused by attrition, as the major airlines hire pilots to replace those retiring [75]. For example, on February 2016, the airline Republic Airways (RJET) ⁵⁴ declared that the shortage of pilots caused it to ground many of its planes and as a result, the company saw themselves forced to file for bankruptcy protection [88]. Figure 5.1 aids the visualization of this situation in which there are more pilots than job positions, i.e. a labour supply shortage. Because most of these pilots pursue a career in major airlines, as said, these companies have a huge disposability of potential pilots, and this is shown in Figure 5.1. This graph shows the historical evolution of pilots hired at major airlines and the commercial pilots created. It is obvious that the curve corresponding to the pilots hired pilots is way lower than that corresponding to the created pilots. This emphasises why major airlines have not yet been affected by shortage of pilots.

The major airlines attract pilots from small regional airlines, and to this it is added the fact that most pilots pursue careers with the major airlines due to salary and hiring incentives [75]. This leaves a void in small and regional operations. Next to that, other contributing factors to pilot shortage are military producing fewer pilots, shortage of flight instructors [75], pilot retirement, increased costs of training and the future growth of the global de-

⁵⁴ Republic Airways: a regional airline that flies smaller regional jets for United Airlines (UAL), Delta Air Lines (DAL) and American Airlines (AAL) [88]. It emerged from bankruptcy as privately held company in 2017 [89].

mand for pilots, which the company Boeing ⁵⁵ has estimated to be 637,000 new pilots in the next two decades [90].

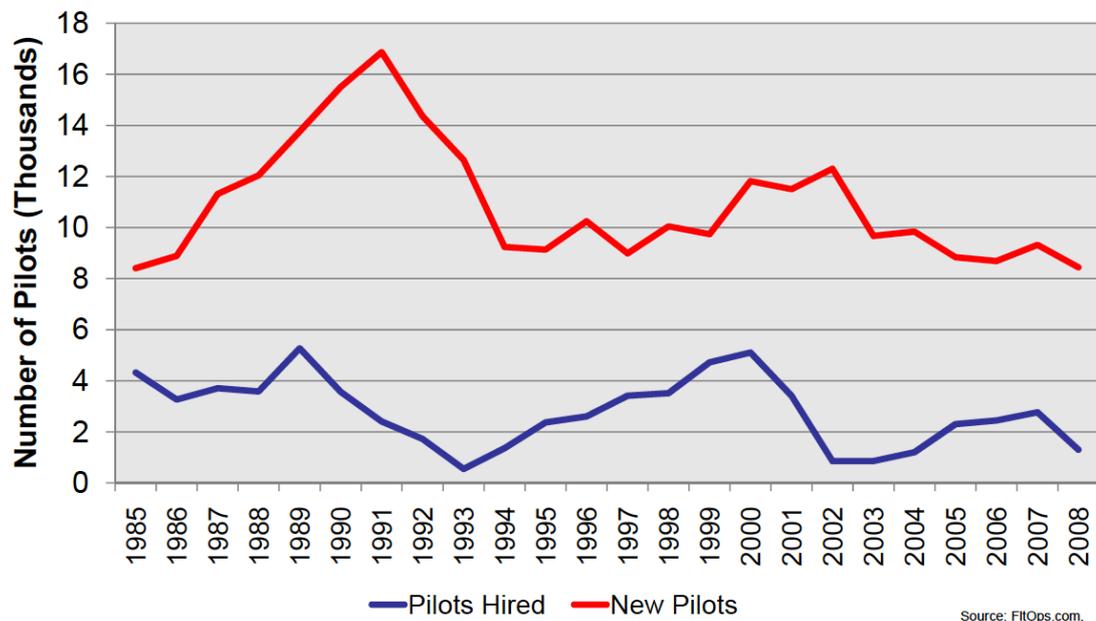


Figure 5.1: Historical pilots hired at major airlines vs. new commercial pilots created. [92]

As personnel demand increases over the next two decades, the aviation industry will need to find innovative solutions to keep pace with training requirements. This can mean both a threat and an opportunity for urban on-demand (VTOL) operations. Widespread urban on-demand operations such as proposed by Volocopter, will initially require a large amount of pilots which will aggravate the pilot shortage and present a threat for the service. Despite this, it might be beneficial for those pilots mentioned before, the ones who are pursuing high paying positions with the major airlines; VTOL operations under Part 135 can be a path for them to acquire the flying experience required to move to those positions.

⁵⁵ Boeing: the world’s largest aerospace company and leading manufacturer of commercial jetliners and defence, space and security systems.

5.2 **Airspace Management**

Related to the legal issue is the topic of the used airspace in which the PAVs are envisioned to operate. Since this thesis is focused on urban mobility, the proposal of PAV being potentially integrated in this program is essentially short-range, low-speed and low-altitude, and thus, will operate outside the controlled airspace, i.e. the uncontrolled airspace, where other flying objects such as birds, remote-controlled aircraft, sport aircraft of various kinds and other PAVs may be encountered [59]. It seems reasonable to locate the PAVs in this section of the airspace because, as studied in Chapter 2, people are constantly moving around the urban spaces, and with the increasing urbanisation being experiences, there is a huge necessity to optimise urban mobility, making it efficient, comfortable for users and sufficient to supply the mobility demand. For this reason, aiming at a concept of the PAV able to fly in actual urban skies is essential for enabling the UAM service to be within everyone’s reach. The consequence of this is that the PAV has to operate at low altitudes and thus, in the uncontrolled airspace.

Nevertheless, despite its high accessibility, flying at low altitude also means a larger impact on the urban environment: more visual presence of the PAVs, which might be unpleasant for the citizens, higher exposure to the PAVs emissions and noise disturbance. The aesthetic issue can be easily addressed by designing a PAV with a more streamlined structure, and colours that blend with the environment, so that they do not stand out and are obvious to the human eyes. Regarding the air pollution, with the developing technologies, this is not much of a concern, as many PAV models are purely electrical thanks to the Distributed Electric Propulsion (DEP), previously introduced in Chapter 3. However, noise emissions are indeed a big concern, as, even though DEP does indeed reduce the noise levels, there has not yet been a PAV designed in which its noise emissions are perceived as humanly bearable. A possible solution to this could be establishing “air main roads” in such a way that the PAVs’ noise contribution would not significantly increment the already existing noise level. This way, PAVs would be more focused instead of using the entire urban airspace and thus disturbing the whole city.

On the other hand, setting “air main roads”, as it leads to a higher concentration of PAVs in a given airspace, jeopardises the safety and security by increasing the risk of collision. This has two main consequences. The first one is due to the fact that because the urban airspace at low altitudes is uncontrolled airspace, the pilot is the one in charge of the separation task. If the scenario and flying conditions become more complex and risky, the required pilot license will be more demanding, and hence, less persuasive for the general

public. The second consequence is related to Air Traffic Control (ATC) ⁵⁶. By increasing the traffic density within a volume of airspace, i.e. establishing “air main roads”, the workload of the Air Traffic Controllers (ATCOs) is increased, and thus it becomes more difficult for them to provide effectively sufficient support and guidance for every aircraft under their supervision. If UAM implies an extra burden in terms of the ATM and ATC, despite the many advantages this mobility type might present, airspace regulatory entities will not support nor promote the integration of PAVs in the airspace. Yet, this former issue can be avoided simple because PAVs do not operate in the controlled airspace.

Operating outside the controlled airspace, or alternatively flying in the uncontrolled airspace, implies that the ATC may provide service or information, but this is not guaranteed because of, for example, workload. This means that the separation task, also known as “sense and avoid”, in the uncontrolled airspace is, as said, within the responsibility of the pilot/operator. At this point, another interconnection is appreciated between the airspace management and the pilot certificate required. By designing a PAV able to fly around the urban environments, at low altitudes and interact with the cities infrastructures (making it simpler and more comfortable for the users to use the service), the vehicle is inevitably flying in uncontrolled airspace, and thus, because the pilot is responsible for the separation task, a minimum pilot licence will be required (independently of the existence of “air main roads”), an issue that slows down the encouragement of many. Again, as it is an innovative mobility mode involving many sectors and industries, a homogeneous operation of the entire project is still being developed, and no certain laws and regulations have been yet established.

Meanwhile, operating in a complex airspace in which both the airspace system and the ground infrastructures coexist, can be eased by equipping the PAVs with the necessary instruments that can carry out, for example, the separation task an lighten the pilot’s workload. This means that PAVs’ system could integrate instruments that are not required in VFR flights (but are compulsory in IFR) but would improve their integration in the airspace, like for example a TCAS (Traffic Collision Avoidance System). A TCAS monitors the airspace around an aircraft for other aircraft equipped with a corresponding ac-

⁵⁶ ATC: Air Traffic Control; a service provided by ground-based air traffic controllers who direct aircraft on the ground and through controlled airspace, and can provide advisory services to aircraft in non-controlled airspace.

tive transponder ⁵⁷, independent of air traffic control, and warns pilots of the presence of other transponder-equipped aircraft which may present a threat of mid-air collision (MAC). Ergo, for this to be useful, all PAVs should have a transponder, but that adaptation is for sure simpler and easier than adapting the actual ATM and ATC.

Besides, integrating IFR instruments in PAVs before these are actually implemented and commercialised is actually being a step ahead of the future; according to NASA, it is expected for PAVs to be integrated into a future generation of controlled airspace [45]. This however is a long-term plan, as it first has to be ensured that vehicle viability is widely recognised, and that its integration in the controlled airspace has the lowest influence on ATC as possible [19].

On the other hand, being initially integrated in the uncontrolled airspace might present some advantages, in terms of simple legislative processes, as the implementation of PAVs would have no impact at all on existing air traffic. That means that the workload on the ATC would slightly be modified. Whilst the concept sounds appealing, this gives rise to another question: given that the airspace over urban areas is highly sensitive, would it be necessary to create control services, or increase the range of the current ATC, for these areas to be supervised? That is, would the airspace organisation be rearranged? Clearly, a fundamental relationship between the level of structuring of traffic and resulting properties, such as safety, is not well established, and different studies in this field report seemingly contradictory findings [93].

5.2.1 Airspace Classes

Until this point, a differentiation between controlled and uncontrolled airspace has been mentioned, but no further detail has been given on how the airspace is classified and organised. It is important to know these classifications because each one of these classes, have specific operating and entry requirements. This means that a business working on the design of a PAV, will have to consider these in order to ensure that their vehicle fulfils the specifications of the airspace class they want it to operate in.

Figure 5.2 presents a profile view of the dimensions of various classes of airspace. These are dictated by the complexity or density of aircraft movements, nature of the operations conducted within the airspace, the level of safety required, and national and public interest

⁵⁷ Transponder: short for “transmitter-responder”; an electric device that produces a response when it receives a radio-frequency interrogation.

[94]. They are characterised by a decreasing level of control executed by the ATC and by different limits for air speed, flight heights, etc. [45]. Each one of these categories belongs to the controlled or the uncontrolled airspace. The controlled airspace is a generic term that covers the classes from A to E, both included, and as explained, it is the region in which ATC service is provided. Meanwhile, classes F and G belong to the uncontrolled airspace.

PAVs, initially, theoretically would operate in classes F and G, where no ATC clearance has to be obtained and a lot of smaller and mostly slower vehicles such as balloons, sailplanes, gliders, trikes, etc., operate. For a safe operation in this airspace, standards exist for minimum clearance to avoid noise disturbance and to provide a safety margin in the case of an emergency landing [45]. For European countries, these rules can be found in the Air Traffic Order (published by the country's Federal Ministry of Justice) [45]. The Air Traffic Order determines the so-called Lowest Safety Altitude (LSALT), which is only to be undercut for starts and landings. Above cities and other dense settlements, industry, crowds of people, and danger zones the LSALT is 300 m above the highest obstacles in a radius of 600 m. In all other cases such as in ground or water environment without the mentioned constraints the LSALT is 150 m. For cross-country flights after VFR with motor-powered air vehicles a higher LSALT of 600 m is in force [45].

