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Factors Influencing the Exterior Design of Autonomous Passenger Drones: Literature Review

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Abstract

Electric vertical take-off and landing aircraft (eVTOLs) have been accessed on various configurations over the past decade. This literature review deals with the issue of determining the appropriate design for an Autonomous Passenger Drone (APD). APDs have been compared with VTOLs on their pros and cons. The authors analysed aerodynamics and propulsion systems of multiple APDs. Further, the comparative analysis aids in designing the best framework for the exterior form of APDs based on human capacity, flying technology, fuel type, travel distance, door type, size, material, safety, cost, etc.

Keywords: autonomous vehicles, energy efficiency, evolutionary design, design review, design analysis

1. Introduction

Globally increasing congestion has rekindled interest in aerial taxis. Urban Air Mobility (UAM) is a contemporary concept that aims to provide an economical alternative to land transportation in overcrowded urban regions (Bauranov and Rakas, 2021). It could offer an on-demand service or adhere to a set schedule of operations. The existing air traffic management (ATM) system's incapacity to regulate urban airspace is the principal impediment to urban air travel expansion (Vascik and Hansman, 2017). The International Civil Aviation Organization (ICAO) segregates airspace as regulated or unregulated, using seven classifications (A to G) based on the air traffic services offered and flight requirements. Categories A to E is covered by regulated airspace, whereas categories F and G are covered by unregulated airspace. Each airspace classification comprises a collection of regulations specifying how aircraft should fly and how air traffic control (ATC) should engage with them. Thus, ICAO defines each airspace category according to the type of flight it serves, the distinctions offered, the type of air traffic services delivered, the speed and altitude limitations, radio communication requirements, and ATC clearances ("About ICAO", n.d.). As a supervisory authority, ICAO enables its member countries to choose airspace classifications that meet their needs. Today, nearly every aircraft activity in regulated airspace is governed through an airspace-based establishment (Bauranov and Rakas, 2021). To implement UAM activities with the present system is to expand its capacity, allowing ATC to organise and monitor all operations inside the relevant airspace categories. This method will be more complicated than the airspace classified by the ICAO's present seven categories of airspace. The challenge of effectively segregating aeromobiles in tight urban airspace can be alleviated by carefully designing new airspace structures that minimise complexity while increasing efficiency (Thipphavong et al., 2018).

Urban air mobility (UAM) services involving helicopters date back as early as the 1940s. Los Angeles Aviation deployed helicopters to ferry passengers and cargo between Disneyland and Los Angeles International Airport (LAX) from 1947 to 1971. Los Angeles Aviation had two mechanical failure accidents in 1968 and terminated services (Thipphavong et al., 2018). Between 1953 and 1979, New York Aviation operated helicopters to carry passengers between Manhattan and multiple airports (LaGuardia Airport, Newark Liberty International Airport, and John F. Kennedy International Airport). Consequently, this system was discontinued due to a series of fatalities associated with mechanical malfunction (Mayor and Anderson, 2019). New York Airlines flight tickets cost approximately $5 and $9 per person back then, around $47 and $86 USD in 2019 (Mayor and Anderson, 2019). Although they were profitable for more than two decades, these early UAM facilities were eventually shut down due to safety concerns. In the case of similar (but safer) UAM services today, these historical examples demonstrate the prospective usefulness to users of such services in the past. Numerous helicopter companies offer on-demand commercial air transportation in urban areas. BLADE[1] connects several sites in Manhattan to each of the city's three major airports. Trips are available for rental within 30 minutes before departure and charge $195 one-way; extra charges begin at $85 for cargo exceeding 11.34 kg (25 lb.) (shipped by surface carrier), last-minute reservations, and cancellations notified under 3 hours of departure (BLADE, 2021). Uber collaborated with HeliFlite[2] in 2019 to provide air travel from Manhattan to JFK airport, Monday through Friday, within 14:00 hours and 18:00 hours. Uber Copter can be reserved on-demand or up to 5 days before the flight ("Introducing Uber Copter | Uber Blog", n.d.). These contemporary on-demand copter facilities were critical to UAM research scientists because they made available data on customers personal tastes (renting patterns, readiness to pay, and most widespread routes) and "operational obstacles associated with a lack of infrastructure, public understanding, and on-demand versus planned routes" ("Helicopters - Airbus", n.d.). These offer assistance to the UAM community's strategy for driving demand via cheaper per-passenger mile (pax-mile) operating costs associated with future eVTOL (electric vertical take-off and landing) aircraft into perspective.

