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Review

Urban Air Mobility Aircraft Operations in Urban Environments: A Review of Potential Safety Risks

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Abstract: The expansion of Urban Air Mobility (UAM) has led to diverse aircraft designs, with piloted systems expected to evolve into remotely piloted and automated operations. Future advancements in Intelligent Transportation Systems (ITSs) will further improve automation capabilities, promising significant benefits to the environment and overall efficiency of UAM aircraft. However, UAM aircraft face unique operational conditions that need to be accounted for when assessing safety risks, such as lower operating altitudes and hazards present in urban settings, thus leading to a potential increased risk of collisions with foreign objects, particularly birds and drones. This paper reviews historical safety data with an aim to better assess the potential risks of UAM aircraft. A survey was conducted to gather quantitative and qualitative insights from subject matter experts, reinforcing findings from existing studies. The results highlight the need for a comprehensive risk assessment framework to guide design improvements and regulatory strategies, ensuring safer UAM operations.

Keywords: urban air mobility (UAM); collision risk; bird strikes; drone impacts; safety assessment; risk management; regulatory framework; aircraft design

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1. Introduction

As aircraft technologies continue to evolve, Urban Air Mobility (UAM) is anticipated to substantially enhance the interaction between humans by making air travel a viable transport alternative in urban environments. There are various definitions for UAM. The Federal Aviation Administration (FAA) and the National Aeronautics and Space Administration (NASA) describe this emerging transport mode as a subset of Advanced Air Mobility (AAM), which facilitates highly automated, cooperative air transportation services for passengers or cargo in urban areas [1]. Similarly, the Australian Civil Aviation Safety Authority defines UAM as "short to medium range and endurance, designed for low altitude point-to-point passenger or cargo carrying tasks in, and between, urban areas" [2].

A. P. Cohen et al. [3] outlined UAM's development in six phases, beginning with the early "flying car" concept and evolving through scheduled helicopter services in U.S. cities to the current phase of on-demand helicopter services, accessible worldwide. The next three phases, expected in the future with autonomous operation, include Vertical Take-Off and Landing (VTOL) corridor services for short-to-medium trips between airports and major cities, air metro services for medium-to-long routes connecting multiple city vertiports, and finally, point-to-point air taxi services offering long-range, on-demand transport across entire regions [3].

The International Forum for Aviation Research (IFAR) and the International Civil Aviation Organization (ICAO) highlight the complex challenges in achieving autonomous

manoeuvrability with higher speed, greater safety, and sustainable transportation solutions in urban environments [4]. The lack of a standardised approach for the aircraft configurations that have been developed to operate in these environments, along with safety concerns, and noise regulations hinder public acceptance. VTOL aircraft face high energy demands, with electric and hydrogen-based propulsion systems still facing limitations concerning their implementation in the short term. Precise obstacle detection is crucial for safe urban operations, thus requiring robust airspace integration systems to properly manage predictable increased air traffic movements in relatively small, low level altitude environments. Regulatory frameworks and cybersecurity measures must evolve to ensure safe, pilotless operations [4]. Addressing these challenges requires incorporating new features and system innovations into aircraft, according to the vision of several industry stakeholders [1].

Given the advanced specifications required for operating the vehicle in urban airspace, traditional aircraft face difficulties in urban operations due to their operating system, limited space for runways, and the small size of airports for air taxis. As a result, the development of VTOL technology and hover capabilities is anticipated to enable air taxis to operate between desired locations, such as building rooftops in urban areas (vertiport), thus facilitating the transportation of passengers over a short-to-medium travel distance [5]. Nevertheless, it should be noted that some manufacturers have developed short take-off and landing (STOL) aircraft that may be a suitable alternative for urban operations conditioned to the availability of short runways or dedicated spaces in highways where these aircraft could take off and land. An example of this concept was proposed by Aeromobil, which has designed a two-seater "flying car" capable of taking off under 400 m [6].

Other possible applications for UAM include goods delivery and emergency services within or traversing urban areas. Since the early 2010s, the application of small Unmanned Aircraft Systems (UASs) for delivering goods rapidly expanded across industries such as consumer deliveries, medical transport, mapping, and surveillance [3]. Key stakeholders include companies like Zipline, Matternet, and Wingcopter, which are transporting medical supplies in countries like Rwanda, Ghana, Switzerland, and the US. In the U.S., the FAA's UAS Integration Pilot Programme (IPP) has partnered local governments with private companies like UPS to explore various drone delivery options, including flights over people and at night [3]. In the passenger transport sector, several companies have started offering helicopter services that can be booked via smartphone apps. BLADE, launched in 2014, offered helicopter services in New York City, operating under FAA Part 135 regulations through third-party operators and has since expanded to locations like San Francisco and Mumbai, with plans to acquire 20 electrical Vertical Take-Off and Landing (eVTOL) aircraft from Beta Technologies [7]. Other key players include SkyRyde, Skyryse, and Uber Copter, which began testing helicopter services in 2016 and was later sold to Joby Aviation [8]. Oregon Helicopters also launched a similar service in Portland. Internationally, Airbus' Voom operated in cities like Mexico City and São Paulo but ceased operations in 2020 due to the effects of the pandemic [9]. NASA and the U.S. Air Force are also involved in advancing UAM systems, with NASA leading efforts to improve safety and scalability, with programmes such as NASA's AAM National Campaign, while the Air Force's Agility Prime programme explores vertical flight for military applications [3].

