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QUO VADIS 3D MOBILITY

Technological readiness, urban and rural use cases & urban integration of flying cars and passenger drones

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1 INTRODUCTION

"Mark my word: A combination airplane and motorcar is coming. You may smile, but it will come."

Henry Ford, 1940

Currently, the most important technology trends in the mobility industry are the electrification of the powertrain, the automation of the movement function and the networking of the vehicles amongst each other for the exchange of information in real time. The convergence of these technological development paths will lead not only to electric vehicles and autonomous taxis on the road but also to innovative mobility concepts in the third dimension: electrically operated and in the long term autonomously, personal and shared air vehicles (PAV and SAV, respectively) such as flying cars and passenger drones.

The concept of flying cars has been discussed for a very long time as the quote of Henry Ford from 1940 (Wall, 2013) shows. The ability to fly has been a dream of people since many centuries leading to different technological concepts such as airplanes and helicopters in the meantime. First prototypes of flying cars were built as early as 1917 (Frost & Sullivan, 2017, p. 33). Nevertheless, no commercial application of flying cars has evolved yet. Due to the latest technological advancements in different important technology fields like batteries or lightweight materials, the discussion of alternative concepts for personal air vehicles gained momentum resulting in a hype of the so-called 3D mobility in recent times. 3D mobility has been regarded as a vital component of the possible cure for the mobility problems of this century because 3D mobility potentially offers many benefits that contribute to the goals set by many cities and regions for a sustainable and efficient mobility. These include in particular the low travel time, the high flexibility and adjustability, the low surface intensity and the elimination of local emissions of pollutants and CO_2 in case of an electric drive. Due to the independence from roads and railways, journeys are less subject to traffic jams leading to significant time savings above a certain minimum distance. Routes can be installed as required and dynamically adapted, taking into account restricted areas with overflight bans. Since for many concepts only so-called vertiports are required as mobility hubs for the vertical take-off and landing, the costs for the construction and maintenance of the infrastructure excluding charging and refueling components can be low compared to the road or rail infrastructure. Combined with goods transportation, a further traffic relief can be achieved. For these reasons, 3D mobility can represent an important and potentially ecological mode of transportation for people in the future. As of today, however, it is not clear what the technological readiness of these concepts is, how certain use cases work in detail, what the market acceptance and preferences are and how the concepts can be implemented into the city and countryside. The present study aims to shed light on these topics and helps to get a better understanding of some relevant aspects of 3D mobility. Due to a more and more restricted city-access for cars with combustion engines in several European countries, this paper focusses on hybrid or fully electric flying vehicles. However, as 3D mobility is primarily used for faster mobility (Duwe & Sprenger, 2019), this paper does not strictly exclude conventionally powered concepts. In general, only the concepts presented in chapter 2.1 have been examined, excluding other concepts such as electrified planes, hoverbikes or jetpacks.

2 TECHNOLOGICAL READINESS OF 3D MOBILITY

The technological readiness of the key technology systems is one of the most important success factors for the diffusion of 3D mobility into the mass market. In this chapter we focus on the analysis of the technological maturity of electrified personal and shared air vehicles. In the beginning, different technological concepts are described. Afterwards, a functional decomposition of the technology systems is conducted to identify the most critical technologies of the different concepts. Finally, the technological maturity of the key technology systems is analyzed based on the information found in scientific publications.

2.1 Overview of 3D Mobility Concepts and Entrepreneurial Activities

In this section, different 3D mobility concepts are discussed and depicted in Figure 1.

Multicopter / Multirotor

This concept features multiple motors and propellers around a cabin to create thrust in vertical direction. To steer, the velocity of single rotors is changed. Compared to other concepts, they still have significant efficiency disadvantages in cruise flight mode which is why some concepts also feature wings. Due to these disadvantages, multirotor concepts are designed for short-range use cases and intracity transportation. Well-known enterprises already testing prototypes under real-life conditions are Volocopter from Germany and Ehang from China.

Dual Phase

Air vehicles designed according to the dual phase concept have propellers mounted to wings which create vertical thrust during take-off and landing. Another propeller is mounted to the tail of the air vehicle creating horizontal thrust. By combining these two different drive trains for lifting and cruising and by featuring wings, it offers the advantages of vertical take-off and landing and an energy efficient cruise enabling the air vehicle to fly longer distances. One well-known company designing dual phase air hevicles is Kitty Hawk, which has run tests with a prototype of this concept called Cora under real-life conditions in New Zealand.

Tilt-Wing / Tilt-Rotor / Tilt-Duct

Characteristic for this concept is the design of the wings, rotors or ducts: they can be tilted. With this ability, it is possible to redirect the thrust from a vertical direction during take-off and

landing to a horizontal direction during cruise flight mode. A well-known enterprise already testing this concept as a prototype is the German company Lilium. The electric jet engines mounted in the Lilium Jet work like turbofan jet engines in a regular passenger jet with circumferential propellers.

Modular Car-Quadrocopter

This combined concept is a modular concept with a capsule for passenger transportation as its core element. This cabin can be mounted (autonomously) on either a fully electric car platform or a fully electric multirotor module. By that, this concept can offer mobility both on the ground and in the air and is a complete vehicle system concept. The concept was mainly driven by a cooperation between Audi and Airbus with their concept called Pop.Up Next which has recently been discontinued.

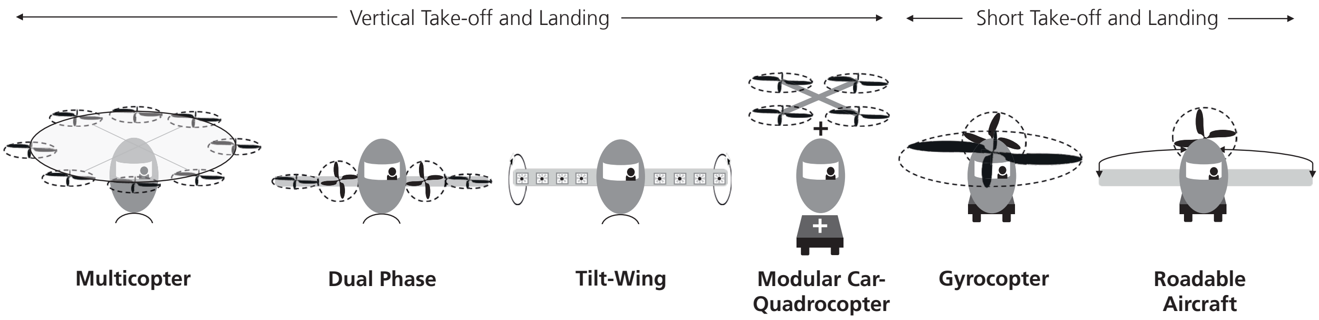
Gyrocopter

This concept has an active propeller creating horizontal thrust and a passive propeller creating vertical thrust through the airflow at the top which is also called autorotation. Some concepts also feature a drivetrain for driving on the road making it functionally similar to the roadable aircraft concept. PAL-V is one company following this conceptual approach with a conventional engine.

Roadable Aircraft

The characteristic feature of the concept of a roadable aircraft is that the aircraft is basically a car which has the ability to fly by using (foldable) wings meaning that this transportation concept can both be used on the road like a car and in the air like an airplane. One well-known enterprise working on this concept is Terrafugia that has been prototyping and testing the hybridized model TF-X. The aircraft has swiveling propellers, which enable vertical take-off and landing. Electric engines power these propellers. Once the TF-X transitions into cruising flight mode, it uses another propeller which is mounted to the tail and powered by a combustion engine to extend the range of the aircraft.

Figure 1: Overview of Different Concepts for 3D Mobility.



2.2 Key Technology System Decomposition

In this chapter, the different technological concepts (see chapter 2.1) are decomposed into their specific key technology systems which again consist of a set of various technologies. This was done based on a literature review and an analysis of scientific literature, indicating the most relevant fields of research for 3D mobility. The result is shown in Figure 2.

Flight Control, Safety & Security

Vertical **take-off and landing** VTOL
Short take-off and landing STOL
Effective highlift systems

Automation / Autonomy
Automated airspace control
Low speed control

Near all weather capability

Factor ten improvement in small aircraft **safety**

Modern **certification** procedures

Safe, affordable, easy-to-use and acceptable personal air vehicle technologies

Hardware

Lightweight structures
Weight increased efficiency
Technology drives the airframe
Economically viable concepts

Affordable **propulsion**
Distributed electric propulsion
Improved propulsion system thrust
Powered rotor and autogyro concept
Duct enclosed counter-rotating propellers

Convert **alternative energy sources** to thrust
Efficiency and environment technologies
Advanced proton exchange membrane
Solid oxide fuel cells

Software & Ecosystem

Digital technologies
Design tools capable of modeling and analyzing unconventional concepts

Low community **noise**

Intra-urban mission technologies

Critical technologies enabling a **near-door-to-door** airborne transportation capability

Investigate the **infrastructure** and technology impact of new systems

Figure 2: Relevant Fields of Research for 3D Mobility in Scientific Literature.

Similarly, Frost & Sullivan identified autonomous flying and VTOL, navigation, communications, cybersecurity, lightweight materials, low-noise propulsion systems, high-capacity batteries, biometric sensors, and artificial intelligence as the key technologies (Frost & Sullivan, 2017, p. 35). On a more abstract level, all the concepts presented in chapter 2.1 consist of similar technological product and operation systems to fulfill the core functions for the successful implementation of flying cars and passenger drones:

Product: All concepts need some source of thrust - in either vertical or horizontal direction or both. For the provision of the thrust, they use propulsion systems. In order to be ecologically sustainable, they often feature electric propulsion systems for at least local emission free mobility. One issue that all of the presented concepts share, however, is the emission of noise which needs to be limited e.g. through distributed propulsion in order to be accepted by the customers especially in urban areas. Furthermore, all concepts have a cabin to carry up to six passengers, depending on the concept. The air vehicles need to be as light as possible to maximize the possible payload and the energy efficiency. Therefore, lightweight materials and lightweight construction play an important role.

Operation: To allow an economic operation of the presented concepts, autonomous flying is necessary. This function decreases the operating costs and offers one more passenger seat. To further optimize the operation in real-time and to avoid crashes of the flying vehicles, navigation and vehicle2X-communication are technological core systems. Artificial intelligence will also be used to allocate, schedule and control the large number of vehicles in fleets in the sky. Finally yet importantly, each of the presented concepts needs some kind of technology for take-off and landing. Because space in urban areas is limited, it often is the aim to avoid the need of a runway in the case of short take-off and landing and try to use vertical take-off and landing instead.

Based on these key technologies, key technology systems were determined to conduct the technological maturity examination in this paper. In the following subchapter, selected technology systems and subsystems are described in further detail.

2.2.1 Propulsion

Thrust generation is the core principle for any flying vehicle and therefore, technologies to create thrust are very important for the success of flying cars. There are different technological concepts for the propulsion of an air vehicle used by different companies in several projects (Reimers, 2018):

- Ducted fans, high- and low-pressure fans (e.g. Airbus e-Fan, Zunum Aero)
- Ducted fans combined with boundary layer ingestion (e.g. Faradair, Ampaire)
- Ducted fans combined with distributed propulsion (e.g. NASA/ES-Aero, Lilium)
- Open fans (e.g. Safran and other research projects)
- Propellers combined with distributed propulsion (e.g. Volocopter, NASA Maxwell, Eviation)
- Regular propellers

The bladeless propulsion system has been another interesting recent technological development (Mohyi, 2017). This concept seems to have better attributes when it comes to noise emissions (Frost & Sullivan, 2017, p. 63) and could be applied in the future. For the analysis of the technological maturity, three subsystems in the technology system of propulsion were differentiated:

- Electric propulsion (battery powered),
- Electric propulsion (fuel cell powered) and
- Distributed propulsion.

2.2.2 Noise Reduction

Another important technology system features technologies supporting a reduction of the externally emitted noise. This is particularly important for the acceptance of flying cars in urban areas. Uber estimates that the noise level should not exceed a value of 62 dB at an altitude of around 150 m or 500 feet (Frost & Sullivan, 2017, p. 63). Experts expect the noise emission of a PAV to be about 65 dB at around 90 m or 300 feet flight altitude which is similar to the noise in a restaurant. The same noise range is specified e.g. by Volocopter in the design specifications for their concept 2X hovering at an altitude of 75 m or 246 feet (Volocopter 2X, 2017, p. 1). This equals to approximately one fourth of the noise emitted by a conventional helicopter with a combustion engine (Porsche Consulting, 2018). When landing at a distance of 30 m, the noise of the multicopter concept of Volocopter is estimated to be around 76 dB (Volocopter, 2019, p. 10). The noise level in urban areas such as Boston is nowadays on average between 60 and 69 dB with some areas with a maximum of up to 80 dB during the daytime (Boston Noise Report, 2016). One option to reduce the noise is the use of electric (Frost & Sullivan, 2017, p. 63) and distributed propulsion systems. However, although electrically powered air vehicles are much quieter than the ones powered by combustion engines, it is still necessary to further reduce the noise resulting from airflows at the body and the tips of the propellers. One future possibility to substantially reduce the noise emissions is the use of bladeless propellers (Mohyi, 2017) as already mentioned in chapter 2.2.1. Also, the noise inside the air vehicle needs to be considered and reduced to increase the comfort and by that the acceptance of the users. For passengers inside the air vehicle there already exist different approaches both in active and passive noise reduction technologies, even from other fields such as active noise cancelling headphones.