In Manhattan, BLADE and Uber Copter charge approximately $30 per passenger mile, while Voom charges roughly $10 per passenger mile (NASA and Booz Allen Hamilton, 2018). Uber Elevate calculates a passenger helicopter transport expense to be approximately $8.93 per passenger mile, whereas McKinsey and Company evaluate the cost as between $6 and $8 per seat-mile[3] (Johnson, T., Riedel, R., Sahdev, n.d.), (Company, 2020). Uber Elevate and McKinsey and Company's UAM projected costs are favourable when contrasted to other findings, such as a NASA study that estimates the cost of a five-passenger eVTOL at $6.25/pax-mile in the approaching future, but "operational efficiency, autonomy, and advanced technologies may cut prices by 60 percentage" (approximately $3.75/pax-mile) in the long term (NASA and Booz Allen Hamilton, 2018), (Hasan, 2019). Although estimates for delivering UAM activities differ, eVTOL services are projected to operate at reduced charges than existing helicopter transportation, leading to increased demand for UAM services in the immediate and extended term.

1.1. Autonomous Passenger Drones (APDs)

Globalisation is facilitated by innovation, and drone technology is one such innovation, with an ever utilisation in various fields, including agribusiness, medicine, and defence. International Civil Aviation Organisation defines a drone or unmanned aerial vehicle (UAV) as a plane flying without a human pilot aboard (ICAO, 2020). There's also the phrase Unmanned Aircraft System (UAS), which refers to a system composed of several parts, including drones, ground-based control mechanisms, and radios (the drone and the controller) (Ayamga et al., 2021). Drones incorporate the following defining characteristics of technological modernisation: data analysis, automation, and unrestricted mobility. However used, drones all have the same goal: to improve workflows speedier and more versatile while

[1] An interruption in on-demand operations occurred because to the COVID-19 pandemic (BLADE, 2021).

[2] Uber Copter service was suspended momentarily due to the COVID-19 pandemic ("Introducing Uber Copter | Uber Blog", n.d.).

[3] Revenue passenger miles (RPM) are paid-for passenger miles, while available seat miles (ASM) are sold seats. Credible reports were evaluated, infer pax-miles are equivalent to RPM and seat-miles to ASM.

increasing accuracy and reducing prices (Kitonsa, 2018). Drones are already ubiquitous in safety, geodesy, and farming as surveillance/sensor instruments, but their employees as transport systems are still in their nascent stage. Despite this, delivery drones can now lift to 2–3 kg and fly operations within an urban area from a strictly technological standpoint (Joerss et al., 2016). There is also the possibility of using passenger drones, known as "air taxis," to carry passengers inside or across cities (Horváth, n.d.). For the first time in aviation history, we have reached a tipping point when low-level airspace could be considered the "3rd dimension" of mobility (Kellermann et al., 2020).
It was determined by ICAO that: a) Remotely Piloted Aircraft System (RPAS) is a remotely controlled airliner, its accompanying remote pilot station(s), the requisite communication and management links, and any other elements described in the type of design operation ("About ICAO", n.d.). b) Remotely controlled or all these terms refer to pre-programmed drones as unmanned aerial vehicles (UAVs). Over a dozen different firms develop eVTOL aircraft for urban commuter use. These innovative new aerial vehicles will be faster, quieter, cleaner, and more affordable than a helicopter and constitute over a billion dollars in capital expenditure by 2020 ("Air Taxis Are Safe", n.d.). Autonomous drones can fly, navigate and hover without the need of a pilot. The travel path is somewhat similar to a helicopter, with differences in the landing platforms. Helicopters have helipads that are not available extensively, needs a considerable amount of infrastructure changes and are available in specific locations only. APD have vertiports and vertistops which will be connected to the road transport system like a metro station which will make travelling uncomplicated. Vertiport, while is designed explicitly for take-off and landing of eVTOLs, vertistop is multifunctional. While performing drone-related functions, it can act as a parking lot, resting station or even a sports field. The transportation platform facilitates the first leg of the trip (commute from the pickup place to a vertiport/vertistop) via on-road automobile travel. The most extended portion of the journey is handled by an air taxi, which transports the passenger from the origin to the destination station. Finally, regular taxis are used for the final mile of the journey (Rajendran and Srinivas, 2020). (Figure 1) depicts the pictorial representation of an eVTOL or air taxi, or autonomous passenger drone (APS) (Rajendran and Srinivas, 2020).