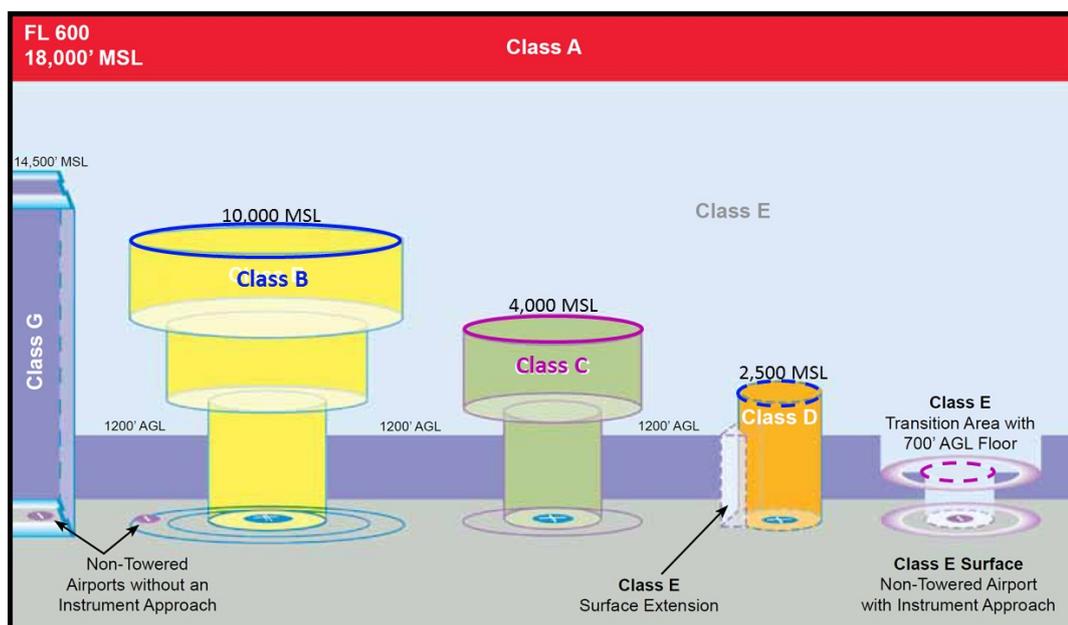


Figure 5.2: Airspace profile. [94]

PAVs, initially, theoretically would operate in classes F and G, where no ATC clearance has to be obtained and a lot of smaller and mostly slower vehicles such as balloons, sailplanes, gliders, trikes, etc., operate. For a safe operation in this airspace, standards exist for minimum clearance to avoid noise disturbance and to provide a safety margin in the case of an emergency landing [45]. For European countries, these rules can be found in the Air Traffic Order (published by the country's Federal Ministry of Justice) [45]. The Air Traffic Order determines the so-called Lowest Safety Altitude (LSALT), which is only to be undercut for starts and landings. Above cities and other dense settlements, industry, crowds of people, and danger zones the LSALT is 300 m above the highest obstacles in a radius of 600 m. In all other cases such as in ground or water environment without the mentioned constraints the LSALT is 150 m. For cross-country flights after VFR with motor-powered air vehicles a higher LSALT of 600 m is in force [45].

It could be argued that these safety heights could be arranged lower for a PAV with a VTOL ability that needs far less space for landing than other air vehicles and, therefore, has a greater choice regarding landing spots, even in a densely populated area. Today, these safety altitudes are already undercut by the military, the police and by emergency services [45]. The issue of noise disturbance would remain though.

Recalling the cruising altitude of 1,650 m AMSL (around 5,500 ft.) of the Volocopter 2X (the reference PAV in this paper) from Table 3.2, it looks as if the class G would be the airspace for this PAV's flights under current assumption and legal framework.

Above these, no matter what class the reference PAV, or any other implemented PAV, belongs to, some areas have to be taken into account because either they are dangerous or no operations are allowed in those regions of airspace. These areas are the following:

- Prohibited Areas
- Restricted Areas
- Warning Areas

Prohibited areas contain airspace of defined dimensions within which the flight of aircraft is prohibited (hence the name). Such areas are established for security or other reasons associated with the national welfare. These areas are published in the Federal Register and are depicted on aeronautical charts [94]. The area is charted as a "P" followed by a num-

ber, e.g. P-40. Examples of prohibited areas include Camp David⁵⁸ and the National Mall in Washington, D.C., where the White House and the Congressional buildings are located.

Meanwhile, restricted areas are areas where operations are hazardous to nonparticipant aircraft and contain airspace within which the flight of aircraft, while not wholly prohibited, is subject to restrictions. Activities within these areas must be confined because of their nature, or limitations may be imposed upon aircraft operations that are not a part of those activities, or both. Restricted areas denote the existence of unusual, often invisible, hazards to aircraft (e.g., artillery firing, aerial gunnery, or guided missiles) [94]. This class of area is charted with an “R” followed by a number, e.g. R-4401. An example of a restricted area is Cabañeros National Park⁵⁹ in Montes de Toledo, Spain.

Finally, warning areas are similar in nature to restricted areas. This type of airspace region is defined by the AIM⁶⁰ as an area of defined dimensions, extending from 3 NM outward from the coast of the United States, containing activity that may be hazardous to nonparticipant aircraft [94]. The purpose of such areas is to warn nonparticipant pilots of the potential danger. Warning areas are designated with a “W” followed by a number, e.g. W-237. In Europe, however there is no such thing as “warning areas”, but instead they have “danger areas”. ICAO⁶¹ defines these as “an airspace of defined dimensions within which activities dangerous to the flight of aircraft may exist at specified times”. This is quite a broad definition and can include whatever the issuing state defines as a

⁵⁸ Camp David: formally known as the Naval Support Facility Thurmont; it is the President’s country residence.

⁵⁹ Cabañeros National Park: (in Spanish: *Parque Nacional de Cabañeros*) it is the best and largest surviving area of Iberian Mediterranean forest, with an enormous variety of plant species. It also includes sites of geological interest [95].

⁶⁰ AIM: Aeronautical Information Manual; the official guide to basic flight information and ATC procedures in the United States and Canada [96].

⁶¹ ICAO: International Civil Aviation Organisation; a UN specialized agency, established to manage the administration and governance of the Convention on International Civil Aviation [98].

danger. Common areas are military training routes/areas, live fire missile ranges, pistol/rifle ranges for military or police [97].

To avoid these areas, PAVs could, for example implement Geofencing. Geofencing is a virtual barrier created using a combination of the Global Positioning System (GPS) network and Local Radio Frequency Identifier (LRFID) connections, such as Wi-Fi or Bluetooth beacons. With a display screen on-board, the pilot/passengers could be able to see a virtual map indicating the areas to be avoided. For example, the company DJI ⁶² has launched a Geofencing system called Geospatial Environment Online (GEO) and offers users up-to-the-minute information when flight bans or limitations have been applied. This includes large public gatherings, natural disaster areas and other events which warrant restrictions. GEO's data also includes sensitive locations such as prisons, power plants and airfields to ensure the aircraft is not in danger of breaking the law due to a geographical misunderstanding. These areas are pinpointed in the map using different colours: green represents a Warning zone, yellow is for a Restricted zone and red for a Prohibited zone [106].



Figure 5.3: Example of the geofencing system GEO. [106]

⁶² DJI: Chinese technology company headquartered in Shenzhen, Guangdong with manufacturing facilities throughout the world [106].

5.3 **Airspace Safety**

Previously in this chapter, during the discussion on the legal aspect of the UAM and circulation of PAVs, there have been several references done regarding the pilot’s responsibility on ensuring the appropriate and stipulated separation between the PAV and other aircraft and obstacles. This comes along with the topic of safety and thus, traffic control.

5.3.1 **Air Traffic Management**

Air Traffic Management, ATM, is a term describing different services necessary to ensure a safe realisation of flights and of a controlled flow of traffic. ATM comprises two distinct, basic functions: one “regulatory”, in a broad sense, and the other “operational” [99].

The first of these functions involves setting broad objectives in terms of the safety, quantity, quality and price of the services to be provided and taking steps to ensure that they are met. It also involves the allocation of airspace to its various users, including military users, and all the measures needed to meet a wide range of other policy objectives to do with such issues as environmental protection, town and country planning, national defence and meeting international commitments [99]. Consequently, any business producing a PAV or any company operating this type of vehicle must be completely aware of the regulations established by the ATM so that all the parameters and functionality of the PAV is legally correct. The second function, the operational, is the actual provision of services, for reward, within the regulatory framework provided by the first function [99].

Nevertheless, as previously explained, the Volocopter 2X is not thought to rely on current ground-based ATC and, initially, should operate outside of the controlled airspace (like other models of the PAV). Despite the lack of ATC in this region of the airspace and effectively, the possibility of a compulsory pilot licence to fly the PAV, flying in the uncontrolled airspace ensures a lot of freedom and creates new possibilities. This set-up also calls for new procedures and a mature management system to enable frequent PAV operations of a safe manner in a comparably low altitude in urban environments (a concern which has already been presented in Section 5.2). This would also mean though, that PAVs would be excluded from certain parts of today’s airspace. In the mean time, NASA predicts that PAVs will be integrated into a future generation of controlled airspace [45], and a controlled airspace means ATM. The responsible body (and the only one allowed to do so) of developing a new generation of ATM is SESAR⁶³. The SESAR project aims at improv-

⁶³ SESAR: Single European Sky ATM Research.

ing the ATM performance by modernising and harmonising ATM systems through the definition, development, validation and deployment of innovative technological and operational ATM solutions [100].

For now, SESAR has released a plan focusing on the integration of drones into Europe's airspace, and to do that, a highly automated set of services intended to interface with air traffic control and enable routine missions will be developed. This set is what they call "U-space" [39]. Also, SESAR states that those UAS operating in urban areas will have more stringent requirements, e.g. accuracy and detect-and-avoid capabilities. This means that, with SESAR's aim of unifying the airspace and including UAS, regulations are being created and a set of requirements is being demanded for these new vehicles flying in the urban airspace. These requirements for UAS will probably affect PAVs too, as PAVs are vehicles aimed at operating in the urban airspace, e.g. PAVs will require sensors to observe the environment around them with higher updating rates and to send the data to the computers in which collision detection are already stored. Despite SESAR establishing stringent requirements for the integration of UAS in the urban airspace and thus, being strict with the integration of PAVs too, it is better that these regulations are set beforehand so that PAVs are designed and manufactured correctly, fulfilling the requirements, instead of being commercialised and then not being able to fly because of missing technology or instruments.

What seems imaginable for a future UAM with PAVs, or technically called PATS, is that the regulation of the "PAV airspace" will be intensified and expanded with increased traffic density. The example of Sao Paulo, a city with an intensive use of helicopters often referred to as the "world's helicopter capital", shows this evolvement of airspace regulations for helicopters. Until 2004, it had a more open structure and pilots coordinated themselves, later on it was developed into a much more regulated system with designated special routes and corridors [45]. In fact, initially the pilots worked with the local authorities to establish a series of main flight corridor, and they kept in contact with one another on an agree radio frequency. But now, Sao Paulo has a dedicated helicopter air traffic control system, with 13 dedicated helicopter air traffic corridors and triggered traffic collision avoidance system alerts [38].

Having mentioned the case of Sao Paulo, this leads to another issue, which is somehow delicate as it is external to the PATS, but affects the smooth and safe operation of this new transportation mode. These are external bodies who exert pressure on the system and as a reaction to this, new regulations might arise that affect the PAV operation. Recalling the example of Sao Paulo, residents living close to helipads or frequent flight routes com-

plained about the noise disturbance. Due to the social protest, a new regulation was established, but pilots imposed self-regulation on themselves to protect their business [45]. The Helicopter Association International's (HAI) Fly Neighbourly programmes (adopted in Sao Paulo by the ABRAPHE, the association of helicopter pilots) encourage the pilots and operators alike to adopt noise abatement measures, by, for example, training them to apply flight techniques that minimize the effects of helicopter noise emissions [67]. A similar solution could indeed be applied for PAVs if these ones caused noise disturbance that would cause to complaints.