2.2.3 Lightweight

Like in other mobility related industries, lightweight materials play a major role for flying cars and passenger drones. There are different reasons, why the manufacturers strive to keep the weight of the air vehicle as low as possible. The laws of physics define a direct interdependency between the mass and the range of an air vehicle, due to its potential and kinetic energy needs[1]. The heavier the air vehicle is, the more energy it needs to be kept and moved in the air. Of course, this is not the only limiting factor for the range as the height and the speed also have an influence on the required energy, but a very important one. The range or the allowed payload of an air vehicle can be improved by using lightweight materials or lightweight construction. Moreover, there are legal regulations that require the manufacturers to keep the take-off mass of the air vehicle under a certain threshold between 450 and 600 kg (Deutscher Aero Club, 2019) to be certified as a two-seat ultralight aircraft in Europe. Otherwise, the user of the PAV would need a more extensive pilot license to use it. Because of these physical and legal reasons the development and use of new high-performance lightweight materials, like new composites or reinforced materials, is very important for the 3D mobility industry.

1.
$E_{POT} = m \times g \times h$; $E_{KIN} = \frac{1}{2} \times m \times v^2$; with:
m = mass [kg];
g = local gravitational field (e.g. 9,81 m/s²);
h = height [m];
v = velocity [m/s]

2.2.4 Autonomous Flying

Fully autonomous flying means no human intervention during the flight. To allow an economic operation of flying cars this is an important factor because pilot costs can be saved. Moreover, one more seat for a paying passenger is available or the vehicle can transport more payload in case of autonomous flying. Another reason for the importance of this technology system is the safety that can be increased in the long-term by the elimination of human mistakes made by the pilot. Further sub-technologies are required to enable autonomous flying. These include (optical) sensors for the positioning, data processing units and electrically controlled actuators. Due to the decision to examine the technological maturity on the level of technology systems, these sub-technologies are aggregated in the further consideration.

2.2.5 Take-off and Landing

For take-off and landing, two different concepts have been pursued: short take-off and landing (STOL), which requires a short runway, and vertical take-off and landing (VTOL). Flying cars face two challenges, when it comes to take-off and landing: limited space available in urban areas and the need to avoid the dependency on airports for take-off and landing. VTOL seems to be the most relevant and promising solution for these challenges. For VTOL, thrust in the vertical direction is required, either through distinct vertical propellers or through tiltable propellers, depending on the concept design (see chapter 2.1). With VTOL, new application areas for flying cars are possible like passenger transportation between skyscrapers with landing platforms on top of them. The VTOL technology originally comes from the military industry. With the new and more efficient energy provision, this concept will be applicable in civil industries.

2.2.6 Vehicle2X-Communication

Communication between vehicles (Vehicle2Vehicle) and especially between vehicles and infrastructure (Vehicle2Infrastructure) is in sum called Vehicle2X-Communication. This technology system is employed to optimize the traffic flow and to prevent accidents through the communication between the air vehicle and the infrastructure similar to current air traffic control facilities. For this, new reliable and robust technologies with low latency like 5G are very important prerequisites, because the greatest potential can be tapped through real-time communication.

2.2.7 Artificial Intelligence

Recent progress in the field of artificial intelligence allows operation optimization and new user scenarios in the field of 3D mobility. Artificial intelligence is for example used for an economic or ecological fleet management with regard to

- Vehicle allocation and scheduling,
- Route planning and navigation and
- Sensor data processing for maneuver planning.

2.3 Technological Maturity of the Key Technology Systems

Despite the growing dynamism of 3D mobility in the media, PAVs have not yet arrived in the mass market. This chapter examines whether the reason for this is a technological one by examining the technological maturity of the most important technology systems named in chapter 2.2.

2.3.1 Maturity Levels

In 1988, the NASA defined nine different technology readiness levels (TRL) to rate the maturity of technologies (Sadin, et al., 1989). For the provision of a first estimation of the maturity level of flying cars and passenger drones, these TRL are too granular and hard to differentiate semantically. To allow statements on the degree of technological maturity for each key technology system, an application-specific technology maturity model was developed[2]. This model consists of five Technology Maturity Levels (TML). The TMLs and their correlation to the TRLs developed by the NASA is shown in Table 1:

2. Another approach with a focus on technology maturity depending on application scenarios was pursued by Ardilio et al., 2012.

TML	Analogous NASA-TRL
Research	1-3
Development	3-5
Testing	6-7
Manufacturing	8
Market Launch (and Operation)	9

Table 1: Definition of the Technology Maturity Levels (TML) and their Correlation with the NASA-TRL.

For the examination of the technological maturity, a semantic text-mining tool was used to analyze the textual dataset of scientific publications. Hereto, the five defined levels are semantically described by words, synonyms and relations describing the technology maturity level in question.

2.3.2 Information Source for Determining the Maturity

Around 850 peer-reviewed scientific papers and articles from a scientific database were selected for the analysis based on their titles, keywords and abstracts. The search term used to select the documents for the investigation contained one or more of the following words and expressions: 'personal air vehicle', 'flying car', 'personal aerial vehicle', 'air taxi', 'flying taxi', 'passenger drone', 'roadable aircraft', 'urban air mobility", '3D Mobility' and 'multicopter'. The publication dates of these documents range from 1969 to 2019.

2.3.3 Results

Global Findings

For the analysis of the technological maturity of flying cars and passenger drones, the number of documents containing the technology system and the word frequency of the technology system were used. Additionally, the ratio between the frequency and the number of documents, which states how often the technology system is named per document, gives an indication of how specific the respective document is about the particular technology system. Table 2 shows the results for all criteria for the considered technologies.

It is evident that battery powered electric propulsion is the most discussed technology system in all documents, both when it comes to the frequency and the number of documents. Also, the key technology systems 'distributed propulsion', 'autonomous flying' and 'VTOL' are discussed quite broadly. The relative share of documents dealing with these systems is also depicted in Table 2 and once again underpins the importance of these systems: almost one third of the documents contain information about battery powered electric propulsion.

	Number of Documents	Share of Documents	Word Frequency	Frequency / Document
Electric Propulsion (battery)	246	29%	638	2,59
Distributed Propulsion	190	23%	400	2,11
Autonomous Flying	167	20%	332	1,99
VTOL	134	16%	401	2,99
Lightweight	100	12%	171	1,71
Low Noise Propulsion	98	12%	203	2,07
Artificial Intelligence	75	9%	136	1,81
Electric Propulsion (fuel cell)	11	1%	36	3,27
V2X-Communication	3	0%	3	1,00

Table 2: Overview of Technology System Specific Documents for 3D Mobility in Descending Order.

As can be seen in Table 2, the sum of the documents which name one of the technology systems is higher than the total number of documents. This means that some of the documents stress more than one technology system as a topic. Nevertheless, the ratio of these documents is low: on average, only 25% of the documents contain more than one technology system, which means that the documents are quite specific about each technology system.

Geographic Hotspots

The analysis of the geographic origins of the documents shows that the majority of the documents comes from the east coast of the United States, Western and Middle Europe (mainly Germany) as well as the east coast of China and Japan, as illustrated in Figure 3.

Besides these expectable hotspots, there are also documents originating from Brazil, the Middle East, Russia and South-East Asia, which might indicate possible future hotspots of this topic.

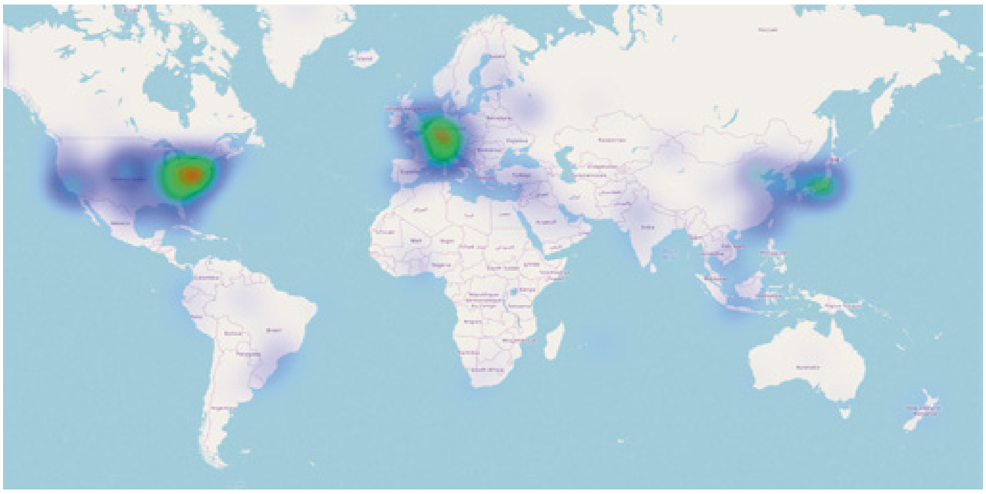


Figure 3: Heatmap of the Origins of the Publications.

Maturity of each Technology System

For the indication of the technological maturity of the particular technology systems, a detailed examination is necessary. Hereto, the average maturity was calculated by dividing the total number of mentions of all technology systems in each maturity level by the total number of all mentions:

Equation 1: Calculation of the Average Maturity.

$$\text{Share}_{\text{maturity level}} = \frac{\text{Sum (mentions of maturity level i)}}{\text{Sum (mentions of all maturity levels)}}$$

with: i = maturity level

The results of the calculations for each maturity level are shown in Table 3.

Nr.	TML	Average across all Technology Systems
1	Research	14,7%
2	Development	60,3%
3	Testing	7,1%
4	Manufacturing	2,0%
5	Market Launch	15,9%

Table 3: Average Maturity Level over all Technologies.

To determine the maturity of each technology system compared to the other ones, the share of mentions of each maturity level was calculated for each technology system. The results of this calculation are shown in Table 4. A comparison of the value for each technology system with the average value for all technology systems gives an indication about the relative maturity level for each technology system. If the value is significantly higher or lower than the average value for the maturity level, the technology system is more or less likely in the considered maturity level compared to the whole system of 3D mobility. The results and especially the anomalies, which are significantly above the average, are highlighted in Table 4.

Table 4: Maturity Levels of the Technology Systems.

TML	Electric Propulsion (battery)	Electric Propulsion (fuel cell)	Distributed Propulsion	Low Noise Propulsion	Autonomous Flying	VTOL	Lightweight	Artificial Intelligence	V2X-Communication
Research Ø 14,7%	14,4%	12,1%	15,3%	13,3%	16,2%	12,8%	14,6%	16,8%	26,3%
Development Ø 60,3%	59,9%	67,4%	59,4%	64,0%	56,6%	59,4%	64,4%	59,8%	42,1%
Testing Ø 7,1%	5,8%	3,5%	9,6%	6,2%	7,9%	8,2%	5,6%	6,3%	15,8%
Manufacturing Ø 2,0%	2,5%	4,3%	1,4%	1,1%	2,4%	1,5%	2,5%	1,8%	0,0%
Market Launch Ø 15,9%	17,4%	12,8%	14,3%	15,3%	16,9%	18,0%	12,9%	15,4%	15,8%

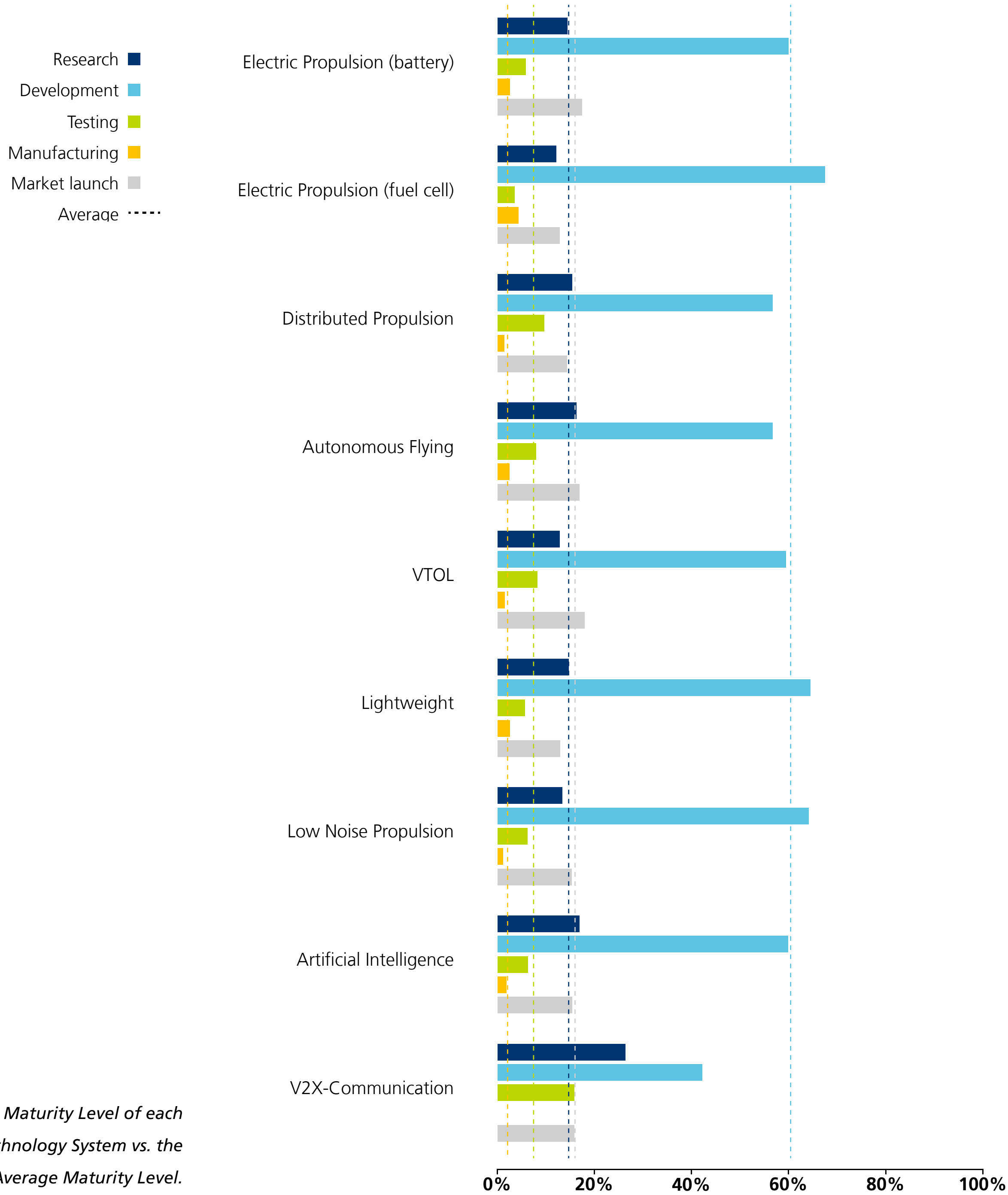


Figure 4: Maturity Level of each Technology System vs. the Average Maturity Level.

