32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021 Pudong Shangri-La, Shanghai, China

Certification Considerations of eVTOL Aircraft

Yingkang MOU[1], Mei JIANG[1], Gang ZHU[1]

[1]Nanjing Engineering Institute of Aircraft Systems 1

Abstract

In this paper, typical eVTOL (Electric Vertical Take-off and Landing) aircraft operating scenarios and design architectures are identified as the certification background. Certification considerations are then analyzed regarding the risk related to eVTOL operation. Regulation relevancy and certification process of eVTOL are discussed or proposed for the future certification of eVTOL.

Keywords: eVTOL, regulations relevancy, consensus standards, certification process

1. General Introduction

1.1 Urban Air Mobility

As driving cars in large cities may come across lots of traffic jams, many believe there should be a better way for the citizens to safely travel to working places and other destinations-and that better way is a concept known as UAM (Urban Air Mobility), describes a transportation system for urban or regional point-to-point connections using small, highly automated aircraft using local take-off and landing sites. Dealing with the traffic congestion, UAM minimize long commutes due to heavy traffic and urbanization in populated areas.

Three main scenarios of UAM operation are identified in this thesis: inner-city, intercity and around city. Inner-city operation means the vehicle may fly directly above the density area, which full of population, buildings, infrastructures. Immediately bring people from point A to point B both downtown, but the technology risk and noise may rise a big obstacle for this operation concept. Intercity operation stands for that the vehicle flies between cities not far away, which normally no more than 80-90km i.e. from the Mega-city to satellite city. It can save lots of time especially within a limit period by facilitating people performing rapid city to city trip. The vehicle flies around the city, which avoid the city center, far from the density areas. The same sense as the inner-city travelling but clearly lay down the burden of technology risks and noise problems.

It seems that helicopters can be a good solution for that. But due to the technical risks, this kind of flying is strictly controlled by the aviation authorities, especially in Europe which introduced the regulation gradually prohibited flights over populated areas below a certain altitude by a single-engine helicopters for public transportations since October 2014. [1]. And the community acceptance of the helicopter noise also blocks the popularity of this solution [2]. Due to the problems and barriers above, most helicopters are not capable to perform these operations. It calls for new concept of vehicles.

1.2 eVTOL

Vertical Take-off and Landing (VTOL), commonly known as helicopter. But with the development of technology, especially the battery, motor and new materials. eVTOL has boosted significantly, typically with all-electric, low noise level, distribute electrical propulsion (DEP) and battery power supply. American Helicopter Society (AHS) [3] has identified three general architectures of eVTOL for UAM, as shown in Figure 1, each of them has their own pros and cons.

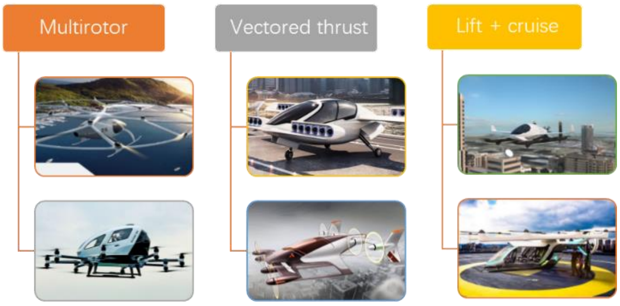

Figure 1 – Three general architectures of eVTOL.

Multirotor, has distribute multiple motors around the periphery of the drone providing the lift. An advantage of multirotor aircraft is the simpler rotor mechanics required for flight control. Unlike single- and double-rotor helicopters which use complex variable pitch rotors whose pitch varies as the blade rotates for flight stability and control, multirotor often use fixed-pitch blades, control of vehicle motion is achieved by varying the relative speed of each rotor to change the thrust and torque produced by each [4]. On the downside, they are hampered by lower travel speed as well as limitations in weight and range due to significantly lower efficiency. Initial multirotor system, however, has a low risk profile and will help define future standards in a step-by-step process.

Vectored thrust, features wings or rotors or ducts that are horizontal for conventional forward flight and rotate up for vertical takeoff and landing. Since it has tilting components that need to reliably and safely handle the transition from the lift to the cruise phase, the complexity of vectored thrust system is significantly higher. By design, tilt-wings, tilt-rotors, or tilt-ducts carry a higher risk of a single point of failure. As such, the underlying technology cannot currently be considered mature enough to handle passenger transport under critical weather conditions and requires further development to satisfy safety requirements. At the same time, this aircraft can cover long distance at high speed and therefore have clear potential for mobility services.

Lift and cruise, equips rotors for lift and fixed wings for forward flight. This type of aircraft system is comprised of various hybrid models, all with separate drive trains for the lift and cruise flight phases. The hybrid models take advantages of the respective properties of fixed wing and rotor aircraft. Wings give them longer range, while rotors enable them to vertically take off and land more efficiently and maintain a higher airspeed. The basic technologies of both elements are already available, and the overall complexity of hybrid models is in the middle range, depending on a particular system's design. The drawback is also obvious that the aerodynamic resistance and the extra mass for different modes reduce the effectiveness and efficiency.

2. Risk analysis of eVTOL

A preliminary emerging hazard assessment was undertaken, using brainstorm and expert analysis with eVTOL designer based on potential operation cases, to identify and assess the general hazard categories for eVTOL design and UAM operation scenario. Most of the risks are related to the technique innovation, also there are some traditional risks more sensitive after embrace UAM operation. As shown in Table 1, risk descriptions and influenced areas are listed, design or operation relativity, whether key hazards are also judged. Further analysis and discussions regarding three typical hazards from both design and operation, shown with bold letters in Table 1, are performed to highlight critical areas where the current regulations or industrial consensus standards may need to be updated or areas where there is tension between current regulatory requirements and vehicle design requirements with current or near-future technology levels.