The general questions for companies in the PAV industry, such as Volocopter, is regarding the corresponding ATM, the entity responsible for the safe separations of aircraft in the air, for the supply of essential information concerning weather, safety and navigation. Furthermore, it is important that it is studied how the delivery of these pieces of information and the execution of the separation task will be securely sustained.

If, however, PAVs are kept within the uncontrolled airspace and pilots do need indeed to take care of the separation task, a totally different approach can be installed. This concept is called "Free Flight" (FF), and it is characterised by being a direct route concept where the pilots, instead of the air traffic controller, are responsible for the separation assurance [45]. In FF, the air vehicles broadcasts information about their altitudes, positions, IDs, velocities, and maybe even about route intentions to all other ones via ADS-B (Automatic Dependent Surveillance-Broadcast) [109], a system which electronic equipment on-board an aircraft automatically broadcasts the precise location of the aircraft via a digital data link. This allows for real-time precision, shared situational awareness and advanced applications for pilots and controllers alike. These pieces of information can then be received and processed on board the aircraft's by an on-board system and displayed on a "cockpit display of traffic information" (CDTI) [45]. This shows the effect on the micro-level design of the PAV because the man-machine interface in the cockpit has to accommodate and be adapted to this new FF function. This is related to Chapter 4 where the PAV is analysed in isolation. On top of that, and focusing on the issues actually covered in this chapter, FF implies that, in the macro-level design, a set of rules and procedures are required to ensure an efficient and safe traffic flow. As it is said at the beginning of Chapter 5, both the micro and macro level designs are interconnected, and therefore require an accurate tuning to arrive at an overall acceptable solution.

The FF allows the aircraft to choose the routes [45]; this characteristic is called "direct routing", and seems to be optimal and allows the whole system of ATC to be decentralised. Nevertheless, in the case that laws are written and regulations are established during the

process of UAM integration, for to be FF installed, PAVs will be seen affected microscopically, as they will require the sufficient technology and systems (like ADS-B and CDTI) to be able to broadcast information about their altitudes, positions, identities, velocities, and maybe even about route intentions to all other ones.

A great advantage presented by the concept of FF is that pieces of information about position, velocity and intended flight route would be exchanged by the PAVs among each other and processed by on-board systems which would be responsible for detecting potential separation conflicts and areas with overloaded traffic or helipads beyond capacity [45]. That is, the vehicle itself would be carrying out the task of separation, not the pilot (nor the ATC).

Having reached this point, what can be assured is that the air traffic control and hence, safety manageability of the urban airspace, are certainly major tasks to be elaborated and tested for future PATS and the obtainment of UAM. In fact, Frost and Sullivan compare this problem with the analogy of “Gordian Knot ⁶⁴” [101] by stating that the duty of “Sense and Avoid” (S&A) depends on how the PAVs communicate with each other, i.e. the radio frequency, the ATM integration and the airworthiness certification standards. Figure 5.3 is a representation of this analogy, showing that the interconnection of rules for airworthiness certification, ATM, and the allocation of RF (radio frequency) bandwidths are located around the central “Sense and Avoid” issue.

5.3.2 Terrorism

One last concern on UAM and its corresponding safety aspects is terrorism. From the last decades (1961, with President Kennedy) until now, the hijacking of airlines has become a new mean for expressing political and social discontent. In fact, President Kennedy signed an amendment to the Federal Aviation Act of 1958 that made hijacking a federal crime and empowered special FAA personnel to carry weapons on-board airlines. Those laws were strengthened significantly following the terrorist attacks on September 11, 2001. Whether dealing with hijacking, terrorism, accidents, or environmental considerations, issues related to public safety rather than civil aviation per se drove legislation as the public’s need for air transportation grew [102]. Regardless of how aviation is governed, safety has always had and continues to have a profound impact. Ergo, no matter how UAM evolves, that there were always be laws to be considered in terms of public safety, and these, of course

⁶⁴ Gordian Knot: term commonly used to describe a complex or unresolved problem.

must be respected by PAVs, PATS, UAM technologies and all businesses involved in this innovate industry.

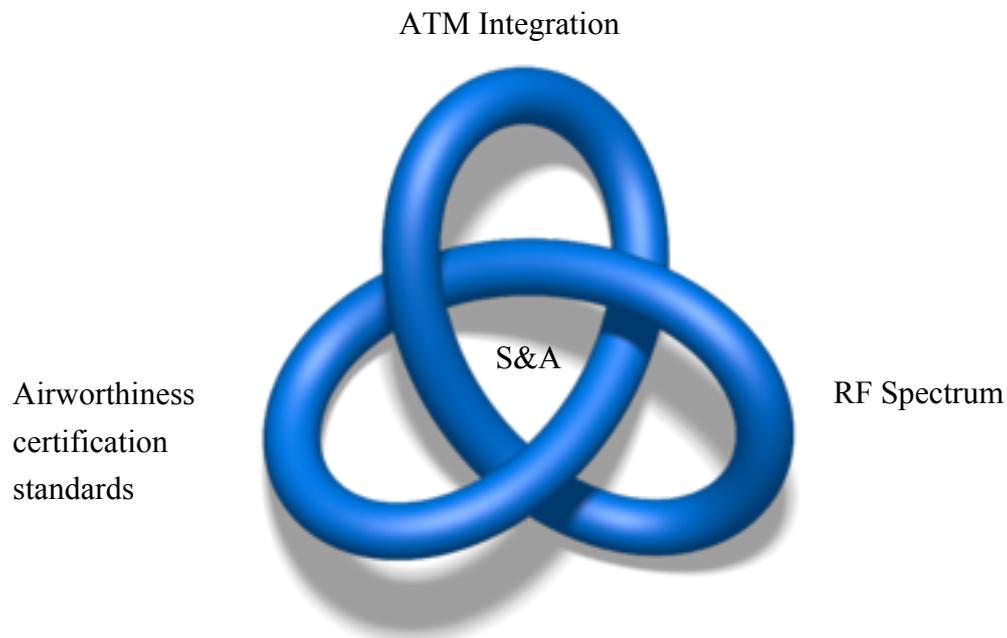


Figure 5.4: The Gordian Knot applied to the sense and avoid issue of PAVs. [101]

Given the complexity of the situation, where all parameters are interrelated and thus, the modification of one affects all others, it is essential that it is all done with the aim of achieving maximum security and safety. That is, the first thing to be done is to establish and impose a series of regulations and laws that ensure safety operations of PAVs, for example: certified pilot required, delimit the areas where they cannot operate (above schools, near helipads for hospitals), prohibit them to take-off and land on rooftops smaller than a certain height, or require a Sense & Avoid system to support the pilot and thus gain redundancy. When the integrity and safety is ensured, UAM will become more trustful and it will attract more customers. As the service becomes more popular, more dynamic, more used, the laws and regulations will be modified so that the operation of UAM and thus, PATS is more flexible. This will perhaps mean an increase in the degree of automation, the incorporations of a transponder and consequently a less experienced pilot. Independently on the path UAM takes in its evolution, the starting point of this complex situation is assuring safety and security by setting laws that “force” the PATS to be fully equipped to fulfil the demanded safety requirements.

6 Integration of UAM

As studied in the previous chapters, society, demographics and social demand of mobility have evolved in such a way that cities are in desperate need of a transportation mode that optimises urban space and does not impose an extra burden on citizens and the urban environment. At the same time, aviation technologies and concepts have reached a level of maturity to such a degree that some aircraft are already flying around and interacting with the urban airspace. This is the case of UAVs (commonly known as drone) or UASs, in more general terms. The combination of these two scenarios may soon enable an era of a concept previously introduced in this paper, the so-called Urban Air Mobility, fuelled by (theoretically) quite, efficient and largely automated aerial vehicles, known as Personal Air Vehicles, or PAVs.

However, successfully bringing such a system to fruition requires, not only a social adaptation, but also an environmental one. A social adaptation means the acceptance of citizens, which leads to users, i.e. customers, and therefore the success of UAM in the transportation market. To gain social acceptance, the UAM system has to follow stipulated and certain requirements, such as ensured safety, maximum noise emission levels, or controlled air pollution. For that to occur, the PAVs have to guarantee that they are designed in such a way that their structure, technical features and performance fall inside the established parameters. This restricts the design of the PAV, as manufacturers have to develop this aerial vehicle within a regulatory frame.

Beyond the social impact, UAM affects the environment too, and as said, integrating such a system requires an environmental adaptation. This includes the optimisation of the requested urban ground spaces when building the infrastructures required for UAM, to introducing orders-of-magnitude [103] more aircraft to a given airspace volume than can be accommodated by the traditional air traffic control system, among other important technical challenges.

It has been discussed in Chapter 4 the limitations and barriers that determine the specifications of the PATS, which includes everything related with both the vehicle and the infrastructures. Businesses involved in the industry of UAM can adapt their designs so that most of these restrictions are complied. Nevertheless, external bodies establish the laws and regulations described in Chapter 5 and these businesses cannot modify them. Besides, it is expressed in Chapter 5 how complex it is (or would be) for PAVs to be integrated in

the airspace, as it has to be ensured that these new aircraft types and their operation do not overly burden traditional airspace users and air traffic control.

6.1 Case Study

This chapter proposes a framework for integrating UAM hypothetically in a city, bearing in mind all the aspects and issues previously presented. Given the difficulties that come along with airspace integration, it seems reasonable to start with the analysis of this one and determine the legal parameters that affect UAM. Once this step has been completed the next step is to evaluate the technical and physical specifications of the PAV according to the legal framework established. This comes along with the determination of the take-off and landing areas, which are affected by the characteristics of both the PAV as well as the external laws imposed. Finally, this chapter proposes ways in which the reference PAV, the Volocopter 2X could be modified so that it could fit the hypothetical scenario, derived from the past successful and unsuccessful research efforts studied throughout this paper.

It is important to take into account that the possible process of integration of UAM in a city studied in this chapter, considers a large metropolitan area, as are the cases of the San Francisco Bay area and New York City. Also, assuming that the UAM will indeed be successful and will therefore be integrated in its plenitude, it is expected for the UAM service to offer 4 trips per hour, each carrying two passengers, over a 16-hour day. This scenario could support approximately 150,000 passengers per day, which would make it an important travel mode alternative to ground transportation, but it would still represent a large proportion of the overall transportation options available to the public (about 2% of the automobile trips take in the San Francisco Bay area per day). Given that this thesis is based on literature research about UAM, neither actual studies nor measurements have been carried out. Consequently, these figures have been borrowed by an evaluation of On-Demand Mobility Operations performed by the American Institute of Aeronautics and Astronautics (AIAA) [103].

Despite being figures obtained from an external study, these data seem quite reasonable in this thesis as first, the reference PAV used, the Volocopter 2X, has a capacity of two passengers and at MTOM, it can fly for 27 minutes with a cruising speed of 50 km/h [34]. This means that with two Volocopter 2X, each performing one round trip, 4 trips would be completed in 1 hour. It is very important that, whenever a PAV is being used, it is not generating a deficit to the UAM business/stakeholder. That is, that the cost of operating

one PAV is less than what is being earned from that operation. For that reason, this estimation of asset rotation assumes maximum occupation of 2 passengers per trip.

6.1.1 Airspace Integration Principles for UAM

As explained, the first step in this integration model is to analyse the airspace integration, as guaranteeing airspace integration improves the probability of success in obtaining the UAM goal. Considering all the aspects discussed until this point in the thesis, from chapter 2 with the social evolution and the increase in mobility demand, up to Chapter 5, with the legal parameters, the following five airspace integration principles for UAM have been derived:

1. Does not require additional ATC infrastructure
2. Does not impose additional workload on ATC
3. Does not restrict operations of traditional airspace users
4. Will meet appropriate safety threshold and requirements
5. Will allow flexibility where possible and structure where necessary

The above principles aim at the smooth integration of UAM in the airspace, but also in the society. They ensure that UAM does not introduce an extra burden, and even, that it improves the quality of lifestyle, a big concern in today's populations (as described in Chapter 2).