The results show that the shares of autonomous flying, artificial intelligence and V2X-communication are well above average in the technological maturity level **Research**. This means that these technology systems are mainly in a very early stage of development. The technologies with a share above the average in the level **Development**, such as electric propulsion (fuel cell), lightweight materials and construction as well as low noise propulsion, are currently under development. Distributed propulsion, VTOL and V2X-communication show an above-average proportion in the subsequent level **Testing** indicating a more advanced technological maturity of these technology systems. Electric propulsion (battery), electric propulsion (fuel cell), autonomous flying as well as lightweight materials and construction are technology systems which already seem to be in the maturity level of **Manufacturing** due to their above-average proportion. For the technology systems electric propulsion (battery), autonomous flying and VTOL, market application scenarios are already discussed as indicated by the above-average proportion in the highest level of maturity **Market Launch and Operation**. This shows that for some technologies, development activities in different maturity levels take place at the same time. The results of the share of each technology system in comparison with the average maturity level of all technologies, illustrated as broken lines, are shown in Figure 4.

2.3.4 Summary

The results of the conducted examination show a good indication of the technological readiness of the most important technology systems of flying cars and passenger drones. It is shown that for the whole system of flying cars, consisting of the technology systems described in chapter 2.2, the technology maturity level Development dominates. This does not surprise considering the used scientific database. However, the results show on the one hand that some technology systems such as artificial intelligence are predominantly in the maturity level Research compared with the other systems and require further research and development efforts. On the other hand, some technology systems are already in a higher maturity level compared with the average maturity level of all technology systems, like the battery electric propulsion, autonomous flying and VTOL. Some of the technologies are already beyond testing and application scenarios have been discussed.

3 URBAN INTEGRATION

In this chapter, strategic reasons for and possible ways of an urban integration of 3D mobility are discussed. This involves both the stakeholder and the infrastructure perspective within the ecosystem.

3.1 Urban Targets and Impacts

Passenger drones and flying cars have the potential to open up the air as an additional space and mode of transportation in a city. They can complement or even substitute existing options across the modal split and expand the scope of action for the city administration when it comes to the implementation of a holistic mobility strategy. 3D mobility offers transportation options which can be used very flexibly since they require only little infrastructure and offer mobility on demand and fast transportation with – in many cases – zero emissions at the same time. This unique set of characteristics distinguishes 3D mobility from already established forms of ground transportation such as cable cars or elevated railways.

Due to the versatility of the air vehicle technology, very different applications are possible as depicted in chapter 3. Urban air mobility solutions can thus serve the strategic mobility goals pursued by the city's mobility concept. However, each city has different needs, challenges, requirements and cultural characteristics. Therefore, the ways how 3D mobility can create value for citizens in an urban environment can be very different. 3D mobility has to be regarded as an instrument to deliver better mobility services with the intention to improve the quality of life for citizens. Under this premise the technology can be employed in a useful way by the responsible decision-makers.

There are different dimensions describing how 3D mobility can add value to a city:

Increase Accessibility
Air vehicles enable cities to create mobility where there has not been any or just rare connection before. This applies to remote areas which the conventional modes of transportation are not or only poorly able to connect appropriately. Citizens in these areas have only little or no access to municipal offerings such as educational institutions or numerous cultural, commercial and recreational activities.

Increase Efficiency and Save Travel Time
Through the integration into existing mobility concepts, air mobility offers an additional or alternative option to increase the efficiency of the mobility system and reduce the pressure on the existing modes. 3D mobility can be used to overcome difficult topographic conditions and to bypass areas where no infrastructure can be built. This refers to areas which are already densely covered with buildings but also to natural obstacles such as lakes, rivers or mountains.

Reduce Infrastructure
The provision of mobility is often connected with significant initial and recurring investments for the long enduring construction and upkeep of infrastructure. Implementing a 3D mobility system could offer an alternative to the construction of streets, tunnels, bridges, rails, and the like. If such a system is used in a way so that it represents an alternative to the ownership usage of a car, less parking lots, streets and supporting infrastructure are needed in a city.

Strengthen Resilience of a City
3D mobility could also be used as a temporary solution to back up the existing mobility services in case of breakdowns, congestions or in other situations of limited capacity. Furthermore, it can serve as a tool to maintain the mobility in situations in which a city faces unexpected incidents such as emergencies, accidents, natural disasters and terror attacks. In these scenarios air mobility is an element to strengthen the resilience of the city rather than a conventional mode of transportation.

Increase Tourist Attractiveness
Flying is perceived as a special experience and a convenient yet expensive way of getting to know the sights of a city. 3D mobility could be a preferred way to offer such an experience. In addition to sightseeing tours, passenger drones and flying cars could be used to take tourists directly to attractions similar to the air taxi described in chapter 3.2.1. By doing so, tourists have an alternative option to travel which can be faster, safer and more convenient than public transportation.

3.2 Involved Stakeholders

The integration of 3D mobility into an urban environment requires the involvement of various stakeholders from the public and private sector. They work collaboratively to set up an air mobility ecosystem which provides the infrastructure for the take-off and landing, the resources and processes for the service operation and the interfaces to other mobility modes. The specific design of such an ecosystem, its corresponding agents and their specific role within the ecosystem varies depending on the specific use case and the extent to which the air vehicles are integrated into the city's mobility system. Table 5 gives an overview of the various stakeholders involved in such an ecosystem.

Actor	Task / Responsibilities
Manufacturer	■ Builds, delivers and maintains vehicles ■ Customizes designs according to new demands and uses
Service Provider	■ Plans the fleet size and capacity ■ Manages the trips (capacity, schedule and price of the trips) ■ Manages the customer interface ■ Coordinates with city authority or among different city authorities (e.g. building authority, transportation authority, energy authority) ■ Organizes campaigns and advertisements to attract and involve citizens ■ Monitors the impacts in terms of mobility access, environment, business, public satisfaction, energy use / re-use etc.
Property Owner	■ Provides and transforms a private property into a public space / infrastructure ■ Rents out the property to administration companies ■ Potentially builds infrastructure (ports) according to demands ■ Arranges the integration of the required energy infrastructure and other amenities to the infrastructure ■ Helps the city administration and authority to strengthen the transportation network
City Administration	■ Coordinates among different city authorities (building authority, transportation authority, energy authority etc.) ■ Initiates the connection of the existing public transportation network with the proposed one ■ Regulates the trips (capacity, schedule and price of the trips) ■ Monitors the impacts in terms of mobility access, environment, business, public satisfaction, energy use / re-use etc.
Air Traffic Control	■ Manages traffic to avoid collisions and enforces traffic separation rules ■ Organizes and expedites the flow of air traffic ■ Provides information to vehicles and riders

Actor	Task / Responsibilities
Energy supplier	■ Provides charging infrastructure ■ Optimizes energy supply for ports
Telecom Provider	■ Provides and maintains digital infrastructure ■ Introduces mobile apps to book and pay a ride and to provide information about the locations of the ports and landing zones, travel schedules and durations, weather condition etc.
Citizens	■ Has to be willing to use the service and accept the new technology and its emissions (noise, light, occupation of space) ■ Pays for the service usage

Table 5: Involved Stakeholders for the Urban Integration of 3D Mobility.

3.3 Selection of Routes

The selection of appropriate routes and sites for taking-off and landing is an important task both for urban planners and the involved companies offering 3D mobility with flying cars and passenger drones. This can be done in detail with complex agent based traffic modeling and simulations. In order to get a first idea of the general suitability of 3D mobility in a city, a more aggregate assessment is expedient at the current stage of development. Multiple criteria e.g. based on travel time and distance, ecological impact and economic viability can be considered for this assessment. From the customer perspective, travel time reduction is the most important reason for the use of 3D mobility (see chapter 5). From the company perspective, a high seat occupancy rate is very important for the economic viability of a service. Thus, these two key figures have been selected for an initial analysis. In the present example, the city and suburban areas of Stuttgart were chosen as they have been ranking amongst the most congested areas in Germany for many years (Bock, 2019).

For the analysis, relevant zip codes with a maximum point to point distance of just under 30 kilometers were chosen so that the considered area is generally suited for all considered types of flying cars and passenger drones. Within these zip codes, mobility data were analyzed for private transportation with cars and public transportation with trains including working days and the weekend. For all connections, the absolute number of travelers and the absolute travel time were evaluated. Whereas the absolute number serves as an indicator for the overall demand and thus the possible seat occupancy rate, the absolute travel time serves as in indicator for the travel time reduction potential and thus the attractiveness to the customer. The results of the analyses for public and private transportation are depicted in Figure 5 and Figure 6, in which the white, grey and black colors depict the relative number of travelers and the numbers 0 to 3 describe the average travel time for each connection. The darker the color and the higher the number, the higher the number of passengers and the average travel time, respectively. Connections of black color and with a value of 3 are thus most relevant. Accordingly, redly framed cells indicate the connections of the highest interest. The diagonal illustrates all connections which start and end within the same zip code.

to / from	70173	70174	70176	70178	70180	70182	70184	70186	70188	70190	70191	70192	70193	70195	70197	70199	70327	70329
70173	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
70174	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1
70176	1	3	3	2	3	1	1	3	1	1	1	3	3	1	1	3	1	3
70178	1	1	0	3	3	1	1	0	1	1	1	1	1	1	1	1	1	1
70180	3	3	3	1	3	3	1	3	3	1	1	3	3	2	3	3	1	3
70182	1	1	1	1	3	3	1	1	1	1	1	1	1	1	1	1	1	1
70184	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70186	1	1	2	1	3	1	1	3	3	3	1	3	3	3	1	3	1	3
70188	1	1	1	1	0	1	1	3	3	1	1	3	1	1	1	1	1	1
70190	1	1	1	1	1	1	1	3	1	3	1	1	1	1	1	1	1	1
70191	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70192	1	1	1	1	3	1	1	3	1	1	1	3	3	3	3	3	1	3
70193	1	1	3	1	3	1	1	3	2	1	1	3	3	0	3	3	2	3
70195	1	1	1	1	3	1	1	3	1	1	1	3	1	3	1	1	1	3
70197	1	1	1	1	3	1	1	3	1	1	1	0	1	1	1	1	1	1
70199	1	1	3	1	1	1	1	3	1	1	1	3	3	1	1	3	1	3
70327	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70329	1	1	3	1	3	1	1	3	1	1	1	3	3	2	1	3	1	3
70372	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70374	1	1	1	1	3	1	1	0	1	1	1	0	3	0	1	2	1	1
70376	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1
70378	1	1	1	1	3	1	1	3	1	1	1	1	3	2	1	3	1	3
70435	1	1	1	1	1	1	1	3	1	1	1	3	2	1	1	1	1	1
70437	1	1	1	1	3	1	1	2	1	1	1	3	0	1	1	1	1	3
70439	1	1	1	1	3	1	2	3	1	1	1	3	3	2	1	3	1	3
70469	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70499	1	1	1	1	1	1	1	3	1	1	1	1	0	1	1	1	1	3
70563	1	1	1	1	1	1	1	3	1	1	1	3	1	1	1	1	1	1
70565	1	1	1	1	1	1	1	3	1	1	1	3	1	1	1	1	1	1
70567	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70569	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70597	1	1	1	1	3	1	1	2	1	1	1	1	1	1	1	1	1	1
70599	1	1	1	1	1	1	3	3	3	1	1	3	3	3	1	3	1	3
70619	1	1	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1
70629	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70734	1	1	1	1	1	1	1	0	1	1	1	0	2	1	1	1	1	2
70736	1	1	1	1	1	1	1	3	1	1	1	3	2	1	1	0	1	3
70771	1	1	1	1	3	1	1	3	1	1	1	1	1	1	1	1	1	1
70794	1	1	2	1	3	1	3	3	1	1	1	3	3	3	1	3	1	3
70806	1	1	1	1	3	1	1	3	1	1	1	3	3	1	1	2	1	1
70825	1	1	2	1	3	1	1	3	1	1	1	3	2	3	1	1	1	3

Figure 5: Scaled Average Passenger Amount (Color) and Travel Duration (Number) of Zip Code Connections for Public Transportation in and around Stuttgart.