Table 1 Major risks of eVTOL

No	Risk description	Influence	Design or operation related
1	**Loss all propulsion (Common mode power failure)**	**Powerplant; Flight**	**Design**
2	**Battery thermal runaway**	**Powerplant; Equipment**	**Design**
3	Battery crashworthiness	Equipment	Design

4	Blade shedding	Occupants; Powerplant	Design
5	Bird strike for windshields	Occupants; equipment	Design
6	Parachute (BRS)	Equipment	Design; operation
7	Ditching	Occupants	Design; operation
8	High voltage charging	Ground service	Operation
9	Collision	VFR; IFR	Operation; Design
10	Emergency exit	Procedure; Equipment	Operation; design
11	**Diversion time limit**	**Procedure**	**Operation**

2.1 Design related risks and mitigation proposals

Hazard qualitative assessment is performed according to each architecture of eVTOL to identify risk severity, potential mitigations, or applicable regulations different significantly from current vehicles certified under Part 23. For each architecture, a list of key hazards was developed and each hazard assigned baseline risk severity using the risk matrix shown in Table 2, which comes from ASTM 3264 [5].

Table 2 Design related hazard qualitative assessment

Risk Severity=Probability X consequence	Multirotor	Vectored thrust	Lift + cruise
Loss all propulsion (common mode power failure)	High	Medium	Medium
Battery thermal runaway	High	High	High
Bird strike	Medium	Medium	Medium

2.1.1 Loss all propulsion

While redundancy in the powertrain is often cited as a reason that DEP vehicles, which appears to be the promising integration benefit [6], will be safer than most aircraft, they are still susceptible to common mode power system failures. Regarding Multirotor configurations, since autorotation is almost impossible to achieve, loss all propulsion due to common mode power system failure would be catastrophic. For Vectored thrust and Lift + cruise configurations, which typically considered as wing borne when the phase changed to cruise, the risk severity may be not as high as Multirotor. The wings are assumed to provide glide capability similar to a Fixed wing vehicle; total power loss at high altitudes has a correspondingly lower consequence. While at low altitude, performing take-off and landing phases, can be regard as the same situation as multirotor configuration, but different takeoff and landing profiles could be used. The Vectored thrust and Lift + cruise vehicles have the ability to quickly transition to wing-borne flight at lower altitudes (a lower risk flight profile) or conducted extended vertical takeoff (a higher-risk flight profile). A low-altitude transition could be beneficial for efficiency, while a high-altitude transition would be desirable to reduce noise exposure of the surrounding population.

There are mainly two ways to mitigate this hazard to acceptable levels, either by reducing the consequence or probability of occurrence.

- System Redundancy and Design Practice (reducing probability)

The aerospace industry has demonstrated the capability to develop safe vehicles where total loss of power is unacceptable, Part 25 commercial aircraft being the most notable example. This is done via good systems engineering and safety assessment practices, including detailed assessments of failure probability down to individual component levels [7]. These processes enable the reliable development of the highly redundant systems necessary to mitigate any foreseen common mode failures to safe levels. The challenge in the context of UAM will be developing systems that meet the required levels of safety while staying within the tight cost and weight targets of those vehicles. Additionally, the need to certify a complex, highly flight-critical system may add to the time needed to get regulatory approval for the vehicle. A key issue here is what the required level of safety should be. The level mandated by the regulations is significantly lower than for a Part 25 commercial air transportation while higher than the general aviation level. This could reduce the difficulty of developing such a system, since it would not have to be as reliable. If the regulation was precisely met, at the scale of proposed UAM operations this would still lead to a significant number of catastrophic failures every year. To build passenger confidence and trust in the system, a higher level of safety closer to current commercial air travel may be desirable.

- Ballistic Recovery Systems (reducing consequence)

Ballistic recovery systems (BRS), or airframe parachute systems, are increasingly popular on small GA aircraft and are widely proposed as a mitigation for total electrical system failure in electric aircraft, especially for Multirotor or Vectored thrust and Lift + cruise configurations in vertical flight modes where autorotation or gliding is not possible. Current BRS technology has been shown to be effective, but only above a certain combination of airspeeds and altitudes. Figure 2 shows the officially demonstrated (dark blue) and likely (light blue) effective deployment envelope of the ballistic recovery systems for a Cirrus SR20 based on the published handbook. This system is the SR20's means of compliance with the spin recovery requirements. The deployment time and corresponding altitude loss (from time of system deployment until full inflation of the canopy) of a BRS system is a function of both altitude and airspeed. In the case of the Cirrus system that altitude loss increases from no more than 400ft if the BRS is deployed while the aircraft is in straight and level flight to more than 900ft if the aircraft is in a spin [8]. While successful lower-altitude deployments have been reported [9] this requires higher speed and is not guaranteed. Vehicle weight and the details of the parachute design can significantly change the effective deployment envelope.

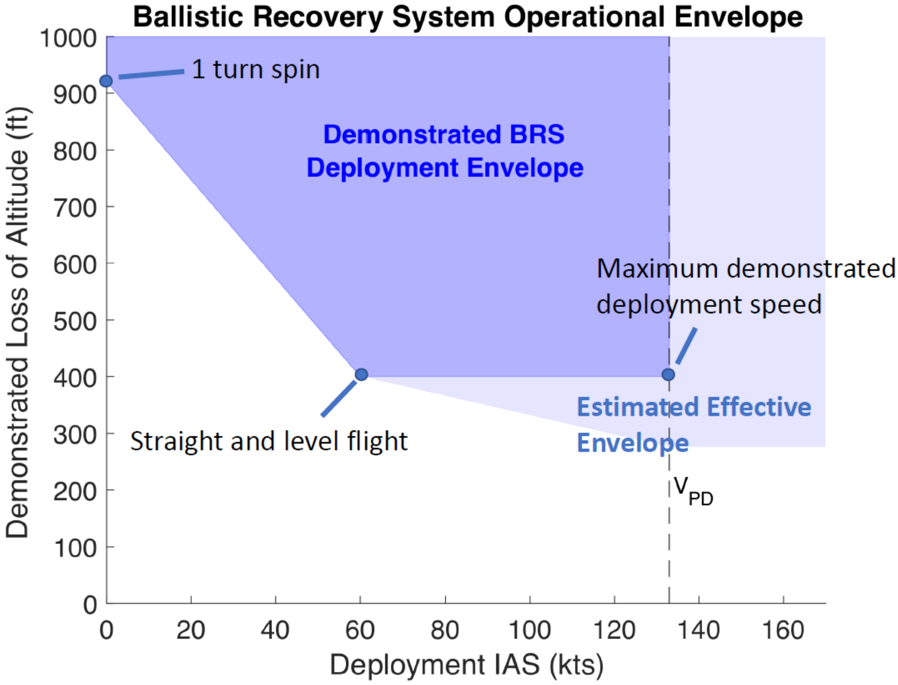

Figure 2 The demonstrated (dark blue) and likely successful (light blue) parachute deployment envelopes for a Cirrus SR20

According to the typical UAM operation scenario, eVTOLs spend a significant amount of time outside the blue envelope during takeoff, landing, and low-altitude flight. During this time, a BRS would not be an effective mitigation against total power loss. The full-airframe equivalent of a zero-zero ejection seat would be required.