Several UAM prototypes are being developed and tested in Australia for both passenger transport and aerial delivery services. Eve Air Mobility, backed by Embraer, is developing eVTOL aircraft with Australian customers such as Sydney Seaplanes, Nautilus Aviation, Microflite, and HeliSpirit [10]. Wisk Aero, supported by Boeing, is working with Queensland government on autonomous air taxis, expected to be launched prior the Brisbane Olympic Games in 2032, while Skyportz is focusing on developing landing

infrastructure to support future UAM networks across Australian cities [11,12]. For aerial delivery and logistics, Wing (Alphabet/Google) operates commercial drone deliveries in Ringwood (VIC), Canberra, and Logan (QLD), transporting food, medicine, and parcels, while Swoop Aero focuses on medical and essential supplies in remote areas [13–15]. AMSL Aero, an Australian company, is developing the Vertiia eVTOL for both passenger and cargo transport, and FlyFreely provides drone solutions for mining, agriculture, and emergency response [16,17]. With growing investment in UAM technology, Australia is at the forefront of urban and regional air mobility innovation. Figure 1 illustrates examples of UAM prototypes.

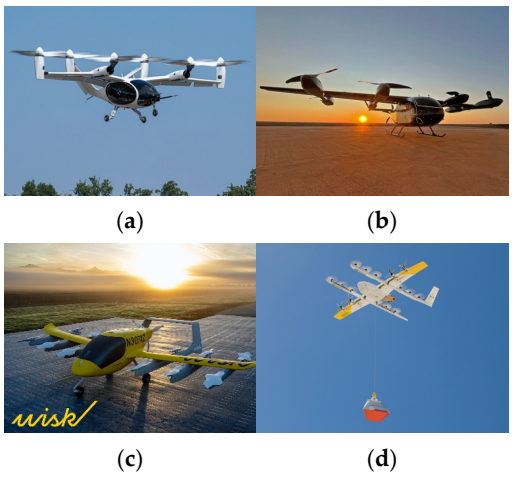


Figure 1. UAM prototypes: (**a**) Joby Aviation [18]; (**b**) Eve's eVTOL [19]; (**c**) Wisk [20]; (**d**) Wing Drone Delivery [15].

Many transport companies have entered the UAM industry in recent years, introducing diverse aircraft configurations and specifications tailored to mission requirements. Initially, UAM operations are envisaged to involve piloted systems, which are projected to evolve into remotely piloted configurations and to incorporate automated flight capabilities based on application needs in the future. IFAR expects remotely piloted operations to be used primarily for emergency and disaster response, with limited automation in the short term [4]. In the long term, higher levels of automation and electrification, particularly with Fly-By-Wire (FBW) and Distributed Electric Propulsion (DEP), are anticipated [4,21]. With advancements in technology, numerous UAM design projects have been launched, focusing on developing prototypes and testing their operational capabilities through flight trials. One such example of how the technology has contributed to improve the performance of the UAM aircraft is the evolution from the M200X, developed by Moller in 1989, which was capable of flying up to 40 feet and maintaining the flight for a duration of 3 min to the crewed aircraft Cora, developed by Wisk, which has successfully completed over 1200 flights in 2017 [22,23]. In 2020, eHANG 216 achieved a successful eVTOL flight, marking a significant milestone for the UAM industry [24]. Recently, Jetson have started commercialising a compact, low-cost, single-seat eVTOL, whose performance characteristics are suitable for personal urban air transport, as showcased by its manoeuvring agility, range, autonomy and safety-oriented design features [24,25].

With the anticipated increase in air vehicles and the lower operating altitudes of UAM aircraft compared to traditional aircraft, several safety concerns arise during operation. One major concern of UAM operations is the risk of collisions with foreign objects, like birds and drones, the estimation of which remains uncertain due to most aircraft in this category still being in the design and development stages, thus lacking real operational data. Also, the review articles that have been published to date on UAM aircraft are scarce and, despite

their contribution to the analysis of many other aspects pertaining to the operation of such aircraft, do not specifically address the risk of collisions with foreign objects [5,20,24]. This paper aims to bridge this gap by reviewing historical safety statistics of impact events in aircraft and their potential implications for UAM operations. As a result, an assessment of the most prevailing risks specific to this category is presented by resorting to the analysis of both direct and indirect data to be discussed in the following sections in this paper.

The paper is structured as follows: First, the methodology for gathering and reviewing relevant literature and information is introduced. Second, a background on the development of UAM aircraft and associated operational risks is provided. The argumentation in the paper puts an emphasis on risks posed by foreign object impacts, including a review of relevant statistical data, as well as current standards and regulations addressing these hazards. The paper also presents findings from a survey conducted with subject matter experts on UAM safety risks, which have resulted in risk matrixes specific to different hazard categories. Finally, a summary of findings and recommendations for improving UAM safety are provided.

This review emphasises the importance of developing a comprehensive risk assessment to understand the severity of such collisions and to inform both design organisations and regulators on how to achieve an enhanced design framework with lower risks for future UAM aircraft operations.

2. Methodology

This study employed a literature review to compile and integrate findings from different qualitative and quantitative data sources on topics of interest around Urban Air Mobility (UAM), as per the recommendations in [25].