The first principle refers to the fact that the airspace integration concept should not rely on additional, centralized ATC infrastructure. The UAM aircraft fleet or its supporting network of services will have to provide the capabilities necessary to operate at significant densities, including accurate tracking of UAM aircraft, i.e. PAVs, locations and intent, and regulating the flows of UAM aircraft into take-off and landing areas. Closely related to this principle is principle number 2, that expresses that UAM operations should not pose an additional burden on ATC workload, a factor that already limits airspace capacity in many regimes [103]. Instead, the services traditionally provided by ATC to ensure safety and efficiency will be the responsibility of the UAM fleet, i.e. the PAVs' pilots or operators, and supporting network. Thirdly, no additional requirements, restrictions, or burdens will be placed on existing airspace users; the PAV will be strategically separated from traditional aircraft during the trajectory planning process. After that comes the fourth principle, which states that UAM operations will meet an appropriate level of safety consistent with

the public's expectation of commercial transportation, and the concepts, technologies, and procedures designed to support those operations will incorporate a safety threshold as a minimum requirement. Finally, the fifth airspace integration principle refers to the key goals of the UAM concept [19]: operational flexibility and efficiency, and the system will be designed to maximize these metrics while adhering to the safety requirements.

6.1.2 Airspace Integration Strategies for UAM

In order to follow the above principles, a strategy that determines how airspace integration will be approached, has to be designed. Given that the concept of UAM has not yet been fully implemented implanted in real life, there is no specific path that guarantees airspace integration. For this reason, below in this section, four different strategies are described, all of them with the same final goal: deploying PAVs, a significant amount that ensures business and service worthiness, anywhere in the urban airspace, including its navigation facilities and associated information, services, rules, regulations, policies, procedures, personnel and equipment [17, 103]. Although each approach grasps a different initial operating concept that is consistent with today's airspace regulations, they will all have frequently in common between one another, the technologies and procedures applied in each of their steps.

As it has been discussed in Chapter 5, there exists a main issue when it comes to the homogeneity between regulations regarding the certifications required by the vehicles that would deploy the service of UAM. Consequently, before any strategy is applied, a preliminary step is required, necessary to introduce the new type (or types) of aircraft and missions, which implies obtaining a certificate of authorisation [84, 103]. Such certificate should allow aircraft and operations that do not comply with all applicable regulations established by the aviation administrative bodies, to employ alternate systems, technologies, or procedures to ensure such operations are safe and do not reduce the efficiency of the airspace.

1) Automated IFR Operations

Chapter 5 describes the trade-off between the pilot certification requirements and the airspace management responsibilities. That is, the debate between who will be responsible for the separation task when UAM is integrated and PAVs are circulating around. Such approach is used by many airspace integration research entities, including NASA [102, 103]. This leads to the first airspace integration strategy, which consists of the evolution of the

roles and responsibilities of IFR ⁶⁵ aircraft or the ATC ⁶⁶ services that are provided to them. Some examples of these services that are relevant for UAM research include: controller advisory tools for the areas of Terminal Sequencing and Spacing (TSS) ⁶⁷, aircraft strategic and tactical separation, efficient trajectory optimization, autonomous aircraft operations for traditionally IFR aircraft, small aircraft transportation systems, and demand-capacity balancing [85, 103].

Given the rise in popularity of UAS in the last several years, the airspace integration research community has been engaged in improving airspace access for a variety of non-traditional aircraft, like in the case of UAVs, and their operations [84, 101]. This project has developed important aircraft-related technologies that have utility for UAM, and these include, for example, traffic displays, separation algorithms, and command-and-control communications radios [103]. Even though the goal of this effort is to make UAS operate in ways that are essentially the same as manned IFR aircraft, the technologies and functions necessary to do so could easily be used to allow the integration and circulation of PAVs.

One should take into consideration that UAS are not further studied in this thesis because they are not the focus point of the research. Instead, the evaluation of UAM systems is. Nevertheless, the research efforts and technologies on UAS (and on traditional IFR aircraft) along with their concepts can be extrapolated and adapted in order to obtain UAM airspace integration solutions. Some examples of these technologies are modelling and simulation infrastructure, algorithms, safety/capacity/efficiency metrics, and human-machine interfaces. Some of them have been previously considered in this paper, when analysing the limitations and requirements of the PAVs.

However, despite the advantages these technical proposals may present, their proposed increase in traditional IFR traffic volume ⁶⁸ (stated in Section 6.1.1) is occasionally quite

⁶⁵ IFR: Instrument Flight Rules.

⁶⁶ ATC: Air Traffic Control.

⁶⁷ TSS: Terminal Sequencing and Spacing; technology developed by NASA that determines where each aircraft should be to maintain their fuel-efficient, continuous-descent approach and indicates to air traffic controllers what speed that aircraft should fly [104].

⁶⁸ Note: the IFR traffic volume density is independent of the type of aircraft, it only matters how many aircraft are operating under IFR.

optimistic, and yet, as optimistic as these estimates are, they do not begin to approach the orders-of-magnitude increase in traffic density necessary to enable an economically viable UAM transportation system [103], i.e. PATS. Achieving the PAVs' airspace integration required for the implementation of a UAM system will require a different approach than this one described, which is founded, as said, upon the evolution of the roles and responsibilities of IFR aircraft or the ATC services that are provided to them. Instead, an approach that is not governed by IFR separation standards and capacity limitations has to be analysed.

2) Automated VFR Operations

The concept of VFR has been introduced in Chapter 5 and to be recalled, it is a set of regulations under which a pilot operates an aircraft in weather conditions generally clear enough to allow the pilot to see where the aircraft is going. These regulations offer a second starting point for the evolution of a PATS, opposite to the one with IFR; in VFR the pilot is responsible for seeing other aircraft and avoid a collision, whereas in IFR, the Visual Meteorological Conditions (VMC) have to be maintained, as the ground controllers deploy the separation task.

The main advantage of this strategy compared to the first one explained is, that although currently VFR flights are limited to operating in a subset of the airspaces and weather conditions available to IFR flights, they are not subject to the geographic traffic density limits of IFR flights. As mentioned, aircraft flying under VFR may also determine the allowable separation between themselves and other aircraft, ensuring that they remain, as stated in the General Operating and Flight Rules⁶⁹, “well clear” of and not operate “so close (...) as to create a collision hazard” with another aircraft [103]. When a pilot is onboard an aircraft, the size of that “well clear” region is a subjective judgment. The degree of autonomy from the existing ATC system provided by VFR operations may prove a better starting point from which to evolve UAM capabilities “forward” to greater operational access, rather than starting from the greater operational access of IFR operations and trying to “roll back” the operational restrictions (capacity limitations and separation requirements) by ATC functions.

⁶⁹ General Operating and Flight Rules: Title 14, Chapter I, Subchapter F, Part 91 of the Code of Federal Regulations (CFR).

Per contra, operations under VFR flights do indeed present some disadvantages, starting from the fact that they not operate in conditions where visibility is not available. That is, they may not fly in Instrument Meteorological Conditions (IMC) [86]. This arises the question of how difficult will it be to add capabilities to the PAVs that enable airspace access equivalent to that of IFR aircraft, given that UAM operations start by being conducted under VFR. For a better understanding of the advantages and disadvantages presented by each one of the flight modes applied to UAM, Table 6.1 summarises their operational differences. These are to be considered when deciding the starting point of UAM in terms of airspace integration.

To be able to answer such question, it is useful to consider the factors that contribute to accidents when such aircraft encounter IMC. In other words, what do VFR aircraft do when visibility is lost and control relies on the instruments? What circumstances prevent a VFR aircraft from operating in IMC? In the case PAVs fly under VFR, they will have to be able to deal safely with the following factors [103], factors that contribute to accidents when VFR PAVs encounter IMC:

- Inability to separate from other aircraft because of the loss or degradation of their see-and-avoid capability.
- Adverse weather in which the aircraft is not capable of flying (e.g. severe icing), and the inability of the pilot to aviate and navigate under conditions in which they cannot reference out-the-window objects, i.e. they do not have visibility.
- Controlled flight into terrain (CFIT) ⁷⁰.

The ability to operate in IMC is not the only distinguishing factor between VFR and IFR; many ATC services are provided to IFR aircraft unrelated to separation in IMC, such as, for example, sequencing and scheduling, and similarly a UAM system that started under VFR operations would need to provide many of those additional services. For example, ATC balances the demand for and capacity of the airspace through a variety of mechanisms and regulates the flow of aircraft in and out of those regions when necessary. When airspace is systematically oversubscribed, i.e. it has more applications than available services, aviation administrative bodies, e.g. the FAA or EASA, can define special airspace

⁷⁰ CFIT: when an airworthy aircraft under the complete control of the pilot is inadvertently flown into terrain, water, or an obstacle. The pilots are generally unaware of the danger until it is too late [105].

constructs, like arrival and departure routes, VFR transition corridors, and special flight rules areas to manage the demand and increase capacity [103]. Consequently, the UAM concept will have to consider how it will achieve these outcomes and how it will design new approaches when necessary.

	VFR starting point for UAM	IFR starting point for UAM
Advantages of VFR	No explicit ATC-imposed capacity constraints.	Severe capacity constraints.
	No ATC imposed separation standards.	Large separation requirements: 3 NM ⁷¹ in terminal areas, 5 NM enroute, 1000 ft. vertically.
	No ATC communication required in airspace Classes E and G.	ATC approval required for all flight plan changes.
	No flight plan approval required.	Flight plan submission and approval required before departure.
Disadvantages of VFR	May not fly in IMC.	Allowed to fly in IMC.
	Excluded from airspace classes B, C and D without ATC communications.	May fly in all airspace classes subject to capacity and separation constraints, additional limits in Class G.

Table 6.1: Summary of operational differences for UAM starting points. [103]

⁷¹ NM: Nautical mile; a unit of length. One international nautical mile is equivalent to 1,852 m.

3) Expanded UTM-like Services

UTM stands for Unmanned Aircraft System (UAS) Traffic Management [84], and as explained before, the technologies on UAS and all their corresponding management and operations can be extrapolated and adapted in order to obtain UAM airspace integration solutions. This brings this chapter to a next strategy, based on introducing the PAVs (or in general terms, the UAM aircraft) following the guidelines established by the UAS during these recent years, which describe a set of operating requirements distinct from either IFR or VFR [103]. Although the current scope of the UTM system is only focused on these small aircraft types operating in uncontrolled airspace (as it is described in Chapter 5), the concept it embodies may well provide a template for a new way of managing the operations of many types of future aircraft. For example, the freedom to operate those small aircraft (popularly known as drones), so as to avoid any interactions with manned aviation, may serve as an inspiration and/or aiding tool when installing UAM, and thus, integrating PAVs in the urban airspace.

The UTM system is described around the same five airspace integration principles described for UAM in Section 6.1.1. In particular, it provides the air traffic services necessary to safely and efficiently manage small UAS at low altitudes without burdening ATC or impacting traditional aviation operations. The central agents in the UTM architecture are the UAS Service Suppliers (USS), which provide demand-capacity balancing, separation, sequencing, data exchange, trajectory planning and other services to a variety of stakeholders including the UAS operators themselves and public safety [107]. In some cases, multiple USS can each provide similar services to UAS operating in the same airspace (e.g. trajectory planning), while in others a single USS should be responsible for a given airspace or constrained resource (e.g. separation, sequencing). The USS can provide these services because they depend on information collected by supplemental data service providers, which manage data related to weather, airspace surveillance, terrain, and other relevant aspects of the UAS operating environment [103].

The only two-way interaction USS' have with the other aviation services systems (such as NAS, in the United States, or EASA, in Europe) is through the Flight Information Management System (FIMS). The FIMS manages data flowing from the USS, including operational data and flight deviations that could impact the NAS, and sends constraints and directives to the USS for distribution to appropriate operators. The USS may also incorporate NAS data sources directly, for example those contained in the system-wide information management system [103]. The UTM architecture has the benefit of allowing public or private interests to develop USS that does not rely on government investment, and

thus is able to be more responsive to the need of users and to take advantage of technological improvements. Bearing in mind the social expectations and the high demand on urban mobility, being able to satisfy the customers'/users' needs is an essential characteristic UAM aims at. Consequently, extrapolating the described aspects of the UTM service onto UAM could potentially be very useful in terms of airspace, social and urban integration.