If most flights take place over congested urban areas, it also raises the question of how the impact of ground population should be considered. In dense urban environments, a UAM vehicle descending uncontrolled under a parachute is still a hazard (albeit less of one than without such a system). A full-airframe zero-zero-like ejection system based on the same rocket technology as current military systems would also have significant safety concerns for any bystanders in the deployment area. While BRS systems are certainly beneficial safety systems and should be equipped on all UAM aircraft, they are not a panacea for all hazards and should not replace a highly reliable vehicle design.

In summary, the hazard of loss all propulsion due to common mode power system failure is challenging to mitigate outside current BRS operating envelopes. This challenge arises from the need to develop a complex, highly redundant system, which could add significant weight and cost, in a vehicle that is very cost- and weight-sensitive. Since this hazard is of higher consequence than for current Part 23 aircraft, the demonstrated probability of failure will need to be correspondingly lower, possibly more in line with Part 25 requirements.

2.1.2 Battery thermal runaway

The high specific energy of lithium series batteries is the key enabling technology for commercially feasible all-electric aircraft. Also, Li-ion is low maintenance, which requires fewer scheduled services. However, all-electric aircraft typically have more battery fractions, especially at longer ranges. They are also more weight-sensitive than a conventional gas-powered vehicle. Using of this technology for large-scale energy storage introduces the typical hazards: thermal runaway.

Thermal runaway is where an internal short circuit cases a rapid and uncontrolled increase in battery temperature, which often results in off-gassing, fire, and/or a battery explosion. This effect can spread rapidly to adjacent cells if they are not physically isolated from each other, and can be caused by a number of factors; over-charging, over-heating, mechanical damage, and manufacturing defects are the most common. While good design practice and operational controls have proven effective in mitigating the first three causes during normal operation, thermal runaways due to manufacturing defects have proven very difficult to reliably prevent. This led to the development and installation of battery containment systems on all aircraft of this type; these are solid structures than can contain the effects of a thermal runaway, but which add considerable weight to the battery system. While thermal runaway events continue to be reported, these containment systems work as designed so it is no longer considered a reportable safety incident. While there are lithium batteries that have less susceptibility to thermal runaway, they have lower specific energy. Current regulations also require a demonstration of the effects of thermal runaway.

Table 3 enumerates the potential mitigations. The most effective current mitigation strategy for battery thermal runaway is the physical containment employed on the Boeing 787. This containment strategy adds significantly to the weight of the batteries. This reduces the effective specific energy, which is a critical metric for the feasibility of UAM vehicles. For some configuration, it may reduce performance to levels which are not commercially viable. This is especially true for any eVTOL configuration, which requires very high power for take-off and landings.

For vehicles with wings, the possibility of storing batteries in the wings and combining containment structure with wing primary structure offers one method of more weight-efficiently isolating batteries from the passengers and the rest of the vehicle. More detailed design work is required to determine the benefits of this approach.

Advanced lightweight fire suppression technologies, improved electrical protection and monitoring, and/or improvements in manufacturing and inspection technology are all ways that this issue could be mitigated in a lightweight way. To date, none of these technologies have been certified by the FAA for commercial use.

Table 3 Mitigation strategies for battery thermal runaway

Mitigation Description	Mitigation Reduces
Battery containment and physical separation	Consequence
Advanced fire suppression	Consequence
Improved manufacturing, testing, and inspection	Probability
Improved electrical protection and monitoring	Probability

The certification challenge associated with the risk of battery thermal runway is the tension between currently acceptable ways of meeting the requirements and the need to reduce battery weight as much as possible to make the vehicles practically viable. Technology beyond what has been certified to date may be required to overcome this challenge.

2.1.3 Bird strike

This is currently an acceptable risk for most aircraft since, while it can be hazardous or in some cases catastrophic, it happens very infrequently. However, it may uniquely impact electric aircraft in two ways. The first is that the probability of occurrence may increase. According to the FAA, 95% of bird strikes take place below about 4500ft AGL, and more bird strikes happen at lower altitudes. Most proposed UAM mission profiles operate in this region of high bird activity, which may lead to higher strike rates than for current aircraft.

The second is that due to DEP, the propeller of eVTOL are generally smaller, impacts could cause more damage. In some configuration, debris from one failed propulsor could impact adjacent ones. This could potentially lead to cascading failures, vibratory issues, and degraded flight control. The probability of this type of failure is highly dependent on the details of the vehicle configuration and propeller design; for the risk assessment here is assumed that the strike on a single bird destroys one propeller. The risk of cascaded propeller failure should be accounted for during the vehicle development process.

The severity of the bird strike hazard depends strongly on the number of birds impacted, flight speed, vehicle design, and a host of other factors. Bird strikes on flocks, while relatively rare, could be much more consequential than strikes on a single bird. The case of bird strike on the fuselage or cockpit, especially during high-speed flight at low altitude, should also be considered. Current standards mandate that cockpit windscreens must survive bird strike up to the maximum flap deployment speed; vehicles which cruise at high speed at low altitude may require additional strengthening. The rankings in Table 2 show average severity results for the impact of a single bird on both the propeller and the cockpit.

Potential mitigations for the hazard of bird strikes are listed in Table 4. Suitable design standards on the windscreens, as well as on the rotors, have proven effective for mitigating these hazards. Those or similar design standards could be applied to eVTOL aircraft. The high standard wearable penetration resisted suits or equipment for pilot or passengers can be applicable. The issue of cascaded rotor failure (whether caused by a bird strike or other debris) can also be mitigated by specific deployment of rotors. Redundant motor systems reduce the consequence of a single bird strike. BRS systems would also be effective at high enough altitudes. It is not clear that there is a current certification challenge around bird strikes but there is uncertainty around how frequently they will occur. Frequent occurrence of bird strikes, especially when multiple birds are impacted simultaneously, would make this a more significant challenge. Frequent strikes with multiple bird impacts could be a difficult-to-mitigate cause of common mode power/flight control system failure.