70372	70374	70376	70378	70435	70437	70439	70469	70499	70563	70565	70567	70569	70597	70599	70619	70629	70734	70736	70771	70794	70806	70825
2	1	2	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	3	1	3	2	1	3	1	1	1	1	1	1	1	3	1	3	1	3	1	3	3	3
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	3	1	3	3	3	3	1	1	2	3	1	1	1	3	3	3	3	3	0	3	3	3
1	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	0	2	3	1	1	3	1	1	3	1	3	1	3	1	0	0	3	3	3
1	3	1	3	0	1	3	1	1	1	3	1	1	1	3	1	2	1	3	1	3	3	3
1	3	1	1	1	1	3	1	1	1	1	1	1	1	3	1	0	1	2	1	3	1	3
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	3	1	1	3	1	1	1	1	1	1	1	3	1	2	1	1	3	3	2	2
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	2
1	1	1	3	1	1	3	1	1	0	2	1	2	1	3	3	3	3	1	1	3	1	3
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	3	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	2
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	3	1	1	1	1	1	1	3	1	1	1	3	1	1	1	1	2	3	1	0
1	1	1	1	3	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	3	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	3	1	1
1	1	1	1	1	1	3	1	1	3	3	1	1	1	3	1	3	1	1	1	3	1	3
1	1	1	1	1	1	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	2	1	1	1	1	1	1	3	1	1	1	1	1	3	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	2
1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	3	1	1
1	1	1	1	1	1	3	1	1	1	1	1	1	1	3	1	3	1	1	2	3	1	3
1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	3	1	1	1	1	3	2	2
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	0	1	1	1	1
1	1	1	1	1	1	3	1	1	1	1	1	1	1	3	1	1	1	1	1	1	1	3
1	1	1	2	3	3	3	1	3	1	1	0	1	3	3	3	1	1	1	1	3	3	3
1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	3	3	1
1	0	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3

The data for public transportation indicates much and long traffic in and around Feuerbach and Möhringen as can be seen on the diagonal. It seems that connections from Bad-Cannstatt (70372), Feuerbach (70469), Möhringen (70567), Vaihingen (70569 incl. university campus)

from \ to	70173	70174	70176	70178	70180	70182	70184	70186	70188	70190	70191	70192	70193	70195	70197	70199	70327	70329
70173	1	1	1	1	1	1	3	1	2	1	1	1	1	1	2	1	1	1
70174	1	1	1	1	1	1	2	1	1	1	1	1	1	1	2	1	1	1
70176	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1
70178	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70180	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70182	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70184	3	2	1	1	1	1	1	1	3	1	1	1	1	1	1	1	2	1
70186	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70188	2	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	2	1
70190	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70191	2	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1
70192	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70193	1	1	3	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
70195	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70197	3	2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70199	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70327	2	1	1	1	1	1	2	1	2	1	1	1	1	1	1	1	3	1
70329	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70372	3	2	1	1	1	1	2	1	2	1	2	1	1	1	1	1	3	1
70374	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70376	3	2	1	1	1	1	1	1	1	2	3	1	1	1	1	1	2	1
70378	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70435	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70437	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70439	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1
70469	3	2	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	1
70499	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70563	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1
70565	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70567	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70569	2	3	1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1
70597	3	1	1	1	1	1	2	1	1	1	1	1	1	1	2	1	1	1
70599	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70619	2	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
70629	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70734	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1
70736	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70771	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70794	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70806	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
70825	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

and the area behind the Heusteig quarter (70184) into the city (70173 incl. main station) and vice versa could be of particular interest for 3D mobility because of the comparatively high number of passengers and the relatively long travel duration.

Figure 6: Scaled Average Passenger Amount (Color) and Travel Duration (Number) of Zip Code Connections for Private Transportation in and around Stuttgart.

70372	70374	70376	70378	70435	70437	70439	70469	70499	70563	70565	70567	70569	70597	70599	70619	70629	70734	70736	70771	70794	70806	70825
3	1	3	1	1	1	1	3	2	1	1	2	2	2	1	1	1	2	1	2	2	1	1
2	1	2	1	1	1	1	2	1	1	1	1	2	1	1	1	1	1	1	2	2	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	3	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	3	1	1	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	2	3	1	1	1	1	2	1	1	1	1	1	1	1	1	1	3	2	1	1	1	1
2	1	3	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
3	3	3	3	1	3	1	3	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1
1	1	3	3	1	3	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1
1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
1	1	3	3	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	3	1	2	2	1	3	3	1	1	1	1	1	1	1	1	1	1	1	1	2	2
1	1	1	1	1	1	1	3	3	1	1	1	1	1	1	1	1	1	1	1	1	1	2
1	1	1	1	1	1	1	1	1	1	2	2	3	1	1	1	1	1	1	2	1	1	1
1	1	1	1	1	1	1	1	1	2	1	2	2	1	1	1	1	1	1	2	1	1	1
1	1	1	1	1	1	1	1	1	2	2	3	3	3	2	1	1	1	1	3	2	1	1
1	1	1	1	1	1	1	1	1	3	2	2	3	2	1	1	1	1	1	2	1	1	1
1	1	1	1	1	1	1	1	1	1	1	3	2	3	2	2	1	1	1	3	2	1	1
1	1	1	1	1	1	1	1	1	1	1	2	1	2	3	2	1	1	1	1	3	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1	2	1	1
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1
3	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	1	1	1	1
2	1	2	2	1	1	1	1	1	1	1	1	1	1	1	1	1	3	3	1	1	1	1
1	1	1	1	1	1	1	1	1	2	2	3	2	2	1	1	1	1	1	3	3	1	1
1	1	1	1	1	1	1	1	1	1	1	3	1	2	2	1	2	1	1	3	3	1	1
1	1	1	1	2	3	1	2	1	1	1	1	1	1	1	1	1	1	1	1	1	3	1
1	1	2	1	2	1	1	2	2	1	1	1	3	3	3	3	3	3	3	3	3	3	3

The data for private transportation generally shows much more traffic compared to public transportation. Also in this case, there is much traffic on the diagonal around Feuerbach (70469), Möhringen (70567) and Vaihingen (70569 incl. university campus), but around Hallschlag (70376) and Filderstadt (70794) as well. For all of the mentioned zip codes with the exceptions of Möhringen and Filderstadt, connections to the city center are of particular interest especially during commuting times. This also applies for Degerloch (70597). Moreover, connections between the area behind the Heusteig quarter (70184) and Stuttgart-East (70188), Stuttgart-West (70197) and Vaihingen (70569), the area around the Northern Station (70191) and Hallschlag (70376), Bad-Cannstatt (70372) and Fellbach (70734), Vaihingen (70563) and Vaihingen (70569), Möhringen (70567) and Leinfelden-Echterdingen (70771), Möhringen (70567) and Degerloch (70597) and partly also other connections such as between Zuffenhausen (70437) and Kornwestheim (70806) seem to be suitable. Interestingly, connections to and from the Stuttgart airport (70629) are not of the highest importance in this mobility dataset, even though airport connections have been considered to be the first implementation connections for 3D mobility (Bock, 2019), indicating that aerial airport connections have to be evaluated case-by-case. However, against the backdrop of on average around 32,000 passengers at the Airport Stuttgart per day (Schunder, 2018) and around 350,500 commuters just into and out of the city of Stuttgart per day (Statistisches Landesamt Baden-Württemberg, 2019), this result seems reasonable. For every possible 3D mobility connection, airspace restrictions have to be taken into account which might prolong the travel time compared to the linear distance. This includes static objects such as nuclear plants or government facilities but also temporal events such as concerts. Werner, Duwe and Busch (2019) give an overview of further important properties for example with regard to the digital infrastructure.

Taking a deeper look at the travel durations for private transportation, it becomes apparent and does not surprise that during the commuting times, travel durations tend to be longer for many connections. As an air taxi service requires a high occupancy rate to be viable because of the high acquisition and operation costs compared to a taxi on the street, certain connections might only be offered during certain relevant times of the day. It is very important in this context to also determine the optimal fleet size for a given operating area so that idle times can be reduced to a minimum. For the vehicle allocation and scheduling, methods of artificial intelligence can be employed.

3.4 Infrastructure Requirements

3.4.1 General Requirements for 3D Mobility in Cities

Urban air vehicles and the corresponding infrastructure have to fulfill certain requirements when being used in cities – an environment, which has not originally been designed for this kind of traffic. The different vehicle and infrastructure concepts are, however, not equally suited or fully interchangeable for the transportation of people in an urban environment. In general, 3D mobility has relatively low demands in terms of physical infrastructure in contrast to other modes of transportation. Nevertheless, finding an appropriate location for a take-off and landing zone is a challenge for legal, architectural and other reasons as shown in the next paragraphs. In particular, the implementation of short take-off and landing solutions is limited since they require more space both on the ground but also in terms of reserved flight corridors. Whereas concepts not capable of vertical take-off and landing may require a runway with a length of up to around 1,000 meters including a safety buffer, the minimum surface for vertical take-off and landing concepts mostly depends on the airfoil of the vehicle. To allow for the ground effect, the area should be larger though and can sum up to a surface of around 15m x 15m. The landing sites have to be illuminated at night. If the air vehicles move autonomously, however, they may not be able to solely depend on visual signals such as lights or analog signage systems within the city because of disturbing signals which is why they need sensor information digitally provided by the infrastructure in addition to the internal sensing. As they are part of the urban air space, the air vehicles themselves also have to be equipped with light sources which make them recognizable in the air. Moreover, when the air vehicles are not in use, they have to be parked, maintained and charged. A corresponding infrastructure has to be provided for this.

In an urban environment, air vehicles can either take-off at ground level or from an elevated position such as the roof top of a building. Potential locations at ground level are city parking lots, park and ride facilities and mobility hubs. Additionally, the existing infrastructure of an airport could provide a proper environment for the take-off and landing for such a service as long as they do not interfere with regular plane flights and thus do not violate regulatory restrictions. Take-off and landing zones on elevated locations can be placed on top of residential buildings, public buildings such as train stations as well as on commercial buildings such as office buildings and malls. The top level of a parking garage would be another suitable option.

Irrespective of the level, the location has to fulfill various requirements. Depending on the extent of integration into the cities' mobility ecosystems, the location should be close to other connecting modes of personal transportation to offer intermodal mobility. Ideally, take-off and landing zones are placed in close proximity to the relevant nodes of the city's mobility system. These locations have to be sites where the arrival and departure flight paths are not compromised by obstacles also taking into account future structural developments such as new buildings or green infrastructure. Good options for such locations can generally be found at sites with an adjacent river or lake. In addition, the proximity to railroads and streets is beneficial since this offers the possibility of combining people and goods transportation and thus makes for a multi-functional land usage. Furthermore, 3D mobility causes additional noise in the city. For this reason, urban ports for 3D mobility should be located at a place where it has as little noise impact on the surrounding community as possible. Again, the proximity of streets could be beneficial, since there is already a certain level of noise accepted by the citizens. Finally, the selection of a take-off and landing area also requires the consideration of wind effects. Vertiports on the top of high-rise buildings have to deal with considerable wind velocities which can complicate the take-off and landing process. However, also lower situated ports can face unfavorable wind conditions when they are surrounded by higher buildings or structures that cause turbulent effects.

3.4.2 Ports at Ground Level

The ground level is naturally very accessible and convenient for citizens as it is easy for them to switch between different modes of transportation when they are on the same level. 3D mobility hubs at ground level could be designed in a way that they can be shared with other modes of transportation. Outside the regular operating hours the spaces could be used by other vehicles such as buses (bus stops) or cars (short time parking). Also, the charging infrastructure could be shared amongst all available, electric modes of transportation (pedelecs, cars, buses, trucks). Hybrid air mobility concepts which are both able to fly and to drive require take-off and landing zones on the ground as an interface between both modes. However, 3D mobility operating directly from the ground could potentially be a threat for the citizens, the animals and the nature. Therefore, proper precautions have to be made which require additional safety infrastructure. Another important aspect with regard to ground level ports is the occupation of public urban space which could be available for citizens as an environment for social interaction, recreational activities or other activities. This is generally referred to as the competition for land use.