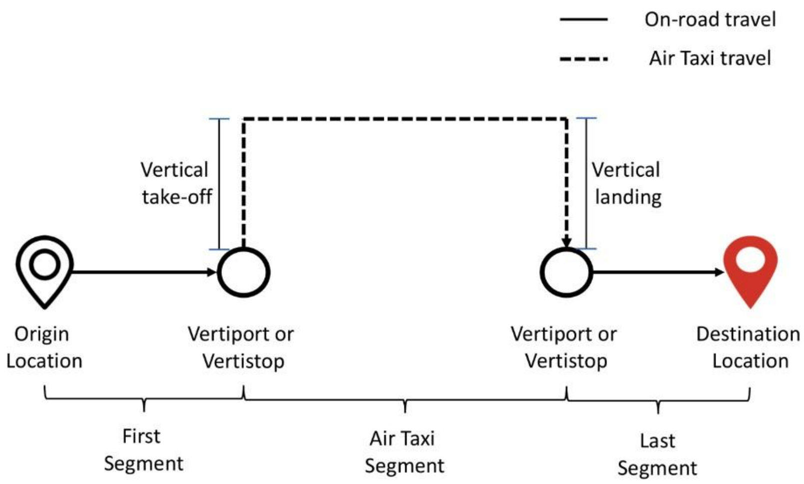

Figure 1. Pictorial representation of a typical trip taken by an eVTOL/air taxi/APS (Rajendran and Srinivas, 2020)

2. Drone components for passenger drone design (exterior)

Pilot types are autonomous (unmanned) or piloted ("eVTOL Classifications", n.d.). The drones are designed on the principles of aerodynamics to suit the lower levels of heights they would be flying than current aeroplanes or helicopters. Aerodynamics is a discipline of fluid mechanics that studies the influence of fluid (air)mechanical forces and moments acting on bodies of interest (Pijush K. Kundu, Ira M. Cohen, David R. Dowling, 2012)(Space, 2005). The fuselage houses the passengers and additional cargo. The engines (jet or propeller) might be positioned on the wings or the fuselage. (Figure 2) depicts an airliner wing from above (or platform). The wing root is the point at which a

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wing connects to the fuselage. The outermost end on a wing that is not attached to the fuselage is referred to as the wingtip, and the length between the wingtips is referred to as the wingspan, s. The chord length, c, is the distance between the leading and trailing edges of the wing. It varies in the span-wise direction. The wing's planform area, A, is its area when viewed from above (Space, 2005). (Figure 3) shows an aerofoil section of the wing.

Aerofoils are responsible for the lift and drag force exerted on the air vehicle by the wind; thus, they hold the highest importance in passenger drones' exterior design. Winglets mainly contribute to the reduction of induced drag while increasing the efficiency of the wings in providing lift, as shown in (Figure 4). This reduces energy consumption from the engines, thus increasing fuel efficiency. Vortices form as high-pressure air beneath the wingtips rushes to the lower regions on top. Three-dimensional vortices swarm the wingtips. They not only pull air up and across wings but also reverse it. Induced drag is the third component. With the addition of winglets, the aircraft can reduce the severity of wingtip vortices and, equally significantly, generate drag throughout the entire wing ("Why Airplanes Have Winglets", n.d.).