Table 4 Mitigation strategies for bird strike

Mitigation Description	Mitigation Reduces
Windscreen/Rotor Design Criteria	Consequence
Penetration resisted suits or equipment	Consequence
Redundancy	Consequence
BRS (Aircraft Parachute)	Consequence

2.2 Operation related risks and mitigation proposals

Operation risks normally rely on the typical scenario eVTOL be used, not depend on the specific eVTOL architecture. These risks can come from the interface between the vehicle and ground service, vehicle and other vehicle or infrastructures, and vehicle itself.

2.2.1 Diversion time limit

Though electric propulsion is the preferred propulsion choice for the UAM eVTOL, the specific energy (the amount of energy per unit weight provided by the battery) of Lithium-ion polymer (LiPo) batteries today is insufficient for long-range operation, the valid power density is far less than traditional fossil fuel. Also, from the certification point of view eVTOL aircraft may require enough reserve battery time for landing (analogous to reserve fuel in the aircraft).

The efforts both from the operational regulations regarding potential reserve time for eVTOL and new air traffic control related to optimal route planning which combining UAS traffic management (UTM) and UAM, need to address the following two critical operational challenges for passenger transportation by the eVTOL:

- Generate the new reserve time regulations or rules for eVTOL UAM operation.
- Plan the optimal energy efficient arrival trajectory given limited battery endurance.

Uber has issued the standard operation concept and requirements for UAM eVTOL [10], which emphasize the mission reserves will be 6 miles cruise to an alternate landing site. Although, this will be discussed and probably approved by the authority, it's a potential solution for the specific reserve time, and can be adapted as the new forthcoming rules for eVTOL operation.

Some research has demonstrated that balance the cruise altitude and cruise distance will save energy consumption for certain capacity of battery [6]. Meanwhile, different categories of areas and UAS operations are discussed in [11], which can be referenced as the applicable boundary for different UAM operational scenario. Based on these results, new route planning strategies for reserve condition could be introduced to satisfy the UAM eVTOL operation. To trade off the safety and efficiency of this operation.

3. Regulation relevancy of eVTOL

3.1 Regulation state of art

Considering the mission and operation scenario [10], three or four passenger seats in addition to the pilot, MTOW no more than about 3200Kg, the certification basis will obviously fall into the domain of CS/Part 23 for normal category airplanes or CS/Part 27 for normal category rotorcraft.

The new CS 23 and Part 23, certification specification 23 amendment 5 and CFR Part 23 amendment 64, have been reorganized or revised since 2007. The purpose of the amendment is to encourage innovation and creation to embrace the new technology for aviation. The smart and flexible rules replace prescriptive requirements with performance-based regulations coupled with consensus standards, which come from industry, for specific designs and technologies. To reduce the certification cost and worldwide cooperation, new CS 23 is almost fully harmonized with Part 23. The consensus standard means industry-based, which allows certification under any set of standards accepted by the administrator [12]. One such set of standards is ASTM 3264, which has been accepted by the FAA as a means of compliance with the Part 23 standards. ASTM 3264 is currently being updated by Committee F44 to allow the certification of electric aircraft, but is one clear path by which the necessary regulations could be enacted.

Certification under CS/Part 27 may be possible but it is expected that the challenges identified will be more. For the rules are still prescriptive requirements, lots of features cannot be found or significantly different with the typical architectures identified above, such as rotor drive system, control system, autorotation system and so on. Besides that, such as multirotor, even if they have vertical take-off and land capability but lack wings can also be certified under CS/Part 23 and not the current Part 27, which has no provisions for the certification of electric vehicles.

Conclusion has been made that about 80% certification basis of new CS/Part 23 will be applicable for eVTOL, and only 50% for CS/Part 27. EASA confirmed that five new type investigations, including eVTOL could use the new rule as certification basis [13]. So, it has been recognized as the common sense that the certification basis will come from the new CS/Part 23 and related consensus standards.

Considering UAM commercial transportation, for safety and operation reasons, applicable rules will only be Part-CAT, Part-SPO, Part-SPA, Part 121, Part 135. Regarding on demand air transportation, the most relevant operation basis is going to be Part 135 which will be used as a reference for this memoir.

Part 135 is FAA regulations about commuter and on demand operations, which rules govern commercial aircraft, such as non-scheduled charter and air taxi operations which are very similar to the UAM scenarios: inner city, intercity and around city. Part 135 operations have very detailed and strict operational requirements and legal aspects to adhere to, having much higher standard of safety requirements than Part 91 operated aircraft which applicable to general private flying, while not as rigid as Part 121 which applicable to scheduled commercial air service. Choosing Part 135 as the operation basis is a trade-off of cost and risk for eVTOL UAM transportation.

3.2 Regulation relevancy analysis

There are more or less three categories of current regulations for eVTOL certification and operation: applicable, not applicable or need modification. Applicable means the regulation is clear for eVTOL configurations or features, and can be perfectly applied, like in case there is an aircraft, it will contain the characteristics of mass, center of gravity, structure loads, performance, onboard equipment, flight manuals, maintenance and so on. These regulations can be directly selected as certification basis. However, not applicable means the regulation is currently out of the eVTOL range. For example, fuel system regulations are the basic requirement for the conventional combustion engine aircraft, the prescriptive rules have no constraints on the full electric aircraft. This part needs to be eliminated when applying the regulations. While, there are some specific regulations which need to be paid attention. These regulations can be applied just after little modification, then it will fit for the eVTOL design and operation. Take an example of windshield protection, based on the design of eVTOL and operation scenario, the bird strike protection will not be limited for pilot, but for the passengers. Also, sizing the velocity is another point to focus.

Analyzing CS 23 amendment 5 or Part 23 amendment 64, there are more or less 80% regulations can be directly used as certification basis for eVTOL, 10% are not applicable, 10% need modification or addition sensible. Regarding operation, in Part 135 there are about 70% rules applicable for eVTOL UAM operation, 10% not applicable, 20% need adaptable change. The proportion shown in Figure 3.