3.4.3 Ports on Elevated Positions

Since most urban space at ground level is already occupied and dedicated to other purposes, it is desirable to create new spaces for urban transportation in elevated positions such as roof tops of buildings. Especially vertiports are conceivable. However, just because a roof top is not used otherwise, this does not mean that it is a suitable place to build a port for 3D mobility. Sometimes there are additional structures placed on a roof such as parts of the air conditioning system or elevator engines. Adding structures to provide the requirements for a proper take-off, landing and charging afterwards can be a challenge both from the architectural and the building regulation perspective. Furthermore, rooftops have to be accessible for the passengers. This implies that the roof top has been designed for the required mass. In addition, openly accessible elevators or – depending on the floor level difference – stairs up to the roof are required. Parking garages and malls could fulfill these requirements. An easy way to overcome some of these challenges is to use existing helipads that can be found on the top of numerous high-rise buildings in larger cities. In general, it is a demanding project to turn a roof top of an existing building into an openly accessible port for air vehicles. However, if all the crucial aspects are known in advance, they can be relatively easily considered in the planning of a new building featuring such a port. Moreover, it is important to keep in mind the potential passenger throughput restrictions caused by the limited capacities of elevators. In summary, it takes a considerable amount of time for the passengers to vertically reach 3D mobility port on a rooftop, which extends the first and last mile duration of the trip, and thus decreases the comfort and utility for the passengers. Against this backdrop, a 3D mobility port at ground level may be a superior solution.

3.4.4 Power Supply Infrastructure

Air vehicles have to be maintained and charged when they are not in the air. Therefore, a port has to provide the matching infrastructure. The corresponding requirements depend on different technological and operational parameters, which are summarized in Table 6.

Take-off and Landing Area	Number of Vehicles at a Time	Reason for Stop	Power Supply
ground level	single air vehicle	quickstop	conductive charging
elevated level	multiple air vehicles	(de)boarding	inductive charging
		charging/refueling	battery swapping
		maintenance	hydrogen refueling

Table 6: Influencing Factors for the Infrastructure Requirements.

Depending on the concept technology, gasoline, electric power or hydrogen has to be provided to refuel or charge the air vehicles. If the necessary infrastructure cannot be provided in an adequate way at a take-off and landing spot, the refueling and charging processes have to be relocated. The same applies to maintenance work. Relocating these processes has the disadvantage that the time for the probable additional transfer cannot be used for the main tasks of the air vehicles and the additional energy consumption increases the operating costs. Therefore, it is preferable to charge or refuel the vehicles as often as they are on the ground. Then again, the operational throughput especially of smaller take-off and landing spots could be increased by shortening the timeslots between the take-offs and landings through the outsourcing of the time intensive processes related for example to maintenance.

Depending on the employed technology, electric charging, battery swapping and hydrogen refueling are possible ways to restore the range of electric air vehicles. If the power supply can be provided at the landing spot, the dimensioning of the infrastructure mainly depends on the number of air vehicles to be served and their technology. To set up a suitable charging or refueling infrastructure for 3D mobility, it is important to consider requirements in terms of space, energy and supply technology. This particularly affects ports on elevated positions such as on high-rise buildings.

Considering the cost structure for the operation of 3D mobility, downtimes have to be minimized. This means in case of charging the batteries directly in the air vehicle, the charging power has to be maximized. The required charging technology is well known from electric cars called fast charging with up to 150 kW power or ultra-fast charging with up to 350 kW power (van Niersen & Schulte, 2019). Even higher power systems have been demonstrated for buses and trucks (Jang, 2018). Current charging stations are connected with the vehicles via plugs and cables. The infrastructure as well as the corresponding charging protocols are standardized and the connection could easily be done by the pilot himself or an optional port operator. In the future, autonomous vehicles could themselves connect to the infrastructure with the corresponding equipment. Wireless, so-called inductive charging systems are currently also under development. In case of wireless charging, no visible but certainly physical infrastructure has to be added on the rooftop.

Fast charging would be the favored option for landing spots on buildings. It requires only little space and construction efforts for the infrastructure as compared to the alternatives. However, in contrast to conventional charging modes with lower power rates, fast charging can reduce the battery lifetime and thus induce additional battery costs which is why some companies such as Volocopter refrain from using it (Volocopter, 2019, p. 21). Moreover, fast charging requires supply conductors with a larger cross-section, which can lead to expensive wiring costs. These supply lines have to be available in the buildings. Additionally, the power rate of even one station could exceed the maximum load of the building. Thus, at least when several air vehicles have to be charged at the same time, an energy management system is mandatory. With such systems, the current energy consumption of the building can be monitored. It is possible to temporarily reduce the charging power or schedule the charging events if needed. Another option is the implementation of an additional battery storage, which can be charged in times with low power demands and discharged when extra power is needed. The planning, simulation, implementation, and operation of smart integrated energy systems (so-called micro grids) are important tasks in current research (Klausmann & Göhler, 2019), in particular with regard to the coming challenges of charging high numbers of electric cars in a small area. Developed solutions should be compatible with the future requirements of charging electric air vehicles.

An even faster option to recharge an air vehicle is a battery swapping system which has recently been pursued by the company Volocopter (Volocopter, 2019, p. 21). In this case, a discharged battery will be exchanged by a charged one and the recharging is done separately. By using this option, charging can be done with lower loads over longer periods, which reduces the requirements for both the battery and the electric infrastructure. An energy management system could monitor the demands of the building and the grid and set charging priorities for the batteries. The battery swap itself can be done manually by a port operator or with fully automated systems. Such automated swap robots have technically already been demonstrated for electric cars by the company Better Place in 2009 (Squatriglia, 2009) regardless of their failure and have more recently been developed by the company Tesla (Lampert, 2017) with patents for both fully automated and manual systems. These systems have the potential to be integrated on rooftops. However, a battery swap station requires additional space for the storage unit. Due to the batteries' susceptibility to temperature, they should not be stored outside the building where they are potentially exposed to extreme weather conditions. Instead, additional space inside the building has to be reserved including the transportation ways for the items. With the planning of the storage rooms also regulations for fire protection and the high mass of the batteries must be taken into account. With the flexibility provided by a battery storage system, additional income could be generated by offering grid services controlled by the energy management system. However, battery swapping has some considerable disadvantages which has led to a low relevance for the application in electric cars. First, the battery is the most expensive part of the vehicle and within the battery swapping concept more than one battery is needed per vehicle. If several different types of batteries were used, each of them must be kept in a storage room. Second, most car manufacturers have not allowed for restrictions of the battery design, packaging and access up to now making the establishment of an over-arching standard for exchanging batteries impossible as of today. Moreover, they expressed concerns about the reliability of the interface connections, which comprise not only the power connections but also the connections of secondary systems such as cooling circuits. These problems will affect electric air vehicles in a similar manner. Thus, new concepts have to be developed for the usability of swapping stations. It seems unpractical to implement multiple systems at one site due to their high costs. However, relocating the air vehicles after the battery swapping process might also be unfavorable because of the energy intensive additional take-offs. Another issue to address with regard to the operation and business model is the ownership of the battery in case of privately owned air vehicles. It is unlikely that private owners are willing to change new batteries against older ones with potentially lower capacities. In summary, battery swapping stations are technically more complex with correspondingly higher risks and maintenance requirements compared with fast charging stations. They need more space, are more expensive and need an operator. However, the battery swapping system is faster and the total charging power requirement of the site can be lower.

For fuel cell based air vehicles, hydrogen must be provided. The time for refueling can be as fast as a battery swapping process but with distinct advantages: the hydrogen storage can be shared. One refueling station can thus be used for multiple air vehicles on different parking positions. The technique is well known and already used for fuel cell cars (Iwan, 2018). Hydrogen is distributed as a gas with high pressure (GH2, 350 bar/700 bar) or as a liquid (LH2, -253 °C, 16 bar). Ports at the ground level can easily be supplied by trucks or by pipelines. The costs for the related infrastructure is similar to a battery swapping station and more expensive than fast charging equipment. For ports on elevated positions, the infrastructure requirements are even higher and more challenging. Storing hydrogen in a building requires space for the tanks. If the supply is ensured via pipelines or trucks, the building has to be equipped with sufficient supply lines to provide the hydrogen at the right place. Another option would be to generate the hydrogen onsite in close proximity to the 3D mobility port on the building resulting in higher investments and maintenance efforts though. Besides that, smaller systems for hydrogen production, for example via electrolysis, are less efficient than centralized plants with higher capacities. Additionally, areas have to be reserved for the local hydrogen production process and a local power source such as photovoltaic systems or a sufficiently dimensioned grid connection is needed. Storing or even producing hydrogen at the top of buildings is challenging with regard to fire protection, especially in combination with air traffic and the risk of a crash. Accordingly, specific regulations have to be considered. Because of the described safety problems, hydrogen could be chemically bound (Teichmann, et al., 2012) when it is placed on a rooftop. Corresponding techniques such as Liquid Organic Hydrogen Carrier (LOHC) are ready for the market (Teichmann, 2018).

A location based evaluation of the available technologies for non-conventional power supply is provided in Table 7.

Table 7: Location Based Assessment of Technologies for Non-Conventional Power Supply.

Key:
++ very positive
+ positive
o neutral
- negative
-- very negative

	Fast Charging		Battery Swapping		Hydrogen Refueling	
	ground	elevated	ground	elevated	ground	elevated
Space	++	++	--	o	-	o
Complexity	++	++	-	o	-	+
Integration & Handling	-	+	-	+	--	++
Capacity	-	-	+	+	+	++
Cost	+	+	-	-	--	-
Safety	++	++	-	o	--	o
Readiness	++	++	-	+	o	++

4 URBAN AND RURAL USE CASES

The advent of flying cars, passenger drones and other vehicles up in the air creates 3D mobility opportunities for people and goods and will probably have radical effects on the mobility behavior and the related industries. In this chapter the focus lies on use cases for the transportation of people. First, an overview of possible use cases is given, before a deep dive into selected use cases is provided analyzing the target customers and suitable technologies.

4.1 Overview of Possible Use Cases

Multiple use cases for air mobility have already been identified in literature – mostly with a focus on goods transportation but recently also on people transportation. Table 8 provides an overview of selected possible use cases for personal mobility. The bold printed ones are discussed in more detail in the following subchapter.

Use Case Context	Use Cases for Passenger Mobility	Main Target Customers
Commuting and Traveling	■ **Urban Air Taxi** ■ **Intercity Air Express** ■ **Airport Shuttle** ■ **Personal Air Vehicle** ■ **Ferry Substitute** ■ Flying Mountain Express ■ Aerial Desert Vehicle	■ Individuals Transportation ■ Service Providers
Surveillance and Safety	■ **Flying Ambulance** ■ Aerial Police Patrol ■ Aerial Border Reinforcement Patrol ■ Flying Fire Brigade ■ Flying Sea/Mountain Rescue Mission Vehicle	■ Public Sector ■ Medical Providers

Use Case Context	Use Cases for Passenger Mobility	Main Target Customers
Working	■ Flying Company Car ■ Flying Warehouse Vehicle ■ Flying Post Vehicle ■ Aerial Construction Vehicle ■ Flying Research Vehicle (e.g. Animals, Ocean, Glacier, Pole)	■ Companies ■ Public Sector ■ Research Institutes
Leisure and Recreation	■ Aerial Amusement Park Vehicle ■ Aerial Vehicle for Professional Air Races ■ Aerial Sightseeing Vehicle ■ Flying Shuttle for Big Events	■ Companies Focusing on Entertainment (Amusement Parks, Sightseeing Companies)

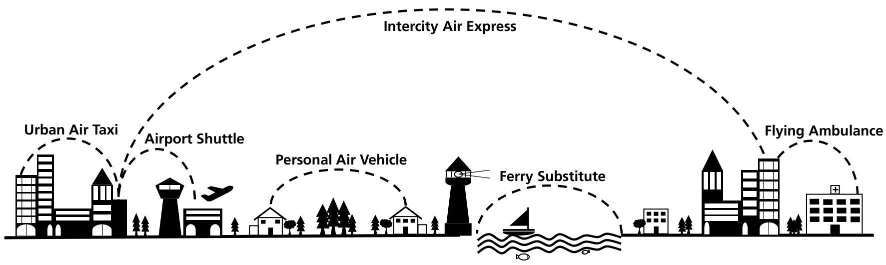
Table 8: Overview of Selected Possible Use Cases.

Thus, potential beneficiaries of 3D mobility include private individuals, companies and the public sector among others. They may use flying vehicles – apart from mobility as the mere purpose – for instance in the context of commuting and traveling, working, leisure and recreation, or surveillance and safety.

4.2 Deep Dive into Selected Use Cases

In this chapter, the highlighted use cases depicted in Figure 7 are elaborated. Before going into more detail, the setting and analysis dimensions of the use cases are explained.

Figure 7: Overview of the Considered Use Cases.



The investigated use cases aim at solving mobility problems for which the transportation by existing mobility modes is either not possible, insufficient or simply improvable regarding the requirements of the user. Each use case presented in Figure 7 is described based on:

- a user story expressing the mobility problem and taking into account the transportation environment
- the real world relevance
- the target customers
- possible technologies and infrastructure
- the customer experience

In the following paragraphs, we will briefly outline and clarify the key terms which are important to understand the use case descriptions.

User Story

The user story describes the mobility problem to be solved through the use case from an individual or corporate perspective. The transportation environment specifies the environment in which the air vehicle is used. That is, whether the passenger uses the mobility mode for trips in urban, suburban or rural areas, for trips across rivers and lakes, for intercity transportation, or a mixture of the possible traveling environments. The vehicle ownership describes whether 3D mobility is consumed as a product or a shared service. Both the transportation environment and the vehicle ownership influence the possible use case. Table 9 classifies the investigated use cases of Figure 7 according to the transportation environment and vehicle ownership.