The literature review was conducted considering various sources available online and in the public domain, including governmental reports, academic publications, journal and conference papers, and technical documents. The review was focused on the following key topics:

1. UAM background and development: exploring the history and evolution of UAM systems and aircraft.
2. Operational risks of UAM aircraft: identifying potential hazards and safety challenges during UAM operations, including piloted and autonomous systems.
3. Risks posed by foreign object impact: focusing on the risks of UAM aircraft colliding with foreign objects, such as birds, drones, and debris, within dense urban environments.
4. Current standards and regulations: reviewing existing aviation standards and regulations relevant to UAM issued by selected aviation authorities, including the Federal Aviation Administration (FAA), the European Union Aviation Safety Agency (EASA), and the Australian Civil Aviation Safety Authority (CASA).
5. Statistical data on collisions of aircraft with foreign objects: gathering data and statistics related to collisions with foreign objects, including birds and drones, to assess the risk severity and frequency of these occurrences.
6. Potential UAM configurations: analysing the different UAM aircraft configurations proposed by different manufacturers and their suitability for urban operations.
7. Impact studies on rotor blade systems: reviewing studies that examine the damage caused by foreign object impact, specifically on rotor blades, and the implications for aircraft safety.

To ensure the research captured the latest developments, an internet search, using search engines like Google, Google Scholar, and ScienceDirect, was conducted to document recent and future industry updates. The search was supplemented by tracking new proto-

type designs, emerging UAM services and technologies, and recent regulatory changes and emerging safety standards.

The collected bibliographic references were categorised by topic area, allowing for a structured analysis of the key themes related to UAM operational risks, regulatory frameworks, including foreign object impacts. This categorization helped identify knowledge gaps and areas that required further investigation. An overview of the references used in this review paper is presented in Table 1. Some papers fall into multiple categories due to their broad scope and interconnected themes.

Table 1. Lists of categories of the bibliographic references used in the literature review in this paper.

Category	Number
Operational Risk Analysis	4
Safety Challenges	6
Conceptual Designs	7
Rotor Structure and Manufacturing	7
Terminology and Definition	8
Advanced Developments/Technologies	10
Standards and Regulatory	10
Others (e.g., Airspace Management, Infrastructure, Social Acceptance, Planning)	10
Impact Analysis	11
Applications of Key Stakeholders	20
Historical Events and Statistics	24

This research acknowledges that some references and other information pertaining to UAM systems may not have been fully captured given the fast pace and the emerging nature of this sector. Additionally, due to the rapidly evolving nature of UAM technologies and underpinning regulatory frameworks, some findings in this paper may be subject to change as this industry sector continues to grow.

In order to inform the development of a more complete and accurate risk management framework specific to impact occurrences of UAM aircraft with foreign objects, a survey was conducted to collect the perspective of industry experts on this issue. These data envisaged to initially identify and determine potential hazards and associated risks that could cause failure or damage to UAM during operation in urban environments, with an incidence in damage to the aircraft structure. The panel of experts consulted in this survey were selected considering their expertise on different sub-areas in the unmanned aircraft (UA) sector, including design organization, manufacturers, operators, and regulators. The provided feedback enabled ascertaining key aspects that are necessary to improve the accuracy of numerical models to be developed in future research by considering operational scenarios, which may lead to different levels of risk of impact with foreign objects (e.g., bird strikes, collision with drones and other aircraft, etc.).

The responses of the potential participants were observed from different angles based on their expertise, including the design, operation, regulatory, and maintenance framework of UAM systems. It should be noted that this survey aimed to identify the hazards and associated risks of impact of UAM aircraft operations. Other aspects pertaining to the operation of these aircraft were not captured by this survey. The survey was setup in RMIT Qualtrics, and it included both qualitative and quantitative questions, which were reviewed and approved by the College Human Ethics Advisory Network (CHEAN) in accordance with RMIT University's ethical guidelines. The participants were contacted via direct mail and/or professional networking platforms (such as LinkedIn), and they were given information on the objectives and risks associated with the research. Since the UAM is an emerging sector in aviation, there were only a limited number of experts who were

available to contribute with technical expertise deemed adequate to this study, resulting in a total of 20 participants (N = 20).

The bar chart depicted in (Figure 2) presents the professional backgrounds of the survey participants. Participants from the "Design Organization/Manufacturer" sector make up 25% (5 participants) of the total, reflecting substantial representation. The "Safety Authority" category constitutes 15% (3 participants) of the respondents, while the "Regulator" and "Maintainer" categories each account for about 10% (2 participants) of the sample. Though several operators were contacted to participate in this survey, only 1 responded, which can be attributed to concerns around disclosing commercially sensitive information. The "Others" group accounted for approximately 35% (7 participants), with the majority of this group (71%) representing academia.

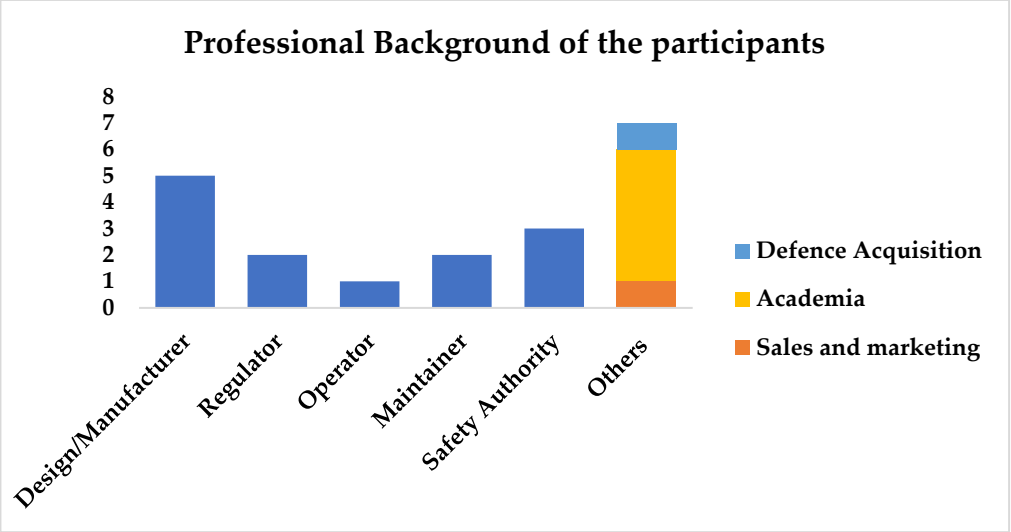


Figure 2. Professional background of the participants in the survey conducted in this research.