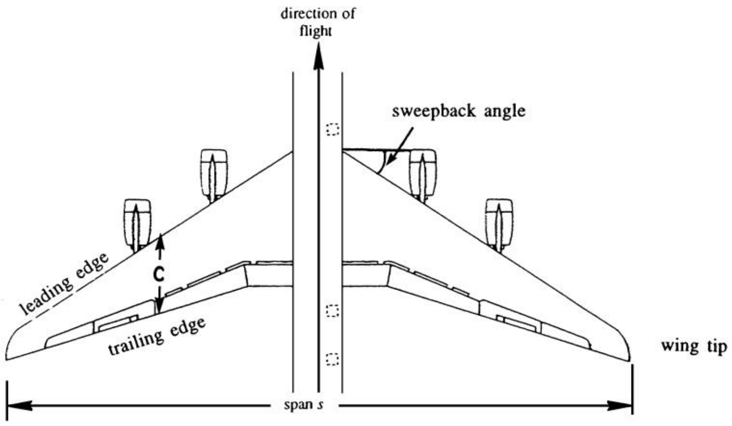

Figure 2. The planform of an airliner wing shows the different wing components (Pijush K. Kundu, Ira M. Cohen, David R. Dowling, 2012)

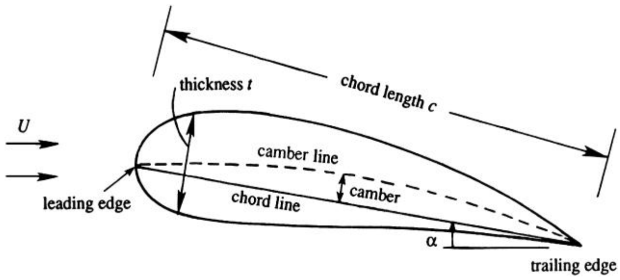

Figure 3. Aerofoil geometry of an airline's wing (Pijush K. Kundu, Ira M. Cohen, David R. Dowling, 2012)

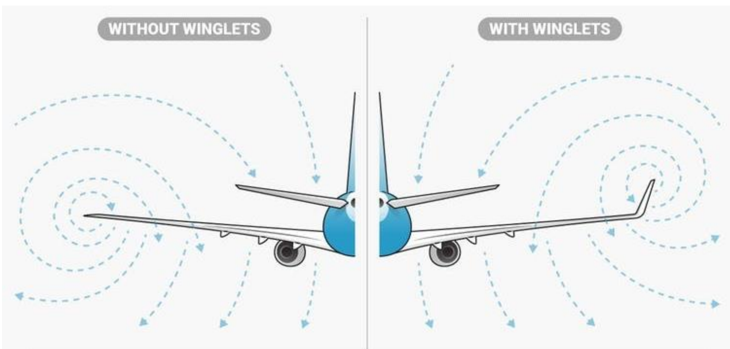

Figure 4. Difference in wind flow with winglets and without winglets ("Why Airplanes Have Winglets", n.d.)

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Numerous corporations and startups have begun designing and testing various passenger electric VTOLs in recent decades. The eVTOL news ("eVTOL Classifications", n.d.), a website run by the Vertical flight society, provides information on eVTOLs, classifies them into the following categories; 1) Vectored Thrust, 2) Lift + Cruise, 3) Wingless (multi-copter), 4) Hoverbikes, 5) eHelos. Based on design maturity, it is further classified as Initial Design, drone in their preliminary stages of design with or without a prototype; Scaled prototype, drones are in their prototype stage and may or may not have been tested; Flight Testing, drones in this category are waiting to be commercialised or be in service in the near future and lastly; In service, such drones are being currently used by passengers. Defunct is the category where the drone has been discontinued in any of the previously mentioned stages ("eVTOL Classifications", n.d.). Energy Sources for such vehicles are in 3 different classes (Bacchini, 2019),

a) Electric/Batteries- drones run specifically on electricity stored in batteries
b) Electric hybrid- such drones use batteries and fossil fuels both as a hybrid system to fly
c) Electric/Hydrogen- drones utilise hydrogen to generate electricity