		Transportation Environment			
		Urban/ Suburban	Rural	Water	Intercity
Vehicle Ownership	Private		Personal Air Vehicle		
	Shared	■ Urban Air Taxi ■ Airport Shuttle ■ Flying Ambulance		Ferry Substitute	Intercity Air Express

Table 9: Considered Use Cases Classified by the Transportation Environment and the Vehicle Ownership.

Real World Relevance

The real world relevance of each use case refers to the practical importance of solving the specific mobility problem. Especially the number of potential target customers in the near and distant future determines this relevance and the economic prospects.

Target Customers

The target customers are groups of people who are likely to use the air vehicle to solve their mobility problem in the near or distant future. They may differ with regard to their requirements in critical product and service dimensions. For each use case, we evaluate the importance of relevant dimensions on an ordinal scale. The considered product and service dimensions of 3D mobility are presented in Table 10. Other important but not use case specific dimensions such as noise and emissions were intentionally disregarded here.

Service dimension	This dimension describes the importance of ….
Time	…the total travel time needed including the first and last mile to get to the vehicle or the final destination, respectively, and the punctuality and reliability of the aerial transportation.
Availability	…the spatial and temporal availability of the vehicle or service referring to the mobility hub locations and the service frequency.
Costs	…the costs for the acquisition and use of the air vehicle or the respective service.
Safety	…the travel safety.
Accessibility	…the ease of (de)boarding of the passengers and goods.
Comfort	…the comfort of waiting, (de)boarding and being onboard including the available interior space etc.
Entertainment & Productivity	…the onboard experience including infotainment and entertainment but also the possibility to work.
Flying Experience	…actively flying the air vehicle.

Table 10: Critical Dimensions of the Customer Acceptance of 3D mobility.

Possible Vehicle and Infrastructure Technology

The technological requirements for the use cases refer to the vehicle and infrastructure technology considered to be suitable for the use case. The technology suitability highly depends on the location of usage such as urban or rural areas. As also other combinations of the vehicle concepts and propulsion technologies than the prototyped examples described in chapter 2.1 are possible, more thinkable combinations are considered for the vehicle concepts multicopter, modular car-quadrocopter and tilt-concepts such as the Lilium Jet.

Customer Experience

The customer experience refers to the onboard and (dis)embarking experience as well as the necessary ground transportation to reach the air vehicle and to depart for the final destination. Table 11 differentiates possible generic journey experiences by the vehicle ownership (private vs. shared) and by the flexibility of the transportation service (stationary vs. free-floating). If the use case requires the user to combine mobility modes to get to the boarding position or to his destination, then the journey experience is classified as intermodal.

Transportation Type	Vehicle Search & Booking	First Mile Transportation to Vehicle	Boarding	Riding	Deboarding & Billing	Last Mile Transportation to Destination	Use Cases
private			no waiting experience, high availability	autonomous or (self-) piloted	no billing experience		Personal Air Vehicle, Flying Ambulance
shared stationary	by digital means	by foot or with public transportation	waiting experience, medium availability	autonomous or piloted	billing experience	by foot or with public transportation	Airport Shuttle, Intercity Air Express, Ferry Substitute
shared free-floating	by digital means	by foot	(no) waiting experience, low availability	autonomous or piloted	billing experience		Urban Air Taxi

Table 11: Generic Customer Journeys of 3D Mobility.

4.2.1 Urban Air Taxi

User Story

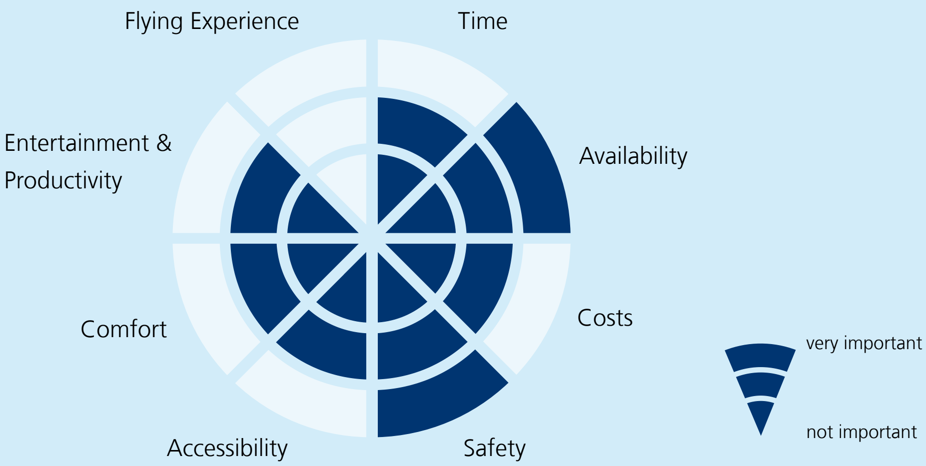
Short-haul commuter: *"As a daily commuter who lives in a close-meshed skyscraper metropolis and just has to travel about 10 miles to my workplace, I wish to not get stuck in traffic jams for several hours per week."*

Real World Relevance

About 1.3 million rides by taxi or rental car per day in Germany.

In 2018, drivers spent more than 250 hours per year in traffic jams in the most congested cities of the world (Inrix, 2019). This is especially straining for inner-city commuters traveling short distances during peak hours. INRIX estimates that the congestion on German roads leads to a yearly delay per commuter of on average 120 hours (Inrix, 2019b). Urban air taxis could help to bypass and mitigate the congestion problem on the ground and save time for instance for those following strict time schedules. Moreover, such a use case would be a promising source of revenue for taxi and rental car operators: There are about 1.3 million passenger rides by taxi or rental car in Germany every day (BZP, 2016).

Target Customer



Premium taxi service customers and first class city-railway travelers may be the first potential users of such a service because of the possibly higher travel costs per mile compared to existing ground mass transportation modes in the beginning. In the more distant future, as the benefits of decreasing unit and operating costs accrue, almost all persons who have to travel short to medium distances within a city could be potential users of such a service. To actually be considered as an alternative to conventional ground transportation, it is recommendable that the service entails the following characteristics: First, the service should offer a close-meshed grid of mobility hubs. Otherwise, the time savings, which most of the potential customers hope for, will be difficult to achieve because of the time spent to travel to or from the mobility hub. Second, a high daily availability of the service has been identified to be of utmost importance for the acceptance by the average commuter (Schuchardt, et al., 2015, p. 25) and should therefore be realized. Third, potential users seem to prefer fully autonomous air taxis over air taxis driven by professional pilots (Sivak & Schoettle, 2017, p. 11; Meyer-Soylu, et al., 2014, p. 18) so that autonomous flying technology could increase the acceptance and should thus be implemented as soon as technically and legally possible.

Possible Vehicle and Infrastructure Technology

	VTOL			STOL
Vehicle Concept	**Multicopter**	**Tilt-Wing**	**Modular Car-Quadrocopter**	**Gyrocopter**
Technology	Electric	Electric	Electric or Hybrid	Conventional
Fuel cell + hydrogen station	◕	◕	◕	Gasoline + gasoline station ○
Electric + fast charging station	◕	◕	◕	
Electric + battery swap system	◕	◕	◕	

Degree of suitability:
- ● *perfect*
- ◕ *high*
- ◑ *medium*
- ◔ *low*
- ○ *not suited*

Vertical take-off and landing capability and relatively small vehicle dimensions are prerequisites for operations in dense urban areas. A multicopter may thus be well suited to solve short to medium distance mobility needs within a city. Also, a shared roof module for flying with a modular car-quadrocopter may be recommendable to save costs and relieve the urban air space because vehicles based on such a concept could be driven on the ground during less congested times or in less congested areas. The additionally required physical infrastructure for charging or refueling varies with the technology of the air vehicle. Battery electric vehicles may be better suited than hydrogen or gasoline powered ones in urban areas because the implementation of charging stations on elevated positions (e.g. on the top level of garages) is cheaper than building tank stations on elevated positions. Furthermore, if the refueling stations are located at ground level and the vertiports on elevated positions, a higher energy consumption would be the consequence. A battery swapping system is more complex and requires an expensive infrastructure. Cheaper fast charging stations could be used to reduce the idle time and to increase the utilization and availability of the electric air vehicles (Uber, 2016, p. 65). However, the wiring and potential groundworks can still be costly and a potentially faster battery degradation has to be taken into account.

Customer Experience

Transportation Type:	Vehicle Search & Booking	First Mile Transportation to Vehicle	Boarding	Riding	Deboarding & Billing	Last Mile Transportation to Destination
shared free-floating	order vehicle online	walk to next pick-up position	pass security check, wait until air taxi arrives and embark	engage in simple activities not related to flying	disembark and do payment	

The customer may order and pay the air taxi via an app and then walk to the next boarding position. Due to the short flight duration, customers can only engage in non-complex activities onboard such as reading or phoning. After the flight, the air taxi drops the customer off close to his destination.

4.2.2 Personal Air Vehicle

User Story

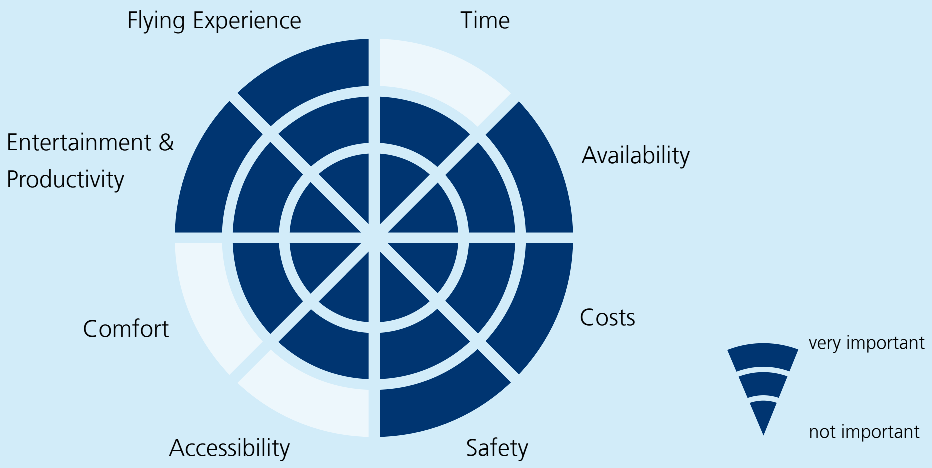
Suburban resident / Country(wo)man: *"As a person who lives in a rather rural area with a poorly developed road network and few public transportation possibilities, I wish that I did not have to drive time-consuming detours every time I visit my friend who lives in a similar area."*

Real World Relevance

In 2019, there are about 47 million cars in use by private households in Germany (Kraftfahrt-Bundesamt, 2019) and the motorized private transportation accounts nationwide for about 80% of the inland passenger transportation kilometers (Bundesamt für Güterverkehr, 2019, p. 5). Especially in less densely populated areas, where the individual motorization rate is higher (Eisenmann et al. 2018, p. 40), personal air vehicles could offer a more flexible form of transportation for people suffering under bad connectivity by car or public transportation.

47 million personal vehicles in Germany.

Target Customer



Premium car owners living in suburban or less densely populated areas could be first potential target customers. They may use PAVs for work, private errands or just for amusement. Other buyers of PAVs might even be sportsmen who want to use such vehicles for professional air races. A focus group analysis of Meyer-Soylu et al. in Tübingen, Zurich and Liverpool shows that the respondents tend to favor automated flying in certain circumstances such as for routine purposes or in situations of high traffic densities. However, they seemingly want to have the possibility of self-piloting in other situations such as during leisure trips, at times of low traffic density, for sports or in case of a system failure (Meyer-Soylu, et al., 2014, p. 21). An online questionnaire of Sivak & Schoettle in the USA shows that males tend to have a greater interest in flying cars than females and that females are more concerned regarding the safety of flying cars than males, e.g. in congested airspace, during bad weather conditions or at night. This is in line with the willingness to pay: males stated, on average, a higher willingness to pay for the purchase of PAVs than females. Further, the respondents of the study preferred a seating capacity between 3-4 and a minimum range of 400 miles (Sivak & Schoettle, 2017, pp. 5-12).

Possible Vehicle and Infrastructure Technology

Degree of suitability:
perfect ●
high ◕
medium ◑
low ◔
not suited ○

	VTOL			STOL
Vehicle Concept	**Multicopter**	**Tilt-Wing**	**Modular Car-Quadrocopter**	**Gyrocopter**
Technology	Electric	Electric	Electric or Hybrid	Conventional
Fuel cell + hydrogen station	◔	◑	◕	Gasoline + gasoline station ●
Electric + fast charging station	◔	◑	◑	
Electric + battery swap system	◔	◔	◕	

Clearly, the technological requirements of PAVs strongly depend on the user's mobility needs. For the considered use case, a flying car such as a gyrocopter or a modular car-quadrocopter may be recommendable since they both allow the user to overcome the limited ground transportation opportunities in rural areas and if necessary, both vehicles would be roadable in the inner city to increase fuel efficiency. Furthermore, if the PAV is compact for instance through foldable propellers or wings, the existing refueling/charging infrastructure would be sufficient and the users could use existing indoor car-parking spaces. For urban inhabitants, however, the VTOL capability of the vehicle is critical so that a personal quadrocopter or a tilt-concept such as the Jet could be a reasonable alternative. They additionally offer a locally emission free propulsion.