The UTM system is essentially an ATC system that runs in parallel to the traditional system but serves a different class of aircraft. While in principle UTM could apply to any aircraft, two fundamental differences exist between the vehicles intended to operate in UTM and those of UAM. In other words, between UAVs and PAVs, respectively. First, and the most obvious one, is the fact that people will be on board the PAV, and second, PAVs will be interacting with other aircraft in controlled airspace to a much greater degree than UAS do under UTM (because UAS largely operate in uncontrolled airspace at altitudes under 400 to 700 ft. (122 m to 214 m, approximately), while PAVs will operate between perhaps 1,000 and 3,000 ft. [103]).

The advantages of using a UTM system are similar for UAM and UAS: they reduce the requirements on individual aircraft and therefore lower the barriers and costs for accessing the airspace. Opposite to the case of UAS, where they simply cannot perform all functions required for airspace integration because of size, weight, and power limitations, PAVs, would indeed be able of providing most of the required airspace integration functions (e.g. under VFR). However, they would need significant additional equipage and capabilities to operate at higher traffic densities, capabilities that would likely make them economically impractical [103]. Further, if the UTM system manages to run safety-critical airspace integration functions separately from the aircraft, this could be used in the PATS so that no pilots are on-board. Eventually, in conjunction with advanced vehicle automation, several pilots in a command centre may manage a fleet of PAVs to intervene in contingency situations, further lowering the costs of UAM operations and improving the scalability⁷² of the system. This is interconnected with an issue discussed before in this thesis: the pilot certification required to fly the PAV, which essentially has an effect on the available users end ergo, market success. If PAVs are able to guarantee safety without the necessity of the passenger to be licensed from a flying academy, this lowering of requirements will attract

⁷² Scalability: the scalability is the capability of a system to handle a growing amount of work, or its potential to be enlarged to accommodate that growth.

more customers, as less time and money will be needed (no investment in pilot certification) to operate this vehicle.

Nevertheless, it has to be reminded that UAM will require services that UAS do not: sequencing, scheduling, and spacing into capacity-constrained take-off and landing area, and trajectory planning that includes wake avoidance criteria [103]. Even for those services that will be common, the PAVs' safety thresholds and robustness to incidents will be significantly more demanding, due to the fact that PAVs will be carrying passengers, and UAVs do not (hence their denomination of "unmanned").

4) Synergising the Airspace Integration Strategies

Given that the strategies covered until now all have their strengths and weaknesses, it is therefore reasonable to believe that the best approach to enable a UAM air transportation system, i.e. the PATS, is likely to make use all three of these previously described airspace integration strategies. The best way to understand and gain the notion of how these three strategies are combined together is by a visual representation. This helps to determine the most optimum strategy by identifying the region in which most of the advantages of each strategy act simultaneously. Figure 6.1 offers a graphical sketch of the contribution of each airspace integration strategy to PATS (and effectively UAM) as a function of density. It is to be reminded that density is an important factor to be considered, because it is what initially determines the worthiness of integrating UAM in cities, in terms of market share and business profitability. Such minimum density means more air traffic to be controlled and managed, and social and environmental impacts to be considered and take care of.

As shown in Figure 6.1, the starting point is the use of VFR operations because those operations can be conducted today; as explained, they allow aircraft to take responsibility for their own separation, sequencing, and trajectory planning functions, are free from existing ATC capacity limitations because they do not burden that system when PAVs density is low, and are relatively inexpensive because they require no new aircraft equipment. The development and deployment of new technologies and infrastructure will enable phases of UAM operations with successively higher traffic densities and less reliance on rigid procedures and airspace constructs [103].

While the starting point of VFR operations for ODM has a number of important characteristics, it is not a long-term solution because of safety and scalability limitations. It can be appreciated in Figure 6.1 how the curve corresponding to the VFR, i.e. the procedural strategy (represented in green), starts high above on the y-axis when Time (x-axis) is zero. However, as time starts to increase (a displacement towards the right-hand side on the x-

axis), the green curve starts to gradually drop. To solve this issue, the functions provided by the pilot's vision and judgement in VFR (e.g. separation from other aircraft, terrain, obstacles, and weather, i.e. IMC) can benefit from the use of advanced on-board technologies to increase safety and aircraft density while relying less on airspace structure and other procedural mitigations. Responsibility for aircraft operations will continue to lie with the pilot and vehicle systems and not with ATC. The safety and density of UAM operations will increase significantly in this phase, but the increased cost of each PAV will be in proportion with those benefits. Therefore this is not the long-term solution for UAM either.

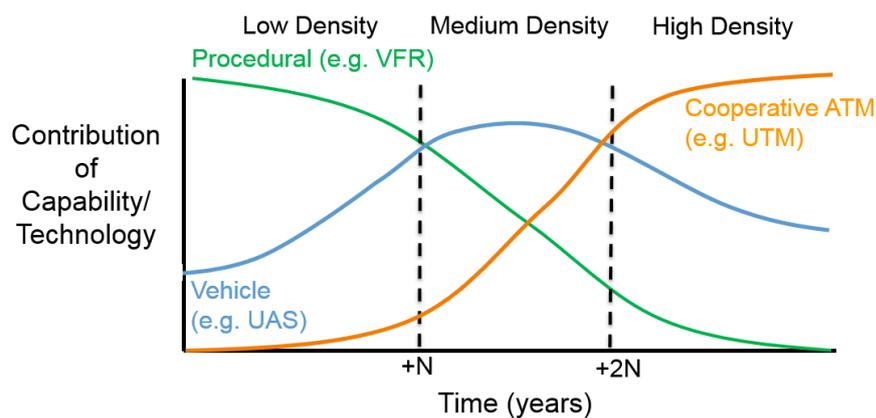


Figure 6.1: Contributions of different airspace integration strategies as a function of PAVs density. [103]

Although the addition of vehicle technologies will enable greater density of the PAVs in the medium term, the additional equipment costs for each new PAV will limit the economic viability of the overall concept. This is why the blue line in Figure 6.1, corresponding to the vehicle (traced in blue), shows a maximum point around the middle of the Medium Density region, and drops from that point onwards, entering the area of High Density with a negative gradient.

Meanwhile, as systems like UTM and their manned aircraft equivalents mature, investments in that infrastructure will partially relieve individual aircraft of the requirements to equip with sensors, algorithms, displays, and their associated flight-rated hardware (backup

capabilities will still be required [103]). Instead, a robust communications capability will allow networked infrastructure to provide these services, lowering the marginal cost ⁷³ of adding aircraft to the system [103]. This evolution is shown in Figure 6.1 with the orange line, which slowly grows initially, as the UTM system first has to mature to show its benefits, but then increases its gradient as it enters the Medium Density area.

A second important advantage of having such a safety-critical communications capability and off-board air traffic services is that the pilot will no longer have a compelling reason to be located on the flight deck. Instead, remote command centres will allow humans to oversee the largely automated aircraft and intervene only when contingency procedures warrant. Procedural approaches to higher airspace densities will largely disappear except to provide continued service for traditional airspace users. This reliance on a matured, human-rated UTM-like system should greatly lower the marginal cost too of additional PAVs and operations. This not only facilitates the airspace integration and production of PAVs, but also the accessibility for users to this innovate service provided by the UAM and PATS.

To summarise the first step of the integration of UAM, the integration in the airspace, the last approach proposed above based on the synergetic combination of three integration strategies is described as evolutionary rather than revolutionary, and this is due to several reasons. First, the key difficulty of airspace integration is that it requires interoperability with all other airspace users, a requirement that is relatively unaffected by the degree of autonomy of an individual PAV (a topic discussed in the previous paragraph). Instead, the required degree of interoperability depends on where that aircraft would operate and which aircraft also plan to use that airspace [103]. Secondly, a highly automated PAV could remove the need for some externally provided airspace services. However, such air vehicle it is expected to be more expensive than will be required when a large number of PAVs are operating, i.e. when there is high-demand UAM. Finally, attempting to completely automate an PAV without relying on a human pilot or external air traffic services may unnecessarily re-invent well-defined airspace integration capabilities and make the PAV more difficult to certify. For these reasons, an evolutionary, incremental approach is preferred over reliance on a revolutionary approach.

This means that there is no exact and specific strategy that will integrate UAM, but a combination of strategies. However, as a starting point, it seems reasonable to propose by

⁷³ Marginal cost: the cost added by producing one additional unit of a product or service.

integrating PAVs in the airspace as a VFR aircraft, which includes some technology from the UAS, like for example Geofencing and a GPS to calculate the optimum routes avoiding the areas where they are not allowed to operate in. This way, not only will they be safer, as the pilot will be supported by on-board instruments, but also, they will be more adapted for when the density increases and they cannot be any longer operated as VFR. Because they will have already integrated in them some instruments, the investment on new technology, for example on the integration of a transponder, will not be so significant. Besides, an increase in density means an increase in the demand of the UAM service, which means clients and thus, profit. For this reason, when the technological adaption in PAVs takes place, it will mean that UAM is a successful transportation system.

6.1.3 Enabling Capabilities

As explained in the previous section, the approach or strategy to enable UAM airspace integration will begin with a level of airspace autonomy established by the precedent of VFR operations and will evolve with technologies focused on the vehicle, i.e. to improve or adapt this one technologically, towards a UTM-like system. Given this situation, there are several capabilities that consequently apply to UAM and thus determine how this one will be implemented and operated. These capabilities are described in this section.

1) Airspace Constructs

Airspace constructs are broadly defined as a set of procedures, equipment and operating requirements, and training standards used in the traditional ATC system to improve operational safety and efficiency and accommodate certain limiting characteristics of the aircraft and ATC equipment [103]. For example, airspace classes (previously introduced in Chapter 5) have been established to differentiate the densities and types of operations contained within them and compensate for the limitations of aircraft and ATC systems and personnel. As said, Class G, the class covering the low-altitude uncontrolled airspace, is not covered by ATC radar and so no IFR services are provided. This means that these types of airspaces are largely restricted to VFR traffic. Per contra, airspace above 18,000 ft. (around 5,500 m), i.e. Class A, is primarily used by jets flying at high speeds, speeds that make the pilot's use of see-and-avoid for separation impractical, and therefore VFR aircraft are prohibited from operating there. This means that during the initial implementation of UAM, as PAVs will be operating under VFR, they will fly in Class G. That is PAVs will fly below 14,500 ft. (4,400 m) MSL⁷⁴. New airspace classes are unlikely to be defined for PAVs, though in

⁷⁴ MSL: Mean Sea Level.

the long term, UAM operations and concentrations may be sufficiently different from traditional users, and as a result of this, it can happen that the UAM airspace access gets standardised.

2) Sequencing, Scheduling and Spacing

When the demand for a take-off or landing area, for a PAV corridor⁷⁵, or for other limited airspace resource exceeds its capacity, it is necessary to regulate the flow of PAVs accessing that resource. Nowadays, such process is done by implementation procedural and operational requirements, for example, requiring voice coordination with an ATC tower at a controlled airport and recommending communication over a common traffic frequency at an uncontrolled airport. In more complicated situations, such as during arrivals into the urban terminal area airspace, the flow is regulated by human controllers using sequencing, scheduling, and spacing algorithms [103]. This approach, which is used with VFR aircraft today, will be applied to PAVs when these get initially implemented, and will be able to satisfy the safety requirements as long as the take-off and landing areas are used occasionally. For those areas in which there is a higher traffic density and aircraft routinely require access, it will be necessary to have a positive control⁷⁶. Because the airspace integration principle is focused on minimising new ATC infrastructure, such positive control will be based on the application of algorithms for automated sequencing, scheduling and spacing.

For UAM it is important that this set of algorithms is centralised, so that it is aware of the overall traffic situation, and therefore can make reasonable decisions considering the preferences of all UAM users.