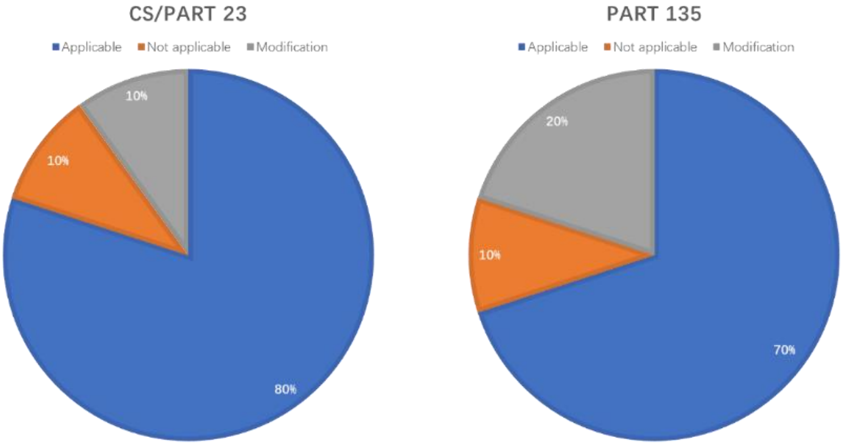

Figure 3 – Regulation relevant proportion

Based on the features of eVTOL, typical regulations are identified according to each classification, such as subpart Flight, subpart Structures, subpart Design and Construction and so on for design domain, subpart Flight Operations, subpart Aircraft and Equipment, subpart VFR/IFR Operating Limitations and Weather Requirements and so on for operation domain, as shown in Table 5.. Besides that, three classic regulations from each category are selected to further analyze the detailed relevancy.

Table 5 – Typical regulations relevancy

No.	eVTOL relevant categories	Regulations
1	Applicable	CS-23 Subpart B - Flight: CS 23.2100 Mass and center of gravity
2		CS-23 Subpart C - Structures: CS 23.2230 Limit and ultimate loads
3		CS-23 Subpart D - Design and Construction: CS 23.2300 Flight control systems
4		CS-23 Subpart F - Systems and Equipment: CS 23.2530 External and cockpit lighting
5		CS-23 Subpart G - Flight Crew Interface and Other Information CS 23.2605 Installation and operation information
6		Part 135 Subpart B - Flight Operations: 135.63 Recordkeeping requirements.
7		Part 135 Subpart C - Aircraft and Equipment: 135.151 Cockpit voice recorders.
8		Part 135 Subpart D - VFR/IFR Operating Limitations and Weather Requirements 135.203 VFR: Minimum altitudes
9		Part 135 Subpart J-Maintenance, Preventive Maintenance, and Alterations: 135.419 Approved aircraft inspection program.

No.	eVTOL relevant categories	Regulations
10	Not applicable	Part 23 Subpart E - Powerplant: 23.2430 Fuel systems
11		Part 135 Subpart C -Aircraft and Equipment: 135.147 Dual controls required.
12		Part 135 Subpart C - Aircraft and Equipment: 135.157 Oxygen equipment requirement
13		Part 135 Subpart D - VFR: 135.211 Over-the-top carrying passengers: Operating limitations
14	Applicable after modification	CS-23 Subpart B - Flight: CS 23.2120 Climb requirements
15		CS-23 Subpart D - Design and Construction: CS 23.2320 Occupant physical environment
16		Part 135 Subpart B-Flight Operations 135.109 Pilot in command or second in command: Designation required.
17		Part 135 Subpart D - VFR/IFR Operating Limitations and Weather Requirements 135.209 VFR: Fuel supply
18		Part 135 Subpart E-Flight Crewmember Requirements 135.243 Pilot in command qualifications.

3.2.1 Applicable regulations

Take flight control systems for example. Flight control systems are most extremely important systems on board, and related regulations offer the essential requirements for almost all aircrafts.

Now days, there are three kinds of flight control methods: mechanical, hydro-mechanical and fly-by-wire (FBW) [14]. Mechanical control is used for early aircraft and is currently used in small aircraft. Hydro-mechanical control solves the difficulties of increased weight and complexity with size and performance of the aircraft, which widely used in large transportation aircraft. FBW system replaces manual flight control of an aircraft with an electronic interface, which are easily achieved by software and hardware development.

Since using electric power chain, the weight and complexity of flight control systems are also more sensitive for eVTOL than normal aircraft, fly-by-wire control system will be more applicable than others, which is used by most of the current eVTOL architectures.

As CS 23.2300 Flight control systems said:

(a) The flight control systems are designed to:

(1) operate easily, smoothly, and positively enough to allow proper performance of their functions;

(2) protect against likely hazards.

Based on the FBW's advantages below, these regulations should be easily fulfilled by eVTOL designing.

- ease of pilot workload through support of automatic control features (i.e. turn coordination, auto trim)
- improvement of safety (i.e. envelope protection)

The movements of flight controls are converted to electronic signals transmitted by wires, and flight control computers determine how to move the actuators at each control surface to provide the expected response. Meanwhile, commands from the computers are also input without the pilot's knowledge to stabilize the aircraft and perform protection against risks.

3.2.2 Non-applicable regulations

Part 23 23.2430 related to traditional aircraft fuel system, which was eliminated by EASA in the new CS-23 amendment 5. The eVTOL will use full electric as power supply, for example the battery as the power source, the wire as the power transition medium, the electromotor as the propulsion. The regulations are not applicable for eVTOL, but the philosophy of some rules can be referenced. For example:

23.2430 (a)(1) Be designed and arranged to provide independence between multiple fuel storage and supply systems so that failure of any one component in one system will not result in loss of fuel storage or supply of another system;

The battery or batteries power supply for different motors or equipment can be designed using the main idea above as reference. In this case, the probability of common mode failure can be reduced by architecture design refinement. Volocopter using 9 independent battery systems, each supply 2 motors to achieve power supply redundant.

23.2430 (a) (4) Provide the flightcrew with a means to determine the total useable fuel available and provide uninterrupted supply of that fuel when the system is correctly operated, accounting for likely fuel fluctuations;

The battery system should be designed to precisely informs the pilot about useable electric power available, despite the battery degradation in chapter 2.

23.2430 (a) (6) Be designed to retain fuel under all likely operating conditions and minimize hazards to the occupants during any survivable emergency landing.