Customer Experience

Transportation Type:	Vehicle Search & Booking	First Mile Transportation to Vehicle	Boarding	Riding	Deboarding & Billing	Last Mile Transportation to Destination
shared free-floating			unlock and enter PAV	fly the PAV	park the PAV and disembark	

The experience of PAVs may not substantially differ from cars on the road: The car offers flexible point-to-point connections and requires the user to park, refuel or charge and maintain the car himself. During the trip (on the ground and in the air) the user may have the choice between either driving and flying himself or engaging in non-driving activities.

4.2.3 Intercity Air Express

User Story

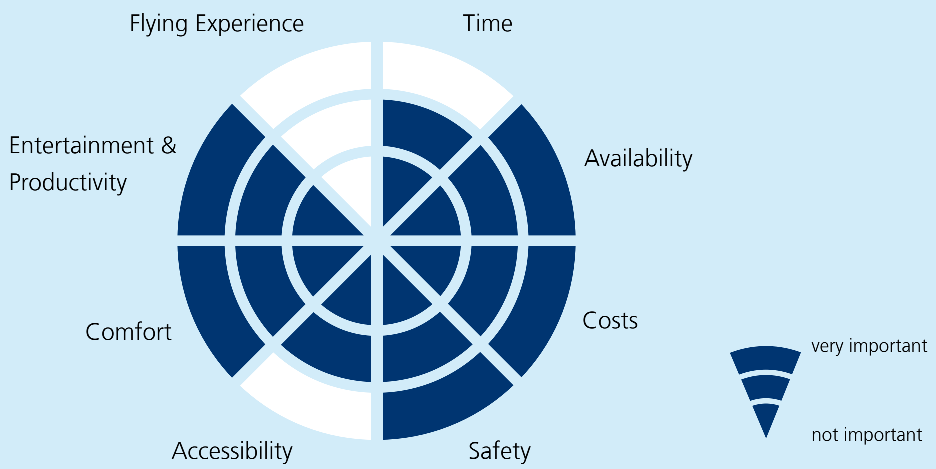
Long-haul commuter: *"As a long-haul commuter who has to drive more than 150 miles each day, I'm looking for a fast and cheap mobility solution. Traveling by car takes too long because of the commuter traffic and traveling by plane is not convenient because of upstream and downstream journeys. Taking the train is also not optimal, because I would have to switch trains more than once. That costs time, often fails and hampers my travel comfort."*

Real World Relevance

About 1.3 million long distance commuters in Germany.

The number of passengers using the railway or the plane has increased over the last years in Germany. Public transportation providers carried 180 million long-distance trip passengers in 2018 – an all-time high (Bundesamt für Güterverkehr, 2019, p. 5). Clearly, commuting plays a significant role for the ever-increasing journey distances to be covered by people. The typical average daily commuting distance in Germany notably surged since 1999. In 2017, the German federal Institute for Research on Building, Urban Affairs and Spatial Development identified more than 1.3 million Germans as long-distance commuters routinely traveling over 150 kilometers for work (BBSR, 2017). Against this backdrop, the intercity air express could complement existing services of railway operators such as the Deutsche Bahn (DB) and may help to address current problems of critical service dimensions. The service would be independent of railway-network problems and irregularities and thus may help to alleviate the punctuality and reliability problems, which increased since 2017 (Deutsche Bahn, 2018). Moreover, the service could take pressure off the transportation system in times of scheduled maintenances and construction works which may last for months.

Target Customer



All people who have to travel long distances or must combine different mobility solutions could be beneficiaries of this service. Potential target customers are therefore long-haul commuters and tourists among others. For mothers with strollers, pensioners, wheelchair users or other disabled persons, who struggle with the difference in altitude between the train and the platform edge, such a service could also offer an alternative public transportation means with better accessibility if constructed accordingly.

Possible Vehicle and Infrastructure Technology

	VTOL			STOL
Vehicle Concept	**Multicopter**	**Tilt-Wing**	**Modular Car-Quadrocopter**	**Gyrocopter**
Technology	Electric	Electric	Electric or Hybrid	Conventional
Fuel cell + hydrogen station	low	perfect	medium	Gasoline + gasoline station: high
Electric + fast charging station	low	perfect	medium	
Electric + battery swap system	low	perfect	medium	

Degree of suitability:

- *perfect*
- *high*
- *medium*
- *low*
- *not suited*

Due to the long travel distances being covered, tilt-concepts such as the Jet may be suitable concepts to solve the mobility problem because vehicles with wings offer the required energy efficiency. This also holds true for concepts with conventional powertrains as electric powertrains offer a shorter range because of the poorer gravimetric energy density of the battery. If the air vehicle only supports STOL, it may have to land at special landing locations at the edge of the city whereas the VTOL technology would enable the vehicles to land on mobility hubs in the city such as large parking slots on buildings or streets. To reduce the urban noise of the air vehicle and to offer a high service level, the intercity air express should further be able to fly on a higher altitude and at a greater speed than urban air taxis and should fly from mobility hub to mobility hub based on schedules.

Customer Experience

Transportation Type:	Vehicle Search & Booking	First Mile Trans-portation to Vehicle	Boarding	Riding	Deboarding & Billing	Last Mile Trans-portation to Destination
shared stationary	by digital means and pay	use public transportation to reach the port	pass security check, wait until air taxi arrives and embark	engage in complex activities not related to flying	disembark	use comple-mentary trans-portation mode to get to destination

The service should be implemented in relatively large mobility hubs so that several persons can almost simultaneously (dis-)embark with their luggage and it should offer the possibility to easily switch the vehicle or even the mobility mode. The interiors should cater for different and sophisticated passenger needs. Depending on the trip duration, the customers may for instance want to hear music, read, be entertained or even perform more complex tasks like working or sleeping. Real-time passenger connectivity and infotainment for the seamless journey planning are further critical factors for the customer acceptance.

4.2.4 Ferry Substitute

User Story

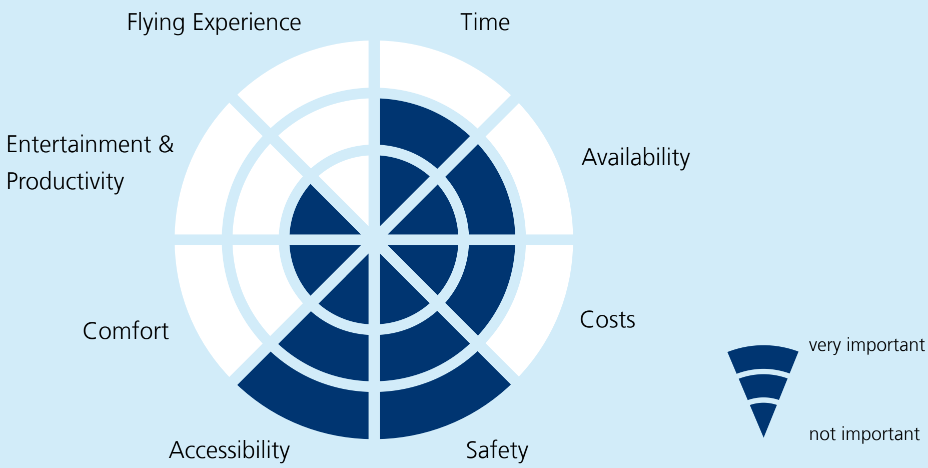
Person living close to a waterbody: *"As someone who lives near a riverbank, I have to take detours with the car to get to work. There are only few, always congested bridges and sparse ferry rides."*

Real World Relevance

In Germany, air vehicles could complement or partly substitute the fleet of around 1,000 passenger ships, almost 200 launches and roughly 120 ferries for passenger transportation (Wasserstraßen- & Schiffahrtsverwaltung des Bundes, 2017, p. 10). Clearly, the importance for such a use case is lower for landlocked and dry countries, but it is still high for landscapes which are rich of rivers and lakes where the topography entails long road trips. With an air vehicle, the trip time in such water-abundant landscapes would no longer be affected by sparse ferry services.

About 940 inland river ships for daily passenger transportation in Germany.

Target Customer



Potential target customers are people who must daily cross a waterbody such as a river or a lake, but for whom traveling by car takes too long because of necessary detours and traveling by ferry or plane is too expensive or does not fit into the time schedule. German ferry users and especially commuters can thus be identified as potential beneficiaries of air vehicles which are able to cover small to medium distances across lakes and rivers. Further potential customer groups are tourists who must use the ferry to get to their holiday destination or people suffering under seasickness.

Possible Vehicle and Infrastructure Technology

Degree of suitability:
- *perfect* ●
- *high* ◕
- *medium* ◑
- *low* ◔
- *not suited* ○

	VTOL			STOL
Vehicle Concept	**Multicopter**	**Tilt-Wing**	**Modular Car-Quadrocopter**	**Gyrocopter**
Technology	Electric	Electric	Electric or Hybrid	Conventional
Fuel cell + hydrogen station	◕	◕	◕	Gasoline + gasoline station ◑
Electric + fast charging station	◑	◑	◑	
Electric + battery swap system	◔	◔	◔	

For the considered use case, in which the distance across the waterbody is rather short, modular car-quadrocopters would be suitable. If a commercial operator offers the aerial ferry service and passenger throughput is high, the terminals should have charging opportunities. For longer distances, concepts with wings offering a higher range are more suitable than others. In this case, also STOL concepts could be of interest.

Customer Experience

Transportation Type:	Vehicle Search & Booking	First Mile Transportation to Vehicle	Boarding	Riding	Deboarding & Billing	Last Mile Transportation to Destination
shared stationary	by digital means and pay	use public transportation to reach the port	pass security check, wait until air taxi arrives and embark	engage in simple activities not related to flying	disembark	use complementary transportation mode to get to destination

The ferry substitute allows the user to reach his destination without possibly getting stuck in traffic jams on congested bridges. It should offer more frequent connections compared to conventional ferry services and might even offer an end-to-end mobility without detours due to the waterbodies.

4.2.5 Flying Ambulance

User Story

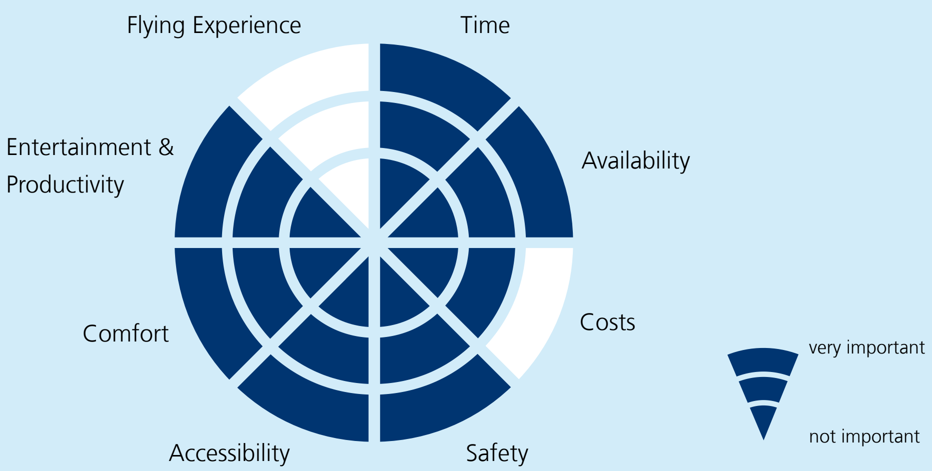
Emergency physician: *"As an emergency physician, I can say that rescue trips in urban areas often take too long because the roads are congested especially in the rush hour. When it comes to the administration of first aid and medical treatment, however, every single minute counts."*

Real World Relevance

The potential value of 3D mobility for the medical industry and its customers is remarkable. In Germany alone, the four largest providers of aerial evacuations operated a fleet of about 80 rescue helicopters and flew about 100,000 rescue trips in 2017 (Westphal, 2018). Additionally, there were about 20,000 ambulance vehicles in Germany in use at the beginning of that year (Statista, 2018). The problems with existing mobility modes for rescue missions are striking though. The relatively expensive use of rescue helicopters can be problematic in densely built-up urban areas. Ambulance vehicles on the road run into difficulties in case of an unclear place of action, are quite slow in emergencies due to the high traffic density, and cannot be used at all in landscapes with no road infrastructure such as mountains. Thus, ambulances and helicopters must nowadays complement each other. Because of the smaller vehicle acquisition and operating costs of 3D mobility compared to helicopters, the medical fleet could be expanded at little costs augmenting the availability and punctuality of first aid and thus increasing the chance of survival for people in critical condition (Consumers Union , 2017, p. 9). Flying ambulances may therefore be beneficial both for health care providers and their patients and could complement ambulance vehicles and helicopters or partly substitute them.

More than 100,000 rescue missions by helicopter in Germany.

Target Customer



Target Customers of flying ambulances are public and private health care providers. They can use them in accident response for people who require first aid and for the airlift of passengers. Fast transportation of patients is, for instance, important for patients living far away from a hospital or in case of motorway accidents when the road is blocked. Other applications in first aid response include the rescue of injured climbers and skiers. Flying ambulances could further be used to transfer patients in serious medical conditions to another medical facility if the local facility has no free capacities, lacks the relevant skills or in case of a power blackout. If the patients do not require extensive medical surveillance during the transportation because they for example just want to relocate closer to family members, the transportation can also be performed autonomously as soon as technologically feasible.