The drone exterior is further designed on the essential human capacity and the number of passengers seated in the vehicle. Human capacity defines the exterior structure. Multiple sensors are incorporated to acquire important project data by unmanned autonomous vehicles (UAVs) ("UAV Deployed Sensors", n.d.). Optical cameras for high-resolution photogrammetry of roads and bridges are used, LiDar (Light Detection and Ranging) sensors, radar for fly control, global navigation satellite systems, and cost-effective ultrasonic sensors to sense the surroundings while taking off and landing ("Sensors Used In Autonomous Vehicles", n.d.).

3. Comparative analysis on different APDs

The vectored thrust eVTOLs, the first category in the autonomous drones, are equipped with a wing for efficient cruising and utilise the same propulsion system for hovering and cruising. The Lilium jet is a fine example of this category, as shown in (Figure 5). It is a tilt duct capable of increasing the wing's lift coefficient during the transition by drawing air from the wing's upper surface and releasing it down with electric jets (Bacchini, 2019). The wingless eVTOL aircraft are multirotor aircraft. They have a large disc actuator surface for hovering but no wing for cruising. These vehicles are ideal for city operations, where they can soar above traffic (Bacchini, 2019). The EHang 216 is modeled on the EHang 184. Still, it has eight arms instead of four, making it the finest example of a wingless Automated aerial vehicle (AAV) shown in (Figure 6a) ("EHang 216", n.d.). Vinata Aeromobility, a company from Chennai, India, is developing a fully autonomous hybrid flying car, as shown in (Figure 6b) ("Vinata", n.d.). It falls under the same category as EHang 216.

Figure 5. Lilium jet 3-dimensional model showing vertiport and charging station ("Lilium and ABB", n.d.)

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6a 6b

Figure 6. a) EHang 216 on the landing pad ("EHang 216", n.d.),b) Vinata Aeromobile ("Vinata", n.d.)

Lift + cruise eVTOLs, like vectored thrust eVTOLs, include a wing for efficient cruise flight, but they use two different propulsion systems for hovering and cruising fly (Bacchini, 2019). Kitty Hawk Cora, known as Wisk Cora since 2019, is the best example of this type, as shown in (Figure 7a). Developed by the Boeing company and Kitty corporation of Unites States of America ("Wisk Cora", n.d.). Archer Aviation, a Santa-Cruz startup belonging to the United States of America, launched "flying car" in June of 2021 in Los Angeles. As shown in (Figure 7b), the aircraft is designed more like an aeroplane and helicopter hybrid than an autonomous car, as the name suggests. It falls under the lift + cruise eVTOLs, and the startup is merged with Stellantis and United Airlines ("Archer", n.d.). The EHang 216, Wisk (Kitty Hawk) Cora, Archer flying car, Vinata Aeromobile, and Lilium Jet have been used as benchmarks for comparing the three primary eVTOL categories. (Table 1) shows the comparative analysis of these five eVTOLs on different types ranging from rotor design to form, battery charge time to flight time, and speed to aesthetics.

7a 7b

Figure 7. Wisk (Kitty Hawk) Cora shows 12 independent lift fans ("Kitty Hawk", n.d.), (Figure 7b). Archer shows its 12- rotor aircraft ("Archer", n.d.)

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Table 1. Comparative analysis of EHang 216, Wisk Cora, Lilium Jet, Archer flying car, and Vinata Aeromobile on various specifications