The battery system should be designed to maximum withstand battery crash risk to protect the occupants, optimize both the battery crash structure design and the battery itself crashworthiness design.

3.2.3 Applicable after modification

As CS-23 “23.2320 Occupant physical environment (b)” said:

For Level-4 aeroplanes, each windshield and its supporting structure directly in front of the pilot must withstand, without penetration, the impact equivalent to a two-pound bird when the velocity of the aeroplane is equal to the aeroplane’s maximum approach flap speed.

Chapter 2 has discussed the risk of bird strike, since the altitude of eVTOL operation will be significantly lower than the commercial aircraft, the frequency of this risk rises up. With the high density of future UAM commercial operation, safety requirement asks the eVTOL to keep a high safety record, so this protection requirement will not only limit to the Level-4 aeroplanes, but the category including eVTOL.

Due to the configuration of eVTOL, no more than one pilot will seat behind the front windshield. Bird strike risk should not only limit to the pilot windshield protection, but the protection of the front windshield, which means protect the pilot and the front passenger or the whole front passenger depend on the design concept.

Besides that, the new bird model and extreme condition need to be modified. Base on the typical altitude eVTOL may be operated, cruise at 1000 ft [10], research should be conducted to sizing the representative bird model characteristics, like the weight, the volume, the standard or extreme flying speed of the bird. Using the result of the statistics or research to amendment the “two-pound” will be adapted or modified. Meanwhile, the “maximum approach flap speed” need to be reconsidered. For the extreme flying speed appears during the cruise period rather than the approaching phase for eVTOL, the maximum cruise speed may be adopted as the input condition for the new regulation.

4. Standards needed for eVTOL

As discussed above, innovative technologies and new risks result in the regulation to change from prescriptive requirements to performance-based rules with consensus standards. The consensus standards are now available due to the philosophy of new Part/CS 23, which has paved the way of using them to certify eVTOL.

Standards from industries mean they will be no more time consuming and more flexible than from authority. The fact that ASTM relevant standards have been approved as AMC or GM by authorities showed the possible solutions. But there are still considerable amounts of standards needed to be initiated and introduced to the technology novelty of eVTOL, such as the domain of design of Electric Propulsion Units (EPU)/Distribute Electrical Propulsion (DEP), battery/ESS, windshield and so on.

- EPU/DEP

The standards of EPU/DEP are specific due to the features of eVTOL. Currently, there are ASTM F39-WK47374: "Design and Manufacture of Electric Propulsion Units for General Aviation Aircraft" and ASTM F44-WK41136: "Standard Specification for Integration of Electric and Hybrid-Electric Propulsion Units for General Aviation Aircraft (Airplanes)". These standards start from CS-E/Part 33, non-related requirements of E-motor are removed, dedicated requirements for E-motor are Added. But they don't address the "ducted fan + e-motor" configuration. Based on what I have analyzed and researched, the standard should at least contain the key points of Rotor integrity and Motor thermal overload protection.

Rotor integrity, which counter against the failure of fan bursts or propeller separation. It's the similar parts as normal aircraft, the content of CS-E/Part 33 can be referenced. For each fan or propeller of eVTOL, it must be established by test, analysis, or combination thereof, that a rotor which has the most adverse combination of material properties and dimensional tolerances allowed by its type design will not burst when it is operated in the EPU for a defined period of time under most critical conditions.

Motor thermal overload protection, one of the biggest flaws of electric motor is the thermal overload effect, especially when the voltage and electric current are very high, which the motors of eVTOL cannot escape. The standard should give specification to limit the temperature rise to protect/ stop the motors against damage, which may further result in common mode failure and loss all propulsion. Once the motor cools down to a safe operating temperature, it continues to work.

- Battery

Battery related standards ought to include the requirements with respect to cells, mechanical design and assembly, electrical design, and maintenance of the pack and the recording of maintenance data. Meanwhile, the standards ask the applicants to show the compliance to dedicated clauses by providing a list of all design features, analysis and tests.

There are two industry standards related to onboard batteries design and installation eVTOL could follow, which approved by authorities, RTCA DO-347 "Certification Test Guidance for Small and Medium Sized Rechargeable Lithium Batteries and Battery Systems" and RTCA DO-311 "Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems". Multi-cell battery electrical energy which above 300Wh is regarded as LARGE size battery which eVTOL propose to use [10]. Based on what have discussed in chapter 2, LARGE size batteries should face thermal runaway in the first place.

The fact of battery thermal runaway constrains that safe cell temperatures and pressures must be maintained during any foreseeable charging or discharging condition. And also, the rechargeable lithium battery installation must preclude explosion in the event of those failures. Due to the large battery size of eVTOL, the standard should rule that besides providing information about Charging and Discharging Protection, Mitigation of Cell Failure Effects, Flammability, Short-circuit Test of a Cell, Short-circuit Test with Protection Enabled and so on regarding DO-347 for small and medium sized batteries, the applicants should also provide design and analysis details of Precautions during charging and discharging, Prevention of Thermal Runaway, Charging and Protection, Design of Protection Circuits and so on based on DO-311.

- Windshield bird protection

In CS-23 (excluding commuter) aircraft categories there are currently no specific bird protection requirements and this is reflected in a higher rate of bird strike accidents (particularly windshield penetrations) [15]. Since ASTM standards regarding windshields and windows only cover ice protection and optical distortion and deviation of transparent, more standards should be issued to protect the people onboard (passengers or pilot). The standards should achieve the balance between economic achievable and people protection as far as possible. Two kinds of them can be introduced as potential proposals.

One should base on the state that relatively high windshield areas are selected as patterns by manufactures, it is hard to achieve strong enough windshield within economic weight-performance limitations. Therefore, consider requiring helmets and protection suit to mitigate the effects of windshield bird strike penetrations like helicopter pilots do. The strength requirements or standards of the helmet and suit should be researched to sustain the impact of windshield penetration. While this proposal may be hard to achieve for commercial reasons.

Another idea is to issue standards of the windshield, which can guide the design and test to introduce hard enough windshield to sustain the bird strike risks. Of course, the bird strike model of commercial transportation aircraft can be used or referenced, but the input parameters need to be modified to keep accordance with the representative or extreme scenario of eVTOL UAM operation. Like what's typical weight of bird which can be met at 1000 ft AGL (typical eVTOL operation altitude), what's the extreme condition? What's the typical cruise speed (about 150 mph from Uber requirement) or the maximum operating limit speed? The related standard should illustrate all of them.