However, this initial human control will evolve as UAM matures and consolidates. With time, it is expected that more and more PAVs will operate around the urban airspace in a dynamic and agile work manner. To achieve this, waiting times for clearances from human controllers have to be reduced, if so, extinguished, and the way to do that is by incorporating technological instruments and computers that control the entire PAV network. These instruments can be TCAS and thus transponder (as mentioned in Chapter 5), to detect other

⁷⁵ Corridor: region of airspace that an aircraft must remain in during its transit through a given region.

⁷⁶ Positive control: the Air traffic control practice of controlling aircraft whose positions are determined by direct radar observation.

PAVs in the vicinity and thus know whether it is safe to land or take-off at that moment, or GPS, to calculate the most optimal route, even considering the traffic density

3) Separation from other Aircraft

One of the most fundamental functions of ATC is to ensure that aircraft maintain appropriate separation so that the probability of collision is reduced to an acceptable level. Besides the ATC, it is also responsibility of all pilots, regardless of the flight rules under which they are operating. While the requirement to “see and avoid” other aircraft has been regarded as sufficient for VFR aircraft separation in most circumstances, the limitations of that capability are responsible for a variety of mitigating procedures and equipment requirements. As said, PAVs aircraft will be subject to those same requirements from the start, because they will initially fly under VFR. However, as time and UAM evolves, the popularity of UAM and thus the demand for PAVs will (hopefully) increase, resulting in higher PAV densities. PAVs flying in these densities will probably require additional procedural and technological solutions in order to successfully separate from aircraft.

Like VFR flights, PAVs will initially be equipped with ADS-B⁷⁷. By being integrated in a PAV, the ADS-B allows the PAV to determine its position via satellite navigation (typically GPS), broadcasting it periodically and enabling it to be tracked. This is highly linked to the instrument requirements mentioned in point 3: by the PAVs being able to communicate with one another via a surveillance system, they can organise the entire network so that they all maintain the safety distances, they all perform the landing and take-off manoeuvres correctly and they are all aware of when a PAV is landing or taking-off. This way, the other PAVs can approach the area appropriately, or if possible, avoid it.

Nevertheless, ADS-B does present some disadvantages, and these are mainly related to the dependency on the navigation satellite system. This one could be corrupted or hacked, leading the issue of cyber-security, or damaged. Damaged means it could be working improperly, and thus transmitting wrong data to the APV network, or simply not working at all and providing no signal. Unfortunately, this scenario is very complex as it means reparation time in which no PAVs would be able to operate and cause a big loss of money, customer dissatisfaction and probably, loss of trust after seeing a system collapse.

⁷⁷ ADS-B: Automatic Dependent Surveillance-Broadcast [109].

4) Separation from Obstacles

Probably, the most challenging separation problem for aircraft flying to non-traditional take-off and landing areas is ensuring that they avoid obstacles during low-altitude arrival and departure flights. This happens, primarily because at low altitudes, such obstacles are far more common than aircraft. For this reason, it is essential that PAVs are equipped with on-board direct detection of local obstacles.

5) Separation from Terrain

Given the fact that PAVs are aerial vehicles with the goal of operating around the urban airspaces at low-altitudes, being able to keep up and ensure terrain avoidance is a critical safety function. In general terms, it is critical for PAVs and for any UAM air transportation system. Nowadays, there are already terrain advisory systems, such as the GPWS⁷⁸ and the TAWS⁷⁹ [103]. If these are combined with synthetic vision⁸⁰, they can reduce the probability of controlled flight into terrain. However, for that to happen, they need direction human action to follow recommendations. Some systems deployed on military aircraft, have already been adapted and flight-tested for UAS, like it is the case of the Automatic Ground-Collision Avoidance System (auto GCAS). This one could be adapted for PAVs too, meaning that a technological solution to the problem of terrain separation could be available.

6) Wake Avoidance

Aircraft wake turbulence hazards for small VTOL aircraft are of particular importance, especially in some situations such as close-proximity flight during approach and departure operations, close-proximity operations in the immediate vicinity of take-off and landing areas or even during encounters with non-UAM aircraft wakes. Despite the great range of proposed designs that currently exist for PAVs, as seen in Chapter 3, most of them feature the VTOL characteristic, and because the reference PAV in this thesis is a VTOL vehicle too, these situations in which wake is of significant importance, must be truly considered.

⁷⁸ GPWS: Ground Proximity Warning System

⁷⁹ TAWS: Terrain Avoidance and Warning System

⁸⁰ Synthetic vision: computer that uses 3D to provide pilots with clear and intuitive means of understanding their flying environment.

Given that helicopters are VTOL vehicles which also interact with the urban airspace, the rules applied to these in order to avoid wake (and also to ensure a minimum safety separation), can also be applied to powered-lift type VTOL PAVs. For operations such as vertical take-off, landing, and hover, the general recommendation for conventional helicopters to mitigate rotor wash⁸¹ hazards is to maintain at least 3 rotor diameters of separation from other airborne rotorcraft [103]. This is to avoid the blade vortex interaction (BVI), a phenomena that occurs when a rotor blade passes within a close proximity of the shed tip vortices from a previous blade. BVI is particularly significant in low speed descending flight condition (as it generates high amplitude impulsive noise) and this is a big issue because it is the moment of the flight near the helipad and thus, near the buildings. However, if the PAVs equipped with a rotorcraft have a higher disk loading compared to helicopters, this can result in increased rotor wash velocities and thus, the applicability of this rule should be evaluated: a factor to determine the speed and size of each rotor as well as the distance between them.

7) Trajectory Planning

An automated system will be required to plan an “optimal” trajectory for PAVs from origin to destination while respecting airspace rules, avoiding other aircraft, meeting a scheduled time of arrival, and conforming to PATS and UAM requirements. Today, the current procedure for creating and filing a flight plan may take a VFR pilot several hours [103]. This is something that cannot happen in UAM, as the operations and organisation of these have to occur fast enough to provide a dynamic service for the citizens/users.

A rapid planning process for UAM trajectories will provide a PAV with a feasible route of flight, all considering the traffic at that time, the availability of take-off and landing sites, the weather conditions, etc. This fast route calculation plays also an advantage for the user, as it will be able to inform him/her of the route, time and flight conditions rapidly. Again, because society is becoming more and more demanding when it comes to mobility, the awareness of the flight situation as well as the fast dynamic, are both two important factors that affect the social satisfaction.

Ideally, the user will select via a human-computer interface, the origin and destination of the route. With trajectory optimisation algorithms, the shortest and fastest route will be calculated, selecting the nearest take-off spot to the origin and the closest landing site to

⁸¹ Rotor wash: vertical down wash of air that becomes a surface wind [108].

the destination. However, this will work if the trajectories of all the PAVs are planned jointly rather than individually optimising them. This way, the number of available PAVs, the capacity and traffic at each take-off and landing site, the congested air routes, etc. can all be established and therefore, operate and manage the PATS (and potentially the UAM) efficiently. To be able to carry out this method, it is vital that PATS have great access to electronic information and to achieve this, one possibility can be that PAV operators, or UTM-like services, build databases of information about the state of the airspace.

One possible way of achieving this is again by equipping the PAVs with GPS and a transponder. With these instruments, one PAV would know the traffic density and distribution in its vicinity, and taking these two factors into consideration, an optimal route could be calculated, avoiding the most congested areas and arriving to the destination as soon as possible in an efficient and safe manner.

8) Take-off and Landing Areas

UAM operations must originate or end at dedicated take-off and landing areas. However, at this point, these have not yet been selected, as the UAM service has not been integrated in real life. The selection of these areas is quite complex, as it must consider the interplay between the locations of these, the design of the UAM airspace and the definition of airspace access requirements.

The choice of take-off and landing areas is quite complex as it has many aspects to be taken into account. For example, one issue to be considered is the proximity of these areas to each other. For the user, this is indeed an advantage, as if one of these areas is inaccessible or unavailable, he/she can simply go to the take-off and landing area next to it. However, having two take-off and landing areas next to each other, e.g. each one on a rooftop of neighbour buildings, affect the approach/departure procedures, the Sequencing, Scheduling and Spacing processes as well as the separation requirements. Again, building a network in which PAVs are constantly communicating with one another, knowing their respective positions, can facilitate these functions and speed up the system operations.

Also, the site selection of these areas should consider the impact on the airspace, so that no airspace classes are disturbed by the PAVs operations. This could be the case, for example, the case of a city with an airport near by, with airplanes flying close during the final ap-

proach⁸²; locating a take-off and landing area in the region near the final approach would be very risky.

Beyond these aspects, it is also complicated to establish where the PAVs can land and take-off because of community noise concerns. However, this can be solved by adapting the rules applied for helipads constructed on rooftops around the cities. Or even, helipads could also be used as take-off and landing sites for PAVs. It must be said that PAVs are aimed at being less noisy than helicopters, due to the integration of electric propulsion and smaller rotors. In the case of the Volocopter 2X, it produces 80 dB during climb and 65 dB at 75 m distance, whereas a conventional helicopter, a R22, produces 90 dB during climb and 82 dB at 75 m distance [33]. Yet, helicopters are socially accepted in urban airspaces. In fact, such is the acceptance that each time more and more people are using helicopters as a short-distance transportation medium in cities like New York City, Los Angeles and Boston. The aviation company BLADE allows users to create their own crowd-sourced flights or purchase seats on pre-existing flights with a mobile platform; it is described as the “Uber for helicopters” and in three years, since its inception in 2014 until 2017, the company’s total funding totalled already \$44 million [111]. This proves how popular the service is, despite the helicopters’ noise emissions. Analogously, by PAVs offering a similar service but in a cleaner and quieter manner should attract the exigent customers even more. Above that, locating take-off and landing areas on rooftops is that they are highly accessible to citizens, as the buildings are already within the urban streets. Besides, tall buildings usually include security guards, and security is an essential requirement in UAM. Starting from the point in which security is already installed in this infrastructure does indeed offer a step ahead.

9) Other Considerations

A significant number of other airspace integration considerations exist in the development of a worthy, feasible and safe UAM system, but they are out of scope for this paper. Important issues to address in the future include airspace flow management, all-weather and night-time operations, community impact (noise, privacy, public acceptance, etc.) and

⁸² Final approach: the last part in an aircraft's approach to landing, when the aircraft is lined up with the runway and descending for landing.

many other specific technologies required for enabling this air transportation system described in this thesis.

6.2 Improvements on the Reference PAV

6.2.1 Overall Scenario

It was previously mentioned that to enable UAM airspace integration will begin with a level of airspace autonomy established by the precedent of VFR operations and will evolve with technologies focused on the vehicle, i.e. to improve or adapt this one technologically, towards a UTM-like system. This initially sets some minimum requirements that the PAVs, the PATS and the users have to fulfil.

In the case of the users, despite aiming at a full automation of the vehicle, they will initially require a pilot certification because PAVs will be considered as VFR aircraft. In previous chapters of this thesis it is explained that this requirement might reduce the initial social demand or hinder the social acceptance, but it is also explained how PAVs can be flown by, for example, pilots looking to complete certain flight hours.

Regarding the PATS, it is very important that the traffic is controlled and efficiently managed to avoid collisions, ensure safety and achieve a dynamic operation of the service (short waiting times, no queues in take-off and landing areas, etc.). For that, it is important that the set of algorithms for sequencing, scheduling and spacing is centralised in order to be aware of the overall traffic situation. Also, with PAV operators, or UTM-like services, building databases that enable PATS to have electronic access to flights information, an optimised trajectory planning can be achieved, and hopefully, long waiting and operating times can be minimised.

When it comes to the PAV, the vehicle itself, it has to be certified as a VFR aircraft. This means it has to have the corresponding technological equipment and fly within certain altitude limitations and distance restrictions. Because they will belong in Class G, they will fly below 14,500 ft. (4,400 m) MSL, and according to the VFR flight rules, they will stay more than 500 ft. (around 152 m) away from any people or anywhere people might be expected (vehicles, vessels or structures) [77]. In terms of the speeds limits, below 10,000 ft. (ca. 3050 m) in classes F and G, the maximum allowed velocity is 250 kt. IAS ⁸³

⁸³ IAS: Indicated Airspeed.