Possible Vehicle and Infrastructure Technology

Degree of suitability:
- *perfect* ●
- *high* ◕
- *medium* ◑
- *low* ◔
- *not suited* ○

	VTOL			STOL
Vehicle Concept	**Multicopter**	**Tilt-Wing**	**Modular Car-Quadrocopter**	**Gyrocopter**
Technology	Electric	Electric	Electric or Hybrid	Conventional
Fuel cell + hydrogen station	◕	●	◕	Gasoline + gasoline station ◑
Electric + fast charging station	◑	◑	◔	
Electric + battery swap system	◕	●	◕	

For use cases in urban areas, VTOL technology is crucial. This also applies to urban rescue operations, so that multicopters and tilt concepts are generally suitable. Because the roof module of car-quadrocopters may not be able to carry the required load – i.e. the patient, the rescue doctor(s), the medical equipment, the pilot and the vehicle itself – it may not be well-suited. Since flying ambulances must be able to fly even during bad weather conditions, emergency air vehicles should have sophisticated flight assistance systems beyond standard equipment such as an autopilot and a weather radar which is indispensable especially for rescue missions in the mountains.

Customer Experience

Transportation Type:	Vehicle Search & Booking	First Mile Trans-portation to Vehicle	Boarding	Riding	Deboarding & Billing	Last Mile Trans-portation to Destination
private	order		unlock and enter PAV	medical treatment	disembark and transfer into hospital	

To be able to reach the patient and provide medical care as quickly as possible, a fast disposition of the vehicle and clearance for take-off are of major importance. Similarly, the landing and (de)boarding processes have to be organized as lean as possible to save time. However, the safety of the transportation process is always of prime importance for all stakeholders. A real-time provision of mission data beforehand is helpful for the vehicle to be properly equipped. Against this backdrop, a stable onboard connectivity is important to manage downstream processes. Moreover, a smooth ride is crucial for a correct treatment of the passenger by the physician to avoid further injuries.

4.2.6 Airport Shuttle

User Story

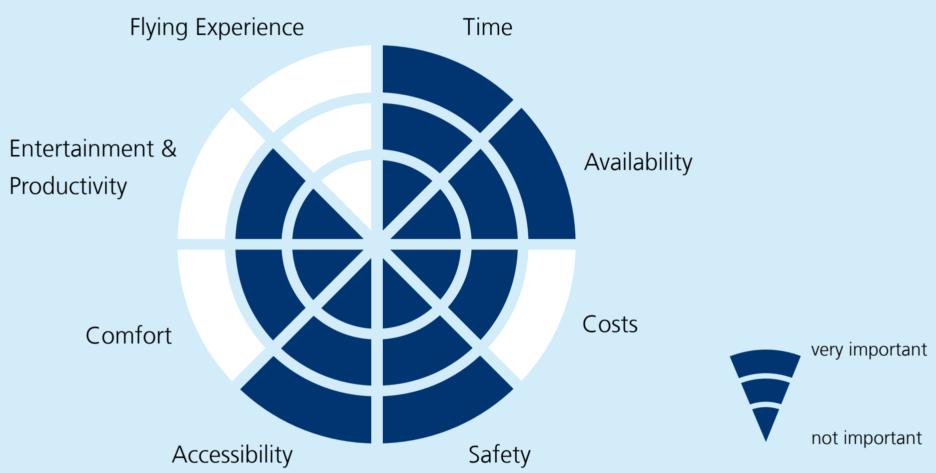
Plane passenger: *"As a suburban resident, I have to complain about the bad airport-downtown connection in my hometown with public transportation. I have to wait too long at the station for a train, then must switch trains to reach my destination."*

Real World Relevance

About 123 million plane passengers per year in Germany.

In 2018, an all-time high of almost 123 million passengers departed from the 24 largest commercial airports in Germany (Statistisches Bundesamt, 2019). An airport shuttle would be a service with the only purpose to help plane passengers reach the airport in time and to carry them back to a mobility hub in the inner city or to their final destination in rural areas. With such a service, plane passengers would no longer be dependent on the delicate and unreliable public transportation in some cities or the expensive ground taxi services in Germany compared to other European countries (EC Report, 2016, p. 15;100) and would thus no longer suffer under the bad and expensive reachability of airports in some cities. The German Federal Institute for Research on Building, Urban Affairs and Spatial Development identified significant deficits regarding the reachability of airports with cars in particular for people living in costal locations or at the national boarder. Moreover, a few German international airports still have no direct connection to the rail network like in Berlin Tegel. It is therefore not surprising that in most German areas it takes at least 60 minutes to get to the next international airport by train (BBSR, 2018, p. 12).

Target Customer



Target customers of a flying airport shuttle are first-class plane passengers in the near future and every plane passenger in the more distant future. The service could be differentiated to address broader customer groups. For people living in rural areas, the service could in the long term even offer connections between the airport and a flexible point at comparatively higher fares but higher comfort. For people living close to the city center a fixed hub to airport transportation service will be enough though. Thus, depending on the operation and business model, such a use case would be a promising source of revenue for airport operators and airlines.

Possible Vehicle and Infrastructure Technology

	VTOL			STOL
Vehicle Concept	**Multicopter**	**Tilt-Wing**	**Modular Car-Quadrocopter**	**Gyrocopter**
Technology	Electric	Electric	Electric or Hybrid	Conventional
Fuel cell + hydrogen station	high	perfect	high	Gasoline + gasoline station: high
Electric + fast charging station	high	perfect	high	
Electric + battery swap system	high	perfect	high	

Degree of suitability:
- *perfect*
- *high*
- *medium*
- *low*
- *not suited*

Each of the considered air vehicles is generally applicable for this use case. A tilt-concept such as the jet has the advantages of a relatively high range, speed and vertical take-off and landing capability. A multicopter or modular car-quadrocopter could also be used especially for short distances. For people in living in rural areas, roadable aircrafts and gyrocopters could be suited quite well in case there are long enough runways at the take-off and landing locations. If the propulsion of the used vehicle is battery electric, then the airport should feature corresponding charging possibilities.

Customer Experience

Transportation Type:	Vehicle Search & Booking	First Mile Trans-portation to Vehicle	Boarding	Riding	Deboarding & Billing	Last Mile Trans-portation to Destination
shared stationary	by digital means and pay	use public transportation to reach the port	pass security check, wait until air taxi arrives and embark	engage in simple activities not related to flying	disembark	

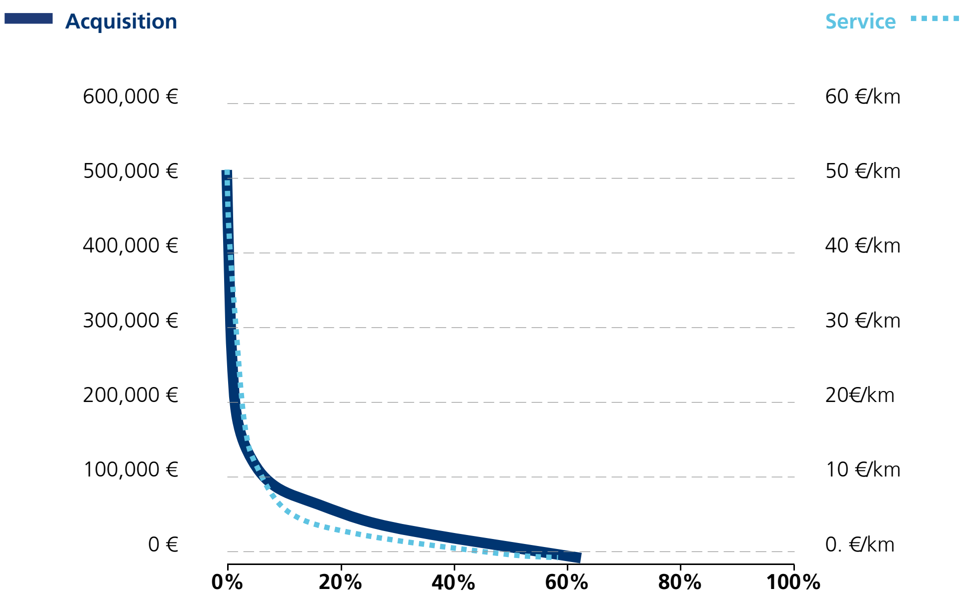
The service user should be able to book the flying airport shuttle via an app and should have onboard access to real-time information about the departing and arriving times of planes. At the airport mobility hub, a sheltered area is mandatory to protect the people and luggage from bad weather conditions.

5 MARKET ACCEPTANCE, PREFERENCES AND WILLINGNESS TO PAY

The market success of flying cars and passenger drones heavily depends on the market acceptance, demand and preferences, which are discussed in this section. A representative study from 2018 has shown an acceptance 3D mobility of up to 41% in Germany (Land der Ideen, 2018). Duwe and Sprenger (2019) conducted a more detailed survey on the acceptance, preferences and willingness to pay for 3D mobility. They differentiated between multicopters such as the Volocopter 2X, gyrocopters such as the one of the company PAL-V, tilt concepts such as the Lilium Jet and modular car-quadrocopters such as the Pop.Up Next of Audi, Airbus and Italdesign. Depending on the concept, the acceptance ranged from 43 to 49 percent for the use with a professional pilot and 26 to 41 percent for the use without one. Whereas people preferred multicopters and modular car-quadrocopters to be used in the city, they considered gyrocopters and tilt concepts to be more relevant on the countryside. According to the study of Duwe and Sprenger, the by far most important reason to use flying cars and passenger drones was faster mobility, followed by emission-free mobility and higher travel flexibility. The by far most important reason to not use 3D mobility were safety concerns, followed by the impaired vision of the sky and the noise. Even though a study of Horváth & Partners testified a quite positive public perception of urban air mobility based on an analysis of not further specified text documents (Brauchle, et al., 2019, p. 11), the direct survey of Duwe and Sprenger disclosed acceptance hurdles. In line with the previously mentioned safety concerns, special equipment related to safety was most important to the people questioned by Duwe and Sprenger. With regard to the propulsion system, only two percent preferred conventional combustion technology. Most people gave reference to battery electric propulsion, closely followed by fuel cell electric propulsion. One third of the people was indifferent. In terms of the operation, the study shows that even though a take-off point close to their home was important to them, they clearly preferred a controlled operational environment. Most of the people wanted to share a flying car or passenger drone and only half of them was willing to abolish any other means of transportation. One third of the people was willing to relinquish the car for instance.

With regard to the willingness to pay, Duwe and Sprenger differentiated between the acquisition of a flying car or passenger drone and the use of a corresponding service. Depending on the concept, between 61 and 63 percent of the people were willing to pay more than 0 € for the acquisition and between 45 and 58 percent of the people for the use of a corresponding service. Aggregated willingness to pay curves are depicted in Figure 8.

Figure 8: Willingness to Pay for the Acquisition and the Use of a Service of 3D Mobility Concepts.



6 SUMMARY AND OUTLOOK

3D mobility has gained significant momentum in the public discourse raising high expectations amongst some people and deep concerns amongst others. Against this backdrop, the present study aims at shedding light on some of its most important aspects. It gives an overview of the concepts under development, describes the relevant technology fields, and gives an indication of the technological readiness of these fields. The study depicts how cities can benefit from 3D mobility, which stakeholders are involved in the realization process, how relevant connections may initially be selected, and which infrastructure is best suited and required on the ground and on elevated positions in a city with a particular focus on power supply. Moreover, the study shows which use cases will be of relevance and deep dives into a few of these with regard to their real word relevance, target customers, possible vehicle and infrastructure technologies and the customer experience. Finally, it features insights on market acceptance and the customers' preferences and willingness to pay.

The study comes to the conclusion that even though some of the relevant technologies are still in the development stage, others already have a higher maturity. Relevant use cases exist and demand is there. The urban integration, however, poses difficulties on the operationally functioning and viable realization of 3D mobility in the short to medium term.

In the future, the theoretical findings on the technological and market readiness as well as on viable business models will be deepened through ongoing research projects. Of particular interest will be the assessment of the specific technological maturity of the different 3D mobility concepts taking into account other data sources, the consideration of other technological concepts and systems, and the identification of suitable developments in the relevant technology systems outside of the traditional aviation industry. Further important fields of action are the seamless, intermodal connection of 3D mobility with other modes of transportation, the air traffic control for 3D mobility, the fair and sustainable sourcing and recycling of relevant materials and the reuse of degraded batteries.

These research activities will be complemented by practical insights from future test fields such as the one in Baden-Württemberg (Staatsministerium Baden-Württemberg, 2019), in which the Fraunhofer Institute for Industrial Engineering IAO is also involved.

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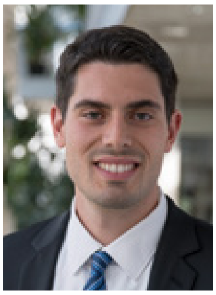

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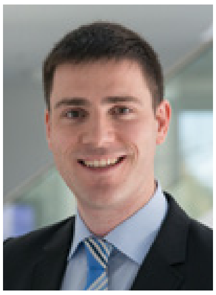

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