The survey brought together a diverse group of professionals with different experience levels, with most (55%) having between 1 and 10 years of experience, making them the largest group in the study, as presented in Table 2. In total, 30% of participants had over 15 years of experience, which is reassuring on the quality of the feedback obtained from these experts regarding the questions in the survey.

Table 2. Experience years of the participants in the survey conducted in this research.

Experience Years in the Expertise Area	Count	Percentage
<1 years	2	10%
1–5 years	7	35%
6–10 years	4	20%
11–15 years	1	5%
16–20 years	2	10%
21–25 years	0	0%
26–30 years	1	5%
>30 years	3	15%

When it came to their knowledge on the UAM sector, the largest portion, 33% (17 respondents) cited certifications and regulations as their primary source of information. Following this, 25% (13 respondents) relied on relevant journal articles and research publications. Industrial reports were the main reference for 20% (10 respondents), while 14% (7 respondents) utilised statistical information from key stakeholders. Another 8% (4 peo-

ple) mentioned other sources like general knowledge, past articles, and discussions with UAM manufacturers. Note that multiple sources/documents were selected for conducting the survey, which explains the discrepancy between the number of participants (N = 20) and the total responses regarding sources/documents.

The diverse professional backgrounds of the respondents provided a comprehensive perspective on the issues explored in this survey.

3. Findings from the Literature Review

3.1. Operational Risks Associated with UAM

The integration of Urban Air Mobility (UAM) operations introduces the potential for several aircraft sharing the same airspace at low altitudes, including both conventional aircraft (i.e., existing fixed-wing and helicopters) and emerging aircraft categories, such as air taxis and drones. In addition to the risks of collision between the multitude of aircraft that are expected to share the air space in metropolitan areas, there is also a risk posed to the people on the ground due to the likelihood of these aircraft colliding with buildings or crashing into the terrain following an in-air collision event [26].

The IFAR launched the Scientific Assessment for UAM, engaging technical experts from research agencies globally [4]. This research underscored various challenges and factors influencing the social acceptance of Urban Air Mobility, such as the absence of dominant vehicle configurations, flight safety concerns, noise issues, resource limitations, and the necessity for new certification standards and noise mitigation strategies.

L. Wang et al. (2023) pointed out the potential risks that could impact the prominent technologies of the UAM sector [21]. The integration of unmanned flights into traditionally manned airspaces has challenged existing regulations and low-altitude operational methods, necessitating cooperation between different flight management platforms. Unstable or severe weather conditions, such as fog, rain, snow, and haze, can impact the visibility and sensor accuracy of UAM, endangering both vehicles and passengers. The increase in unmanned aircraft also complicates airspace management for low-altitude flight networks and take-off and landing procedures. From the perspective of city residents, privacy and noise, particularly during nighttime operations, are significant concerns that mirror issues with conventional aircraft. Additionally, safety concerns arise from the integration of remote piloting and automation in UAM, due to the unpredictability of current algorithms affecting consistent flight behaviour. Therefore, a thorough understanding of the unique characteristics and potential risks of new technologies, including VTOL, autonomous systems, propulsion systems, communication and navigation, and traffic management, is crucial for successful UAM implementation [21,27].

Courtin and Hansman (2018) [28] examined the safety and certification considerations of small electric aircraft, focusing on current technologies and regulatory requirements. These authors identified risks associated with various electric aircraft configurations operated with lithium-ion batteries, evaluating the severity of these risks in relation to the vehicle's architecture. The study highlighted issues with weight due to low battery energy density and energy variability. Ensuring power system reliability and certifying FBW systems in multirotor or DEP configurations may also lead to increased safety, weight, and cost challenges. Additionally, the risk of bird strikes was noted due to low-altitude flight and smaller rotors, which could increase the likelihood and impact of failures involving smaller propulsors [28]. Updating regulations and implementing strategies such as redundant motors and adherence to design standards can help mitigate these hazards. NASA conducted a Failure Hazard Analysis (FHA) and Failure Modes and Effects Criticality Analysis (FMECA) to identify potential failure modes and hazards in conceptual UAM air vehicles [27]. This study found that the criticality of specific vehicle configurations was

heavily influenced by the failure rates of motors and inverters, emphasising the need for collaboration among UAM designers, regulators, and subsystem suppliers to address safety challenges and ensure robust architectures.

3.2. Risks Posed by Impact with Foreign Objects

According to FAA statistics (2024), there has been a notable increase in flight operations across the US post-COVID-19. From the 2019 (prior to the pandemic) to 2023 financial year (FY), the number of flights rose from 12.9 million to 14.1 million, a 4.7 percent increase [29]. This upward trend is expected to continue, potentially surpassing the aircraft usage levels seen in FY2005-2007.