(around 460 km/h). Besides, the PAVs have to have ADS-B on-board in order to maintain the safety distance between them and other aircraft, as well as on-board direct detection of local obstacles, to avoid the collision with other obstacles, and terrain advisory systems, to avoid terrain collision.

Finally, PAVs need take-off and landing areas, which have to be secured, at locations where PAVs can have access to, and be operated together with the PAVs trajectory planning process to ensure an optimised flow and service. Besides, they have to be well indicated so that it is easy for PAVs to detect them easy enough, ensuring safe landing manoeuvres.

6.2.2 Volocopter 2X 2.0

Before establishing the minimum requirements for the PATS and to initialise the integration of UAM, the Volocopter 2X was selected as the reference PAV in this thesis. In the hypothetical case of using this model as the PAV to carry out the service of UAM, there could be some modifications to be done in order to ensure the entire fulfilment of these established rules.

The Volocopter 2X is designed to satisfy the users as much as possible, and make it as easy as possible for them to use. However, as it has been seen throughout the entire paper, there are many factors that are interconnected in UAM and consequently, most of the times, when establishing parameters for the integration of UAM, many trade-offs arise between, for example, pilot certification and user accessibility. For this reason, some aspects of the actual Volocopter 2X have to be adapted in order to make this vehicle suitable for the hypothetical scenario, probably at the expense of other parameters, such as minimum, if at all, pilot certification.

From Chapter 3, the Volocopter 2X's design specifications can be recalled; it is a VTOL rotary wing aircraft certified as a light-sport multicopter. This type of aircraft has to fly under VFR, meaning that an initial possible integration of the Volocopter 2X would be possible. The Volocopter 2X has an MTOM equal to 450 kg, which is appropriate compared to the weight of helicopters. That is, for flying above urban spaces, landing at and taking-off from helipads or similar, and being operated as VFR, a weight of 450 kg is tolerable, as it is much lighter than that of helicopters. However, as the UAM system evolves and PAVs get to be operated by a UTM-like system, the vehicle will require equipment for automation, implying an increase in weight, but at the same time, because it will be more integrated in the urban airspace, it will require a lower weight due to safety

reasons. Consequently it is believed that although 450 kg to start off seem reasonable, lowering this value now at the beginning, will facilitate future modifications.

Moreover, the Volocopter 2X has a diameter of the rotor rim of 9.15 m, including propellers. If the aim were to have a couple of these flying around the urban airspace, this dimension would be manageable because the infrastructures to store them would not need to be very big, or not many would be needed. The same applies to the take-off and landing areas: if these ones were not often used, it would be fine for the Volocopter 2X to measure this. Nevertheless, for a financially worthy integration of the UAM, a significant amount of PAVs have to be operated. The bigger these are, the larger the required infrastructures will need to be and thus, the higher the economical investment. Beyond that, the social and environmental impact is larger and more noticeable if PAVs are big robust aerial aircraft rather than subtle flying vehicles. For this reason it is proposed that the Volocopter reduces this diameter or rearranges the rotor in such a way that its size is minimised.

In addition, the Volocopter 2X can reach a cruising airspeed of 100 km/h, which is an airspeed below the speed limit for flights below 10,000 ft. (ca. 3050 m) in Class G. As both the altitudes of service ceiling and hovering for the Volocopter 2X are below 10,000 ft. (2,000 m and 1,650 m, respectively), this parameter is acceptable. Notwithstanding, to achieve this speed, the Volocopter 2X counts with 18 propellers and 9 batteries, which all produce a noise level of approximately 65 dB(A) at 75 m. In this chapter, no exact parameter has been established for the maximum noise emission level, but for a noise level to be considered as acceptable to communities, it is required for it to be more on the order of 55 dB(A) [17]. Ergo, this paper suggests that the Volocopter 2X should reduce its noise level so that it effectively blends into the background noise. This could be done by, for example, relying more on the electric propulsion and generating more power with the batteries and reducing the number of rotors.

Also, the flight control system of the Volocopter 2X presents many advantages that might initially not be very relevant, but as UAM evolves and more automation is required in the PAVs, they will play an important role. Because the Volocopter 2X is aimed at the user and at its automatic control, it presents many features to ensure safety and an easy manageability. It disposes of gyroscopes, acceleration sensors, magnetic field measurement sensors, and manometers, as well as one triple redundant primary flight control unit and one simple joystick for an interactive one-hand control. Despite the possible sufficiency as these, as mentioned in Chapter 4, the vehicle should have safety measurements to protect these systems and instruments from possible cyber-attacks.

Besides, Volocopter has designed the Volocopter 2X in such a way that extra features can be integrated and assimilated, such as “sense and avoid”, GPS point tracking, and even air traffic management (including UTM) to coordinate autonomous Volocopter fleets [34]. This possibility of additional equipment facilitates the adaption to the evolving UAM, and thus makes the Volocopter 2X a good candidate.

Last, but not least, the Volocopter has designed the infrastructure necessary to operate and scale the UAM service, already with the intention of growing and becoming a full network system spanning over mega cities. Such infrastructure is composed of Volo-Hubs and Volo-Ports [33] and it can be appreciated in Figure 6.2. The Volo-Hubs resemble cable cart stations with Volocopters 2X landing and taking off, and once landed, the Volocopter 2X is moved inside the Volo-Hub. Theoretically, battery packs will be swapped automatically in a protected area by robots before moving on to the section, where passengers embark for take-off. According to the German company, “Volo-Hubs are the key to substantially increase the capacity of any Volocopter system. Aside from protected deboarding and embarking, they offer sufficient space to park all Volocopters in operation and provide the infrastructure for charging and maintenance.” The advantage if this is that by the use of computers and robots, the control and operation of PATS, i.e. both the infrastructure and the vehicles, will be optimised. However, this means a high economical investment. To solve this and as a starting point, existing heliports could be used as a Volo-Port with minimal modification. Yet, it is believed that the infrastructure proposed by Volocopter should not be denied, but saved for future applications, once UAM is deeply integrated and laws and regulations for this type of mobility have been well defined and specified.

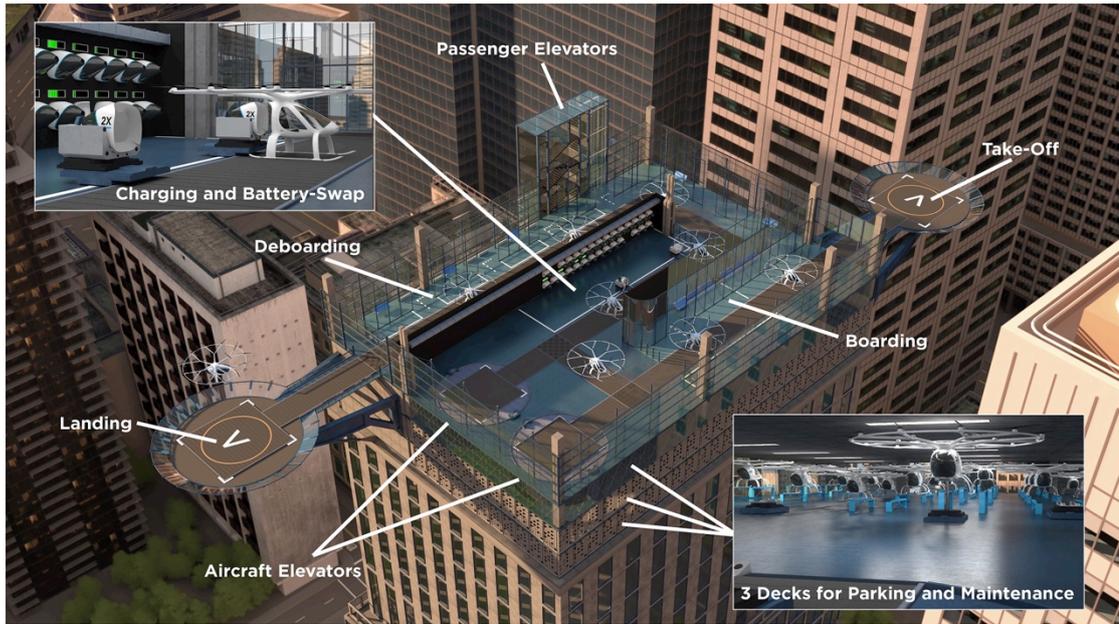


Figure 6.2: Infrastructure to integrate and scale UAM. [33]

7 Summary and Outlook

This thesis describes the necessity of reinventing urban mobility and proposes the solution of Urban Air Mobility (UAM). By bringing together all the topics researched until today related to UAM, it synthesises all the aspects that have to be considered when evaluating the potential integration of UAM.

The main elements analysed are, firstly, the vehicle that would carry out the service of UAM, i.e. the Personal Air Vehicle (PAV), including its characteristics, i.e. roadability, take-off and landing capability (VTOL, CTOL or ESTOL) and type of propulsion (fan, propeller, rotor or jet). Secondly, the socio-economic factors and challenges that could possibly be experienced by both the vehicle and its required infrastructure, i.e. the entire Personal Aerial Transportation System (PATS). These are, the guarantee of safety in different aspects (e.g. bad weather conditions, cyber-attacks), the achievement of an environmentally friendly design (e.g. noise levels, energy consumption) and also the technical and operational limitations that exist regarding the automation of the PAVs and the infrastructures required by these. The third element analysed is the laws and regulations that would be applied in the implementation of UAM and operation of PAVs. Taking into all these aspects, a series of strategies are proposed in order to integrate UAM in a hypothetical city. Given the complexity of the problem, an initial point is suggested, in terms of the state of the airspace regulation and the requirements of the PAV at the moment of initially implementing UAM. Considering safety and security the most important parameters, the initial point is such as to guarantee these two by proposing that PAVs are integrated in the airspace as VFR aircraft (as they would fly in the urban environment at low altitudes and thus in the uncontrolled airspace), but also include technologies required for UAS, like for example Geofencing and a GPS to calculate the optimum routes avoiding the areas where they are not allowed to operate in. This way, both the vehicle and the pilot would be taking care of the safety and security tasks.

Given this initial starting point and established boundary conditions, some modifications to an already-existing PAV are proposed. That is, the adaptations the thesis' reference PAV (Volocopter 2X) should undergo to that it would suit the requirements set for the integration of UAM in a hypothetical city. For example, the Volocopter 2X the possibility of integrating a GPS as an "extra", but from the established requirements the production series of this vehicle should include the GPS as a compulsory feature.

This thesis portrays how difficult implementing UAM actually is, as the three main elements previously mentioned are all interconnected: the slight modification of one aspect has a significant effect on many others. This leads in many cases to compromises between technological, legal and economical aspects. This is the case of integrating instruments for the automation of the vehicle; this measure avoids the necessity of having a pilot certification, and thus the service would be more accessible to the general public. However, the complexity in the vehicle's system would increase, as so would its weight. Consequently, structural and mechanical parameters should be recalculated, besides the economical investment done in the integration of these instruments. Probably, such complexity it is the reason behind the delay of the integration of UAM. However, as UAM is subjected to legal restrictions and regulations, this thesis suggests that these are first established, and after the legal framework being known, other parameters, such as the design specifications of the PAV or the infrastructures required, can be determined. That is, by settling one of the three main elements, compromises have to be taken only between the other two, simplifying the integration. Nevertheless, it is fundamental to take into account every parameter when building the legal framework related to UAM, so that the advantages of the UAM system can be maximised.

It has to be emphasised that the thesis does not propose a rigid and unalterable set of requirements to be fulfilled and laws to be followed. Instead, it proposes, as said, a starting point from which UAM can derive, and further evolve. According to the analysis carried out in this thesis, due to the progress and advancements of technologies and the continuous social evolution, this thesis predicts UAM to be integrated in an evolutionary way too. That is, as UAM starts to be implemented, depending on the path this service takes, laws will adapt accordingly. This update in the legal framework will lead to changes in the air vehicles, in the infrastructures, in the way it is operated and even in the user's experience. Hence, a slow but progressive and developmental integration of UAM is predicted.