Specifications	**EHang 216**	**Wisk Cora**	**Lilium Jet**	**Archer "flying car."**	**Vinata Aeromobile**
Aircraft type	eVTOL	eVTOL passenger aircraft	eVTOL Jet	eVTOL passenger aircraft	eVTOL passenger aircraft
Piloting	Autonomous	Autonomous	Autonomous in future	Autonomous	Autonomous
Passengers	2	2	5	2	2
Cruise speed	100 km/h (62 mph)	110 mph (180 kp/h)	300 km/h (186 mph)	150mph	120 km/hr
Maximum altitude	3 km	3.04 km	3 km	3 km	0.914 km
Range	35 km (22 miles)	62 miles (100 km)	300 km (186 statute miles)	60 miles (96.5km)	62 miles (100 km)
Flight time	21 minutes	19 minutes with a 10-minute reserve	60 minutes	60 minutes	60 minutes
Payload/Vehicle weight	220 kg (485 lb)	400 lb (181 kg)	Unspecified	3,324lbs (1,508kg)	990 kg
Propellers	16	12 + 1 pusher	36	12	8
No. of motors/ type	16	100% electric (number unspecified)	36	100% electric	Biofuel-8 motors
Windows	Expansive windows allow passengers to enjoy stunning views.	Expansive windows allow passengers to enjoy stunning views.	Excellent surround-view due to the dome-shaped window	Expansive windows allow passengers to enjoy stunning views.	Panoramic window canopy offers panoramic views spanning 300 degrees
Doors	Two gull-wing doors	Gull-wing	Gull-wing	Gull-wing	Unspecified
Landing gear	Fixed skid type	Wheeled tricycle stationary landing gear	Tricycle retractable landing gear with wheels	Fixed skid type	Quadricycle landing gear
References	("EHang 216", n.d.)	("Wisk Cora", n.d.)	("Lilium and ABB", n.d.)	("Archer", n.d.)	("Vinata", n.d.)

4. Framework for exterior form

A fundamental trade-off exists between the size of the battery and the time it takes to complete an expedition. Larger batteries store more energy, allowing for more extended missions. However, higher battery capacity results in increased aircraft weight, which might result in increased acquisition costs. According to current battery technology, eVTOL aircraft will almost certainly require partial or complete recharge following each mission (Garrow et al., 2021). Battery size affects the interior volume, which in turn affects the exterior design structure of the aeromobile. Velan Y.et.al (Velan and Musica, 2017) has done a study analysis on the material of manned drones and has found carbon fiber to be the best. The study further details the design of a manned drone capable of transporting a human for short distances in comfort and safety. The system is entirely electric and fully redundant, ensuring that the drone can still safely land even if one of the four armed craft's four propellers fails. It broadens the scope of future adaptation and development in defense, surveillance, and search and rescue missions.

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The five primary eVTOL designs (EHang 216, Wisk Cora, Lilium jet, Archer flying car, and Vinata aeromobile) have been examined. Multirotors excel at short-range missions due to their superior hover performance. They are unable to carry out long-range missions due to their limited range. The five eVTOL have some advantages and disadvantages over each other in terms of exterior design on various factors, as discussed in this section. (Table 2) shows the comparative analysis of all the factors mentioned.

Table 2. Factors influencing the exterior form of autonomous passenger drones

APD	**Size** (Velan and Musica, 2017)	**Material** ("eVTOL Classifications", n.d.)	**Safety** (Rajendran and Srinivas, 2020)	**Cost** ("Community Air Mobility Initiative", n.d.)
Lilium	Largest	Carbon Fiber	Wings help in gliding, parachute added	Expensive
Archer	Medium	Unspecified	Wings glide, Multirotor system- one or more fails, others help in vertical landing, parachute as well	Moderate
Wisk Cora	Medium	High-modulus carbon fiber	Wings glide, Multirotor system- one or more fails, others help in vertical landing, parachute as well	Moderate
EHang 216	Compact	High-modulous carbon fiber	Multirotor system- one or more fails, others help in vertical landing, parachute as well	Least
Vinata	Compact	Unspecified	Multirotor system- one or more fails, others help in vertical landing, parachute as well	Least