Similar trends are observed in Australia. Data from the CASA show significant increases in passengers on domestic Regular Public Transport (RPT) flights, with a 9.7 percent increase in 2022 and a 4.8 percent increase in 2023 [30]. RPT flights also rose by 4.9 percent, reaching 52.6 thousand flights by April 2024 [31]. These flight number trends underscore the demand of air transport in the future, as well as the emerging urban sector, which is also expected to be growing and potentially bringing challenges into existing airspace infrastructure. As the demand for air vehicles in the urban setting continues to expand, one major concern is the potential for collisions with foreign objects, like birds, drones, natural obstacles, and buildings [32,33]. If not properly studied and managed, these collisions could result in catastrophic outcomes, both in terms of fatalities to passengers and people on the ground, as well as damage to infrastructure.

It is important to include a brief note on the definition of foreign object debris (FOD) in the context of the risk scenarios contemplated in this paper. In general, FOD is defined as a large object that either is misplaced or mismanaged from its natural state, which can cause any malfunction, damage, or destruction to the object system [34]. FOD in an airport context is referred to by AC 150/5210-24, Airport Foreign Object Debris (FOD) Management as any object, live or not, located in an inappropriate location in the airport environment that has the capacity to injure airport or air carrier personnel and damage the aircraft [35]. This very same concept can be extended to other segments of aircraft operations. The presence of FOD is a continuing concern not only to the traditional aircraft operation but also to new categories of aircraft, such as UAM, posing safety hazards that can ultimately impact safe operations. Based on these definitions, the FOD concept considered in this paper involve those objects external to the UAM aircraft that substantially pose a risk of collision event and potentially cause catastrophic consequences to its operation, including birds, Unmanned Aerial Vehicles (UAVs)/drone, obstacles (e.g., building, antennae/communication towers, etc.), and other air vehicles [36].

3.3. Currrent Standards and Regulations Related to Impact Events on Aircraft

Since April 2019, the EASA has a dedicated department for eVTOL aircraft, with key advancements including the introduction of airworthiness regulations for small VTOL aircraft, issued in 2019, and for light UAS in medium-risk operations in 2020, along with UAS design verification guidelines in 2021 [37]. These new vehicles have advanced control systems and varying levels of autonomy, setting them apart from traditional helicopters and airplanes.

Due to the reduced size and lower operating altitude of UAM compared to traditional fix-wing aircraft, air taxis bear a greater susceptibility to bird strikes as the majority of bird-related incidents occur at altitudes below 3500 ft [38,39], as shown in the chart in Figure 3.

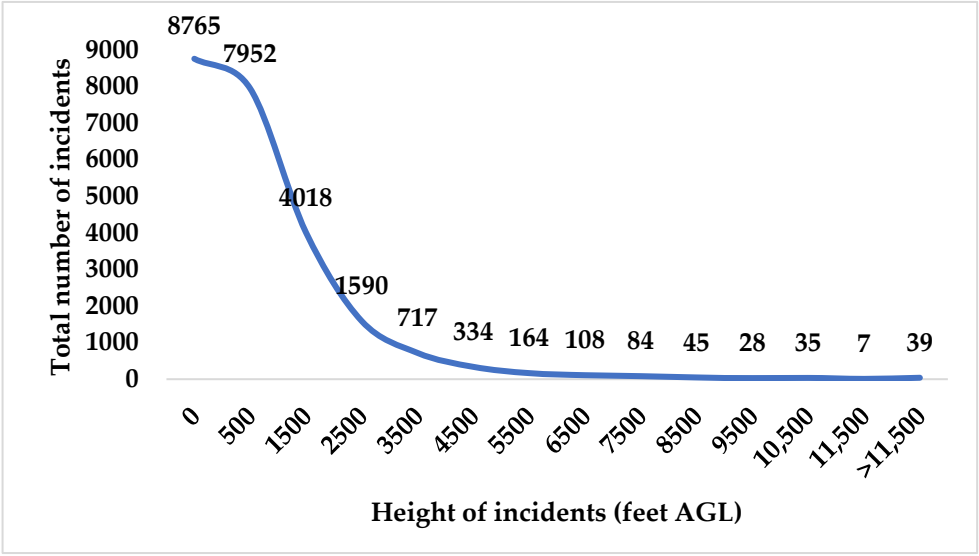


Figure 3. Number of reported bird strikes by height above ground level (AGL) from 1990 to 2023 based on data in [39].

Since bird strike occurrences are one of the general risks for air operations, there should be standards and regulations specific for managing the risks associated with such events. However, the current safety standards, particularly the ones around bird strike certification requirements, by both the EASA and the FAA are not suitable for UAM operations due to differing criteria and approaches related to the features and performance characteristics of these aircraft, as identified by [40]. With the emergence of DEP systems in UAM/eVTOL aircraft, the use of smaller propellers with multiple rotors has become a promising design. However, these aircraft may suffer more severe damage from bird impacts compared to conventional aircraft, potentially leading to cascading failures in nearby propulsors and compromising flight control. Therefore, it is imperative to expand the scope of structural integrity requirements beyond Level-4 aeroplanes (CS-23), which include commuter aircraft type for 19,000 lbs or 19 passengers as a maximum amount, to include UAM/eVTOL aircraft (Level-2 classification), which allow only two to six passengers [41].