For cities to actually and really be equipped with UAM, it is not enough with aerospace companies and manufacturers designing innovative aerial vehicles, potentially suitable for UAM. These companies have to work alongside with airspace regulatory bodies, so that they can all evaluate the entire scenario, taking into account every aspect, and come to an agreement that enables the optimal integration of UAM, because, as seen in this thesis, the individual study of each aspect is pointless, as it affects and it is affected by all the others.

List of References

- [1] <http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html>
- [2] <https://dictionary.cambridge.org/es/diccionario/ingles/urbanization>
- [3] “World urbanisation prospects” – United Nations (2014)
- [4] <http://www.un.org/en/development/desa/news/population/world-urbanization-prospects-2014.html>
- [5] http://ec.europa.eu/eurostat/statistics-explained/index.php/Urban_Europe_-_statistics_on_cities,_towns_and_suburbs_-_executive_summary
- [6] “The evolution of urban mobility: The interplay of academic and policy perspectives” - Peter Jones (2014)
- [7] <http://environmentalhistory.org/20th-century/sixties-1960-1969/>
- [8] <http://www.airbus.com/innovation/urban-air-mobility.html>
- [9] <https://www.nasa.gov/aero/taking-air-travel-to-the-streets-or-just-above-them>
- [10] <https://eu-smartcities.eu/initiatives/840/description>
- [11] <https://aviationbenefits.org/social-development/tourism/>
- [12] <https://data.worldbank.org/indicator/IS.AIR.PSGR?end=2016&start=1970&type=points&view=chart>
- [13] <https://aviation-safety.net/statistics/>
- [14] <http://money.cnn.com/2017/02/28/news/companies/flying-is-cheap/index.html>
- [15] https://en.wingly.io/index.php?page=content&sub_page=about
- [16] <https://www.revolv.com/main/index.php?s=Personal+air+vehicle>
- [17] “Personal Air Vehicles: a rural/regional and intra-urban on-demand transportation system” – American Institute of Aeronautics and Astronautics (2003).
- [18] “America on Wheels – The First 100 Years: 1896-1996” – Frank Coffey (1996).
- [19] “On-Demand Mobility – Goals, Technical Challenges, and Roadmaps” – Mark Moore (2015).
- [20] “System-Of-Systems Modeling for Personal Air Vehicles” – Daniel DeLaurentis, Taewoo Kang, Choongiap Lim, Dimitri Mavris, Daniel Schrage (2002).
- [21] “Fast-Forwarding to a Future of On-Demand Urban Air Transportation” – Jeff Holden, Nikhil Goel (2016).
- [22] <http://www.airbus.com/innovation/urban-air-mobility.html>
- [23] <https://www.volocopter.com/en/>
- [24] <http://www.ehang.com/ehang184/>
- [25] <https://www.volocopter.com/en/company/>
- [26] <http://www.ehang.com/about/>
- [27] <https://www.uber.com/info/elevate/ecrm/>

-
- [28] “Silicon Valley as an Early Adopter for On-Demand Civil VTOL Operations” – Kevin R. Antcliff, Mark D. Moore, Kenneth H. Goodrich (2016).
- [29] “eVTOL Vehicle Requirements and Missions” – UBER Elevate (2018).
- [30] ABI Research Presentation on Service Robotics at Innorobo Conference (Paris, 2016) – Dan Kara.
- [31] <https://www.tecnam.com/innovation/p2006t-x-57-maxwell-nasa/>
- [32] “X-57 Power and Command System Design” – Sean Clarke, Matthew Redifer, Kurt Papathakis, Aamod Samuel (2017).
- [33] <https://press.volocopter.com/index.php/volocopter-presents-air-taxi-services-at-scale>
- [34] “Design specifications Volocopter 2X” – e-volo GmbH (2017).
- [35] <https://www.aopa.org/advocacy/advocacy-briefs/regulatory-brief-sport-pilot-light-sport-aircraft-final-rule>
- [36] <https://www.helis.com/database/model/Volocopter-VC200/>
- [37] <http://evtol.news/aircraft/>
- [38] <https://www.ainonline.com/aviation-news/aviation-international-news/2008-10-27/sao-paulo-worlds-helicopter-capital>
- [39] <https://www.sesarju.eu/U-space>
- [40] “Environmental Sustainability in Transport Engineering “ – Professor Markus Oeser, RWTH Aachen (2017).
- [41] “Agent-based forecasting tool for NASA’s SATS program” - J.-H. Lewe, A. Khalid, E. Upton, Taewoo Kang. (2004).
- [42] “An integrated decision-making method to identify design requirements through agent-based simulation for personal air vehicle system.” - Daniel DeLaurentis, J.H. Lewe, B. Ahn, Dimitri Mavris, Daniel Schrage (2002).
- [43] “Aeromobile Air Transport System Design and Testing” – Ladislav Smrcek, Stefan Klein, Antonin Pistek (2010).
- [44] “Design Synthesis and Optimisation of VTOL Personal Air Vehicles” – Omar Katamish (2012).
- [45] “D7.1 - Screening Report of Socio-technological Environment” – Sarah Meer, Michael Decker, Torsten Fleischer, Jens Schippl (2011).
- [46] <https://aviation-safety.net/wikibase/wiki.php?id=122340>
- [47] <http://www.girodynamics.com/what-is-a-gyrocopter/>
- [48] “WP1: Operational Concepts, PPlane Survey 1st Round Results” – M. Roudstein (2010).
- [49] “The Delphi technique” – Shakila Thangaratnam, Charles WE Redman (2005).
- [50] “D7.3 – User Perspectives and Expectations” - Sarah Meer, Michael Decker, Torsten Fleischer, Jens Schippl (2014).
- [51] “Autonomous Flight Rules - A Concept for Self-Separation in U.S. Domestic Airspace” – David J. Wing, William B. Cotton (2011).
- [52] <https://www.aviationtoday.com/2004/10/01/autonomous-flight-management-a-third-way/>

-
- [53] “Wing-Tip Vortices, Turbulence and the Distribution of Emissions” – Thomas Gerz, Frank Holzäpfel (1999).
- [54] Federal Meteorological Handbook No. 1, Chapter 5, Definition 5.4.4 Wind Gust.
- [55] https://www.aviationweather.ws/051_Induction_System_Icing.php
- [56] https://www.skybrary.aero/index.php/Piston_Engine_Induction_Icing
- [57] “Out of the box – Ideas about the future of air transport” – European Commission (2007).
- [58] “Advisory Circular – FAR Part 135 Icing Limitations” – U.S. Department of Transportation, Federal Aviation Administration (2008).
- [59] <http://www.mycopter.eu>
- [60] <https://www.easa.europa.eu/easa-and-you/air-operations/specialised-operations-spo>
- [61] “Annual Safety Review 2017” – European Aviation Safety Agency (2017).
- [62] “Weight and Balance Handbook” - U.S. Department of Transportation, Federal Aviation Administration (2016).
- [63] “Aviation and the Global Atmosphere” – Anu Vedantham (1999).
- [64] “A White Paper: Assessment of Noise Annoyance” – Paul Schomer (2001).
- [65] “Future Noise Policy – European Commission Green Paper” – Commission of the European Communities (1996).
- [66] “Position paper on dose-effect relationships for night time noise” – Working Group on Health and Socio-Economic Aspects, European Commission (2011).
- [67] “Aeromobilities” – edited by Saulo Cwerner, Sven Kesselring, John Urry (2008).
- [68] <http://www.mdpi.com/1660-4601/15/3/519/htm#B22-ijerph-15-00519>
- [69] <https://www.flyer.co.uk/volocopter-shows-2x-multicopter-to-go-on-sale-in-2018/>
- [70] <http://www.helittraining.co.nz/training-and-courses/course-fees/private-pilot-licence>
- [71] <http://www.ultraleicht-homepage.de/ultra-leicht-faq.htm>
- [72] “The Geography of Transport Systems” – Jean-Paul Rodrigue, Claude Comtois, Brian Slack (2013).
- [73] “Commercial Intra-City On-Demand Electric-VTOL – Status of Technology” – Anubhav Datta, NASA Aeronautics Research Institute (2018).
- [74] <https://www.radio-electronics.com/info/power-management/battery-technology/lithium-ion-battery-advantages-disadvantages.php>
- [75] http://batteryuniversity.com/learn/article/lithium_based_batteries
- [76] “Energy consumption analysis of battery electric vehicles in underground movements” – M. Hudyma, Y. Potvin (2017).
- [77] “EUROCONTROL guidance notes for pilots – 1. Rules for VFR Flight” - EUROCONTROL Headquarters (2009).
- [78] <https://www.easa.europa.eu/the-agency/faqs/general-aviation#category-permits-to-fly>

-
- [79] <https://www.terrafugia.com/about-terrafugia/>
- [80] <https://newatlas.com/terrafugia-transition-flying-car/15584/>
- [81] <https://www.easa.europa.eu/easa-and-you/aircraft-products/aircraft-certification>
- [82] <https://www.easa.europa.eu/the-agency/faqs/agency>
- [83] <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1474978980580&uri=CELEX:32008R0216>
- [84] “Rulemaking Directorate – Policy Statement: Airworthiness Certification of Unmanned Aircraft Systems (UAS) – E.Y013-01” - EASA (2009).
- [85] “Aeronautical Information Manual – Official Guide to Basic Flight Information and ATC Procedures” – U.S. Department of Transportation, Federal Aviation Administration.
- [86] <https://www.pea.com/blog/posts/vfr-ifr-mean/>
- [87] https://studentscholarships.org/professions/523/unemployment/airline_pilots_and_flight_engineers.php
- [88] <https://money.cnn.com/2016/02/26/news/companies/pilot-shortage-bankruptcy/index.html>
- [89] <https://www.ainonline.com/aviation-news/air-transport/2017-05-01/republic-airways-emerges-bankruptcy>
- [90] “2017 Pilot & Technician Outlook” – William Ampofo, Boeing (2017).
- [91] <https://www.boeing.com/company/>
- [92] “Factors affecting Pilot Supply” – Kent Lovelace, Jim Higgins (2010).
- [93] “The Influence of Traffic Structure on Airspace Capacity” - Emmanuel Sunil, Jacco Hoekstra, Joost Ellerbroek, Frank Bussink, Andrija Vidosavljevic, Daniel Delahaye, Roalt Aalmoes (2016).
- [94] “Pilot’s Handbook of Aeronautical Knowledge. Chapter 15 – Airspace” – Federal Aviation Administration (2016).
- [95] http://www.visitacabaneros.es/el-parque_elparque_59.html
- [96] https://www.faa.gov/air_traffic/publications/
- [97] <http://www.internationalflightresources.com/international-prohibited-warning-and-danger-airspace>
- [98] <https://www.icao.int/about-icao/Pages/default.aspx>
- [99] “Air Traffic Management – Freeing Europe’s airspace” – Commission of the European Communities (1996).
- [100] https://ec.europa.eu/transport/modes/air/sesar_en
- [101] “Study Analysing the Current Activities in the Field of UAV” – Frost & Sullivan, European Commission (2007).
- [102] “NASA Strategic Framework for On-Demand Air Mobility” – National Institute of Aerospace (2017).
- [103] “Enabling Airspace Integration for High-Density On-Demand Mobility Operations” – American Institute of Aeronautics and Astronautics (2017).
- [104] <https://www.nasa.gov/aero/nasa-delivers-traffic-spacing-tools-tss>
- [105] <https://www.iata.org/whatwedo/safety/Pages/controlled-flight-into-terrain.aspx>

-
- [106] <https://www.dji.com/de/flysafe/geo-map>
- [107] “Unmanned Aircraft System Traffic Management (UTM) Concept of Operations” - American Institute of Aeronautics and Astronautics (AIAA) Aviation (2016).
- [108] “Rotor Wash” – Ann Suter, Wildland Fire Chemical Systems (2005).
- [109] <https://www.faa.gov/nextgen/programs/adsb/>
- [110] FAA Regulations – Certification: Pilots, Flight Instructors, and Ground Instructors (14 CFR Part 61) - §61.52 Use of aeronautical experience obtained in ultra-light vehicles.
- [111] <https://blade.flyblade.com>