5. Certification process

Certification processes are meant to provide a risk-based, multi-level regulatory structure to give us safe aircraft designs and operations. They are not all the same, and are applied in a risk-based manner, depending on the type of aircraft and purpose. Personal light sport aircraft certification requirements are not as complicated as larger transport aircraft carrying hundreds of passengers. Also, the eVTOL operating far away from people doesn't have the same requirements as that operated above the congested areas.

5.1 eVTOL certification process considerations

While regarding the current aircraft certification process (CS-23/Part 23, CS-25/Part 25), it is based on the common sense of airport A to airport B which normally far away from population, more focus on the design or aircraft requirements rather than the operation considerations. Even for helicopters, it's the same case. However, single engine helicopter, even certified, not allowed to operate in congested area in Europe since October 28 2014. EASA has been strictly enforcing a rule that prohibits single-engine helicopter flights above densely populated and other "hostile" areas [1]. This means the certification process may have to include the operation considerations, which for eVTOL UAM operation it is inevitable.

Like the proposed certification of UAS also consider the operation when apply type certificate [16], different operation subcategory mapping specific class of UAS will not follow the same type certification process, eVTOL for different UAM scenarios will also be limited to specific operations due to different type certificate.

The current certification process of aircraft can be referenced by eVTOL certification, but some parts or phases need to be modified or supplemented, as shown in Figure 4.

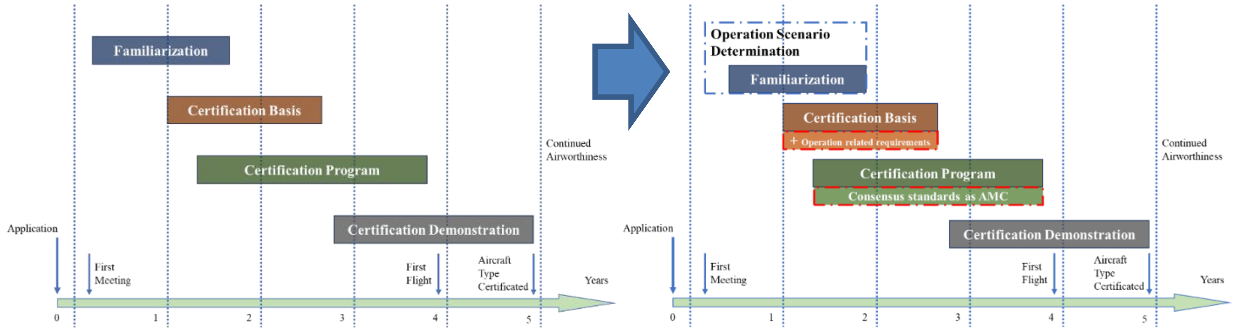

Figure 4 – From current aircraft certification process to eVTOL certification process

For eVTOL, one phase can be supplemented, which can prior to Familiarization, or even the main points of this phase being included in Familiarization phase, to analyze and confirm the operation scenario or category of this eVTOL. It will directly determine the specific technical requirements and safety levels the eVTOL should achieve for these scenarios or categories during the Certification Basis period. Furthermore, operation related requirements need to be considered during the Certification Basis phase. Besides that, in the Certification Program phase, the consensus standards which will be used to show the satisfaction to the authorities, that the proposed eVTOL architecture and design complies with the novelty and specific requirements from the certification basis.

5.2 Proposed certification process of eVTOL

Based on the certification process of normal aircraft and UAS, potential certification process of eVTOL is proposed as shown in Figure 5. As demonstrated in the previous section that the main differences of certification process between typical aircraft and eVTOL are the periods of Familiarization, Certification Basis and Certification Program, the detailed illustration of these processes will focus on these three phases.

When the applicants want to get their eVTOL certified, they have to present not only the design features of the product, i.e. the general architecture, but the operation scenario. In this case, the applicants should show the operational concept (OPSCON) or the most relevant UAM subcategory they want to operate the eVTOL. Typical UAM subcategory: Inner-city, Intercity or Around the city, will be selected that leads to different certification requirements and corresponds to different certification classes, as shown in Table 6. Different UAM subcategories have their own specific safety level requirements which finally translated into basic performance requirements and operation related requirements. The Inner-city has the highest safety level requirement because it will be operated directly above the congested area, it will call for more operational requirements (reserve time, anti-collision system, minimum altitude and so on) and more rigid performance related demands (higher DAL of function, HW & SW). The Intercity scenario will have relatively lower requirement for safety level, since the density of suburb which connects two cities is relatively low. The requirements can reference the general aviation operation with modest conservative. The safety level of the subcategory Around city is in the middle of Inner-city and Intercity, which may require DAL not as high as Inner-city but more rigid than Intercity scenario and almost the same situation of operational requirements.