To develop the certification procedure for the next generation of small electric aircraft, it was recommended to propose new standards based on FAR Part 27 and Part 29 (the regulations for rotorcraft) [40]. These standards would be adapted to account for the specific operational conditions of VTOL aircraft. Part 29 (14 CFR 29.631) states that the rotorcraft must be able to perform safe flight and/or landing after striking a 1 kg bird when the maximum horizontal cruise speed of the rotorcraft is reached. However, small rotorcraft (under Part 27) are not certified for such requirements [40]. Although current regulations address bird strikes, uncertainty remains about their frequency of occurrence, especially when multiple birds are involved, which could present a major safety challenge. EASA's 2024 Special Condition, SC-VTOL-02, sets safety rules to small aircraft saying the aircraft must be designed to withstand likely bird impacts, ensuring that for Category Basic with 7 or more passengers, it can perform a controlled emergency landing, while for Category Enhanced, it can continue safe flight and complete a landing without compromising safety [42]. From these safety standards, it is necessary that the aircraft flying over urban areas must be able to safely complete its flight operation even after a critical propulsion failure resulting from a collision with a foreign object, which leads to the necessity of UAM aircraft to be designed based on improved standards to mitigate this risk. Without adequate certification requirements, the safety of small or private rotorcraft may become compromised. As reviewed in [5,21], many researchers have conducted flight networks

and transport simulations of UAM, with studies focusing on infrastructure requirements and operational constraints. EASA introduced the first Easy Access Rules (EAR) for the U-Space concept, adopted in 2021, which outlines the regulatory framework for U-space airspace to safely incorporate UAS operations and UAM into urban areas, ensuring smooth operations [43,44]. Nevertheless, the mode selection functions for UAM are still in the early stages, which could pose uncertainty around shared airspace activities between UAM and drones. This could increase the likelihood of mid-air collisions, thus making this a risk of particular concern that should be taken into account and investigated.

Unlike birds and drones, rotorcraft collisions into buildings can typically be attributed to the failure of aircraft systems or weather conditions, as evidenced in many helicopter crash accidents [45–47]. In such events, the impactor is the vehicle itself, not the foreign object. As the latter is the focus of this paper, collisions with buildings and other static objects are therefore outside the scope of this paper.

Nevertheless, the existing aircraft design standards used for bird strike occurrences cannot adequately cater to collision events with other foreign objects, such as drones. This is due to the different characteristics of the impactor object, such as density, geometry, and velocity, consequently causing dissimilar impact behaviours and severity levels to the impacted aircraft. With no specific design standards and regulations currently tailored for UAM, there is a lack of adequate measures to mitigate the risk of aircraft collisions with foreign objects.

3.4. Statistics on Aircraft Collision with Foreign Objects

3.4.1. Historical Data of Bird-Strike Events on Conventional Aircraft

Between 2008 and 2017, the Australian Transport Safety Bureau (ATSB) reported 16,626 bird strikes, with the highest number occurring in 2017 at 1921 incidents [48]. The data, which can be categorised by year and location, show bird-strike rates per 10,000 aircraft movements. Larger commercial aircraft experience a significantly higher rate of bird strikes than other aircraft types, likely due to their greater speed, size, frequency of flights, and longer operational hours. However, statistics indicate that between 2006 and 2015, smaller aircraft, such as general aviation (GA), had the highest proportion of bird-strike incidents resulting in damage among all aircraft types, accounting for 25% of reported cases [49]. There were 781 incidents where birds were ingested into aircraft engines, including 11 cases involving both engines. Six aircraft were destroyed due to bird-strikes, including four remotely piloted aircraft systems and two light helicopters damaged by large birds impacting their tail rotors [48]. A study of Wildlife Strikes to Civil Aircraft in the United States [39] reported two forced landings of both US Airways and Ural Airlines during the 1990–2023 period due to bird ingestion. Although there were no human fatalities resulting from these occurrences, aircraft engines and other structures were critically damaged. There was also a report over this period showing increased bird-strike incidents, with 12 strikes on average per year for just one bird species [39]. Birds with mass over 4 lbs struck 20 civilian aircraft as a minimum in North America over this period, with bird populations including geese, snow geese, and red-tailed hawks [50].

3.4.2. Historical Data of Bird-Strike Events to Related Aircraft Types

To forecast the likelihood of bird-strike events involving UAM aircraft, historical data involving other aircraft types that operate within or traversing metropolitan areas, such as GA aircraft, private jets, and helicopters, was analysed. The Aviation Safety Network (ASN) database reported more than 40 incidents between 2017 and 2023 involving damaged strikes on GA aircraft (e.g., Cessna, Cirrus, Piper) and helicopters (e.g., Robinson R44, Robinson R66, Bell 407), which have occurred in the United States, Brazil, Canada,

Australia, France, South Africa, Switzerland, Japan, and Zambia [51,52]. More recently, a fatal accident involving a Bell 206L-3 helicopter near Hydro, Oklahoma, occurred in January 2024. Despite low bird activity reported by the US Air Force, several geese struck the helicopter, with one embedding in a flight control servo, leading to the crash and the loss of three lives [53]. Another incident occurred in March 2024 with a Eurocopter AS350B3e Ecureuil, where two red-tailed hawks collided with the helicopter during its approach to a hospital helipad near Fort Morgan, United States, severely damaging the windshield and rotor blades [54]. The pie chart in (Figure 4) shows the percentage of reported bird strikes between 1990 and 2023 in the U.S., with it being evident that most events occurred during the take-off and approach phases [39].