According to Sherman. et al. ("Community Air Mobility Initiative", n.d.), a vectored thrust layout, prominent among prospective eVTOL designs—is likely to be the most efficient eVTOL aircraft. Still, it will also be the most difficult to monetise due to the difficulty of designing the aircraft to transition between upward and forward flight modes safely. A notable safety distinction between many eVTOL designs and conventional aircraft (specifically, aeroplanes and helicopters) is that eVTOLs frequently lack an effective method of passively creating lift in the case of a power system failure. Even if its engines are not operational, an aeroplane can rely on its wings for lift. In some instances, giant planes with numerous engine issues have been able to land safely via controlled long-distance glides. Alternatively, helicopters can autorotate, generating enough lift from the unpowered rotor to perform a regulated descent and landing. Hence, the hybrid of the two, lift+cruise ones, provides the safest flights ("Air Taxis Are Safe", n.d.). Wisk Cora and Archer flying car are the best case examples for this type. Distributed Electric Propulsion (DEP) enables VTOL flight with many propellers; if one or more of the propellers fails for whatever reason, the drone can still land safely. Triple Redundant Flight Computer, consisting of three different flight computers, each of which calculates its position. If one of them fails, the aeroplane can still navigate reliably. No solitary point of failure exists. Additionally, the aircraft (Wisk Cora and Archer flying car) is equipped with a parachute if else fails ("Wisk Cora", n.d.).

5. Conclusion

The review concludes the reason for choosing factors influencing the exterior design framework for Autonomous Passenger Drone compared to other air vehicles. It explicitly distinguishes the difference between VTOLs and eVTOLs based on cost per mile, airspace, and safety factors. The paper further provides analysed data between APDs, about the parameters like human capacity, flying technology,

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fuel type, aerial distance to travel, door type, size, material, safety, cost, etc. This data can be utilised as recommendations while designing optimal future APD designs as per requirements.

The conclusion drawn from the comparison was the cost of eVTOLs will be 60% lesser than VTOLs, they will fly in unregulated airspace level 'G' (specified by ICAO), and they are safer than VTOLs. The review further defines the terminology 'autonomous', as specified by ICAO guidelines, as remotely piloted and pre-programmed. The travel path of an eVTOL is graphically represented while each language is explained in comparison with a helicopter. The aerodynamics of the eVTOL vehicles provides the essentiality of winglets and aerofoil geometry in a winged APD (Lilium, Archer and Wisk Cora). Drone exterior defining components consist of classifications, design maturity, battery type and sensors. Five different drones belonging to three different categories are compared, and they are either in the prototype stage or testing phase. Section 3 compares vectored thrust (Lilium) with lift+cruise (Archer and Wisk Cora) and Multirotor (Vinata and EHang 216) on various parameters. It was found that Lilium is the largest amongst them all in terms of size and passenger-carrying capacity with five passengers. Rest four have two passenger capacity. Vinata is the only APD that will fly at the height of 0.914 km, while the rest four will fly above 3 km. Cruise speed is highest in Lilium jet while least in Wisk Cora and EHang 216. Wisk Cora has the least flight time of 19 minutes, while Lilium, Archer and Vinata each have 60 minutes. Except for Vinata, a hybrid of biofuel and electric engines, the rest are 100% electric. Gull-wing doors are used for all the APDs except Vinata, which is unspecified by the company.

The final section of the paper defines the best framework to define the form of a drone. The comparative study provided in (Table 2) on the factors affecting the form talks about the size, safety, cost and material used. EHang and Vinata are compact aeromobiles having multirotor systems, and the absence of wings helps them have close lengths. Carbon fiber was the best material for the structural design of four APDs, except Vinata for being unspecified. Safety plays a significant role in design as the exterior structure depends on it. Parachute is provided in all the APDs, but the wings provided in Lilium help it glide and land. At the same time, multi-rotors in Vinata and EHang make sure that if one or more rotors fails, the other rotors can land it vertically. Archer and Wisk Cora have the added safety features of wings and multirotor, which makes them one of the safest aeromobile designs. The cost of vehicle construction will affect the cost per mile for passengers. Lilium, due to its vectored thrust design, although it has the highest engine power and higher number of passengers, its size and cost are more significant due to design complexity. Multirotors are compact aero vehicles and have the least expenditure on construction. Still, Archer and Wsik Cora have a moderate cost of construction but the highest amount of safety to counter the price.

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