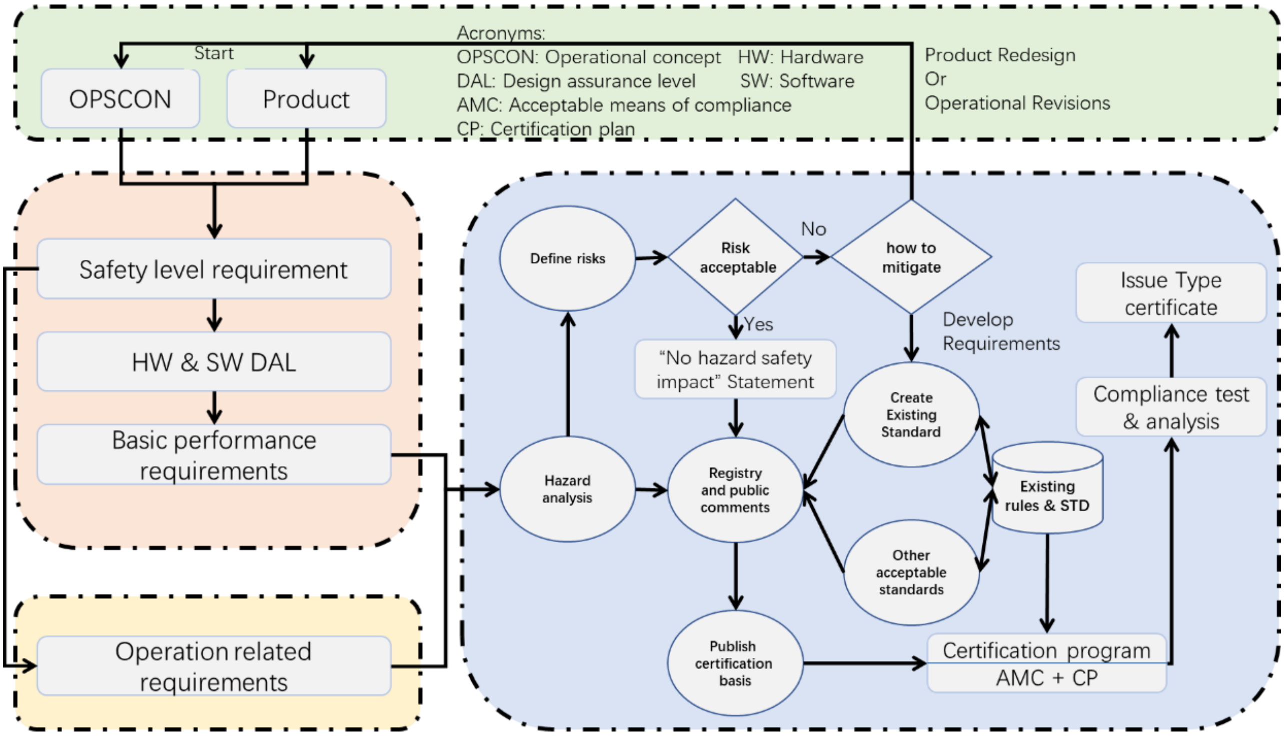

Figure 5 – eVTOL certification process

After getting the general requirements of performance and operation, the certification basis dedicated to specific eVTOL architecture and operation scenario should be determined. The hazard analysis process ought to be carried out to define whether risks have been identified or not. Requirements regarding conventional design of eVTOL parts and general operation are normally not considered as new risks, after registry and public comments, can be directly covered by existing certification basis. However, new risks shall be defined and if risks are not acceptable, related mitigation proposals must be developed. Otherwise, the dedicated eVTOL must be redesigned or have its operation scenario changed. Mitigation proposals can lead to standards creation or revision base on existing related rules, which can be designated as certification basis after public confirmation. Also, other acceptable standards related to eVTOL performance and operation can be selected as certification basis. Finally, the authority confirms the certification basis for the eVTOL that the applicant wants to get certified.

The applicant then follows the certification basis, introduces the AMC which may come from ASTM or other organizations approved by authority to show the proposed design and operation complies with the requirements. Meanwhile, applicant issues the certification program which is established based upon the agreed MOC to facilitate carrying out the plan.

After certification demonstration, including compliance test and analysis, finally get the Type Certificate of the eVTOL from the competent authority, and the applicable operational scenario or certification class will be on the TCDS.

Table 6 – Proposed certification classes for eVTOL

UAM			eVTOL		Certification classes
Subcategory	Area of operation	Safety level	Operation requirements	Performance requirements	
Inner-city	City center	High	Anti-collision system; more reserve time	More demand on Flight control systems; More stable	D1
Around city	Outside of city center	Medium	Anti-collision system	Flight control systems; Stability	D2
Inter-city	Suburb between cities	Low	-	Flight control systems; Stability	D2

6. Conclusions

In this paper, three kinds of UAM mission and operation are defined: Inner-city, Inter-city and Around-city, which can be regarded as typical requirements for UAM operation scenario. Specific risks related to eVTOL configurations and UAM operations are discussed and relevant proposals are put forward to mitigate the hazards. Based on the scenarios, architectures and risks, regulation relevancy is analyzed to discuss the applicability of the existing and forthcoming rules and standards. Due to the fact that the reorganized new CS/Part 23 introduced consensus standards as Acceptable Means of Compliance (AMC) or Guide materials (GM), basic standard requirements or main ideas are proposed related to the novelties of eVTOL. Finally, specific certification process for eVTOL is discussed based on the new certification features of this vehicle, which can be used as references by the eVTOL designers and competent authorities.

7. Contact Author Email Address

Mailto: 76211623@qq.com

8. Copyright Statement

References

[1] Alg. Study on single-engined helicopter operations over a hostile environment. Literature Survey Report, EASA, 2014.

[2] Fast-Forwarding to a Future of On-Demand Urban Air Transportation, Uber Elevate, 2016.

[3] http://evtol.news/2018/07/16/evtol-news-directory-breaks-100/

[4] https://en.wikipedia.org/wiki/Multirotor

[5] Christopher Courtin, John Hansmany. Safety Considerations in Emerging Electric Aircraft Architectures, American Institute of Aeronautics and Astronautics, pp 1-17.

[6] Moore, M. D. NASA Distributed Electric Propulsion. In: Symposium E2-Fliegen, DLR, 2015.

[7] SAE. Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment, SAE ARP4761, SAE International, Warrendale, PA, 1996.

[8] Guide to the Cirrus Airframe Parachute System (CAPS) User guide, Cirrus Aircraft Corporation, Fromhttp://cirrusaircraft.com/wp-content/uploads/2014/12/CAPS-Guide.pdf. Accessed Oct. ,2017

[9] Whitfield, B.,How It Works: BRS Aircraft Parachute, Flying Magazine, https://www.yingmag.com/how-it-works-brs-aircraft-parachute, Accessed: 2018.

[10]eVTOL Vehicle Requirements and Missions, Uber Elevate, 2018

[11]Jones, H. W., Common Cause Failures and Ultra Reliability, 42nd International Conference on Environmental Systems (AIAA), 2012, pp 1-10.

[12]Part 23 Amendment 64, EASA, 2015.

[13]https://www.easa.europa.eu/newsroom-and-events/news/easa-ga-roadmap

[14]https://en.wikipedia.org/wiki/Aircraft_flight_control_system

[15]FERA, Bird Strike Damage & Windshield Bird Strike Final Report, EASA, 2008.

[16]Opinion No 01-2018, EASA, 2018.