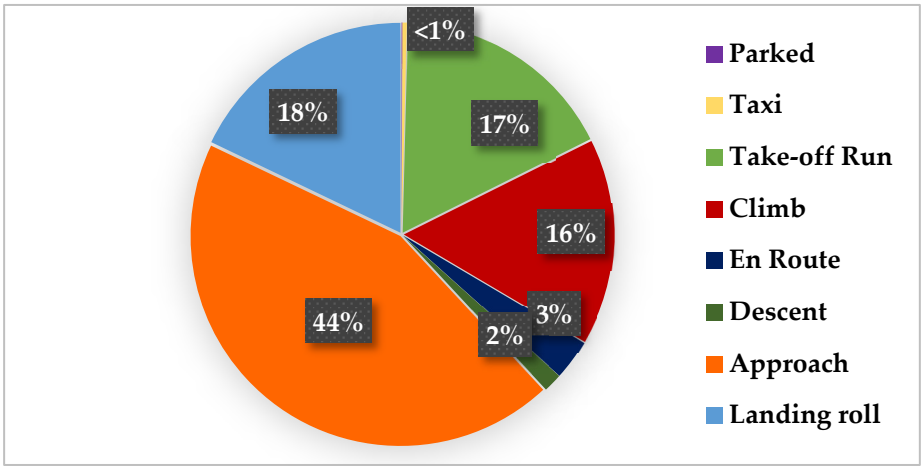


Figure 4. Number of strikes by different flight phases from 1990–2023.

3.4.3. Challenges Posed by UAM Operations in Urban Environments Specific to Bird Strikes

Statistically, the majority of reported bird strikes that resulted in damage on the aircraft occurred above 500 ft above ground level (AGL) and below 1500 ft AGL [39]. The probability of bird strikes decreases with increasing altitude, but the severity of damage may vary depending on the characteristics of the birds and aircraft in a certain airspace.

In Australia, the bird species most frequently involved in strikes were galahs (801 incidents), followed by plovers (602), bats (582), magpies (516), and flying foxes (464) [48]. The World Bird-strike Association Europe Conference highlighted that birds of prey, gulls, pigeons, and crows could potentially pose challenges to UAM, which was concluded from monitoring urban areas in 2021 attributed to their natural habitats [55]. There are some raptor species that are now more frequently found in urban area, such as great horned owl, peregrine falcon, and black sparrowhawk, as reported in Isaksson's research [56]. The number of birds strongly depends on the types of urban habitats such as buildings, greenery, and other potential nesting areas. In this sense, air transport at lower altitudes in urban areas poses new challenges for flight safety management. Experts from various organizations anticipate bird and wildlife strikes to remain a challenge in the future, emphasising the need for global attention to assess these risks and their mitigation strategies. According to a survey on the societal acceptance of UAM conducted in Europe, the top three expected concerns towards the introduction of air taxis in the future were safety, security, and environmental issues [57]. On the latter, and in addition to the threats to animals, the most critical risk identified by participants in this survey was hazards posed by wildlife to the normal operation of UAM, highlighting the priority of risk mitigation strategies to address this issue.

3.4.4. Lessons Learnt from the Operation of Drones in Urban Settings

Due to the increasing popularity of drone applications in many industries, the number of flying drones in shared airspace keeps increasing, posing a threat to other air vehicles, including UAM aircraft. Unmanned drones and air taxis, the fastest-growing sector in aviation, present one of the greatest challenges for airspace integration. A study by the German Unmanned Aviation Association predicts that Germany's commercial drone market will grow by 525 percent from 2019 to 2030, reaching approximately 126,000 drones, alongside 721,000 private drones [58]. Drones and air taxis operate very differently from traditional aviation as they typically fly at much lower altitudes and have shorter take-off and landing times [58]. The addition of even a few thousand of these vehicles could result in hundreds of thousands of daily aircraft movements. Consequently, the risk of collision could be critical due to their operation altitudes being within similar ranges. This increased risk is supported by evidence from other conventional aircraft that also operate at lower altitudes, such as helicopters [59].

The Academy of Model Aeronautics [60] reviewed the interaction events between drones and aircraft over the past years, where these incidents were divided into two categories: "Close encounters" and "Sightings". "Close encounters" are defined as incidents where a drone almost hit a manned aircraft, i.e., within 500 ft distance or where a "Near MidAir Collision" action was declared by a pilot. A "Sighting", on the other hand, is when a drone is spotted but does not pose a clear potential for a collision. In total, 28 incidents were accounted for, in which pilots reported taking evasive action to avoid a drone. It is also possible that no evasive action was taken in some certain cases when the pilot did not have sufficient time to react to the drone. There was a steep increase in sighting cases of unmanned air vehicles, rising from 238 to over 650 events from the FAA reports in 2015 [60]. In total, 160 of the recorded incidents (>50%) involved GA aircraft, such as private planes, while 99 incidents involved commercial aircraft, operated by airlines and cargo carriers [60], as presented in Figure 5. The number of 'close encounters' between drones and manned aircraft was found to have increased twofold in three years, i.e., from 87 in 2016 to 194 in 2019 [61]. A total of 628 occurrences were recorded between 2010 and 2019, with 538 involving commercial airplanes and 85 involving helicopters. Researchers from Embry-Riddle Aeronautical University and Unmanned Robotic Systems Analysis (URSA) identified 24 close calls between drones and piloted aircraft from 2018 to 2021. Since most data on these incidents come from pilot reports, many unspotted drones go unaccounted for, as pilots must simultaneously detect and avoid them [62]. Despite this limitation, the FAA recorded drone encounters in 2021, more than twice the cases reported in 2015; the first year such incidents were officially tracked.

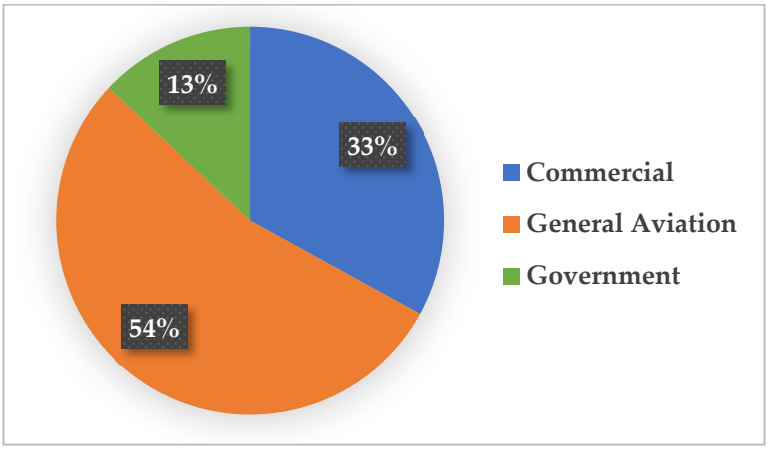


Figure 5. Percentage of close encounters with drones per aircraft operation category [47].

Even though a serious accident has not occurred during this period, potential collision risks should not be overlooked given the high number of occurrences that have been reported. A striking example of the risks posed by drones was a near-miss report in 2017, when a drone flew directly over the wing of an Airbus 319 during the approach phase to London Gatwick, putting 130 lives at risk [63]. The EASA Annual Safety Review 2024 reported that two out of 12 drone-related safety occurrences in 2023 involved large passenger aircraft during take-off or landing. One fatal accident occurred when an 8 kg drone struck a remote pilot, while another 31 kg drone veered off course, seriously injuring another pilot [64]. EASA also noted that many drone incidents likely go unreported, as most recreational drone operations are not covered by current reporting requirements.

Based on this information, the risk of mid-air collisions between drones and aircraft is quite concerning, particularly for GA aircraft and helicopters, which operate at lower altitudes and have smaller structures compared to commercial airliners. These factors make them more vulnerable to drone strikes, increasing the potential of critical damage posed by the incident. Relatively, the severity of a drone impact on UAM vehicles can also vary significantly depending on their design and operational characteristics, which needs to be highlighted when developing risk mitigations actions specific to this sector.

3.4.5. Safety Considerations Related to Different UAM Rotor System Configurations

Previous research [39,40,65] has identified the propeller and main rotors of air vehicles as being one of the primary structures that are likely to be impacted by foreign objects. FAA revealed bird-strike incidents between 1990 and 2016 related to Part 27 and Part 29 rotorcraft corresponded to approximately 85% of all impact events occurred in front of the main rotor component including windscreen, main rotor, radome, and fuselage. Approximately 30% of bird strikes occurred on the main rotor component, presenting a high likelihood of incidents closely to those affecting the windshield [66]. Further supported by recent data, the chart in Figure 6 illustrates strike percentages on aircraft components from 1990 to 2023, distinguishing total strikes (blue) from damaged strikes (red). The windshield, landing gear, and main rotor present high percentage of total strikes compared to most other components, while the main rotor and engine not only experience frequent strikes but also have a significant damage rate. The relatively high probability of bird-strike occurrences on the main rotor system as well as the likely severe consequences resulting thereof (e.g., loss of control and/or significant thrust degradation) highlight how critical this aircraft component is from a safety risk perspective.

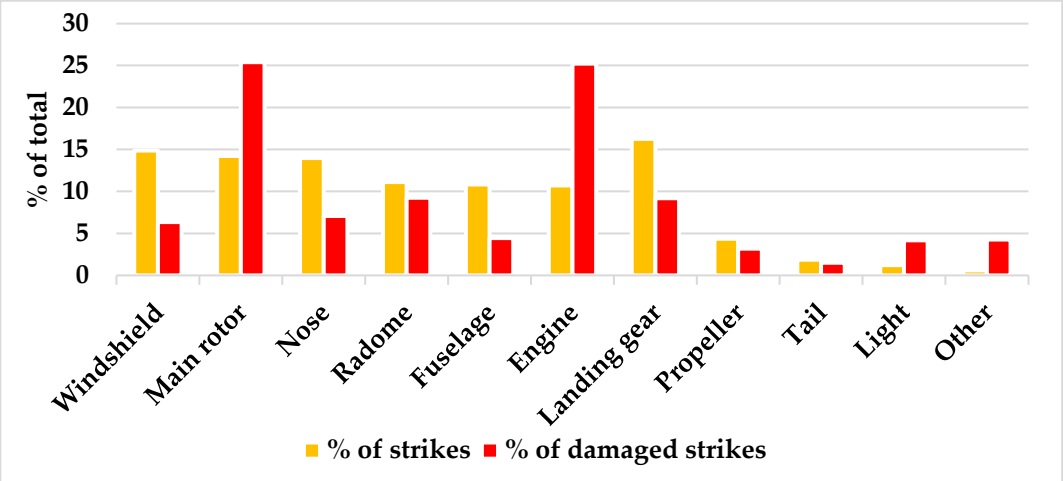


Figure 6. Percentage of strikes on main aircraft components from 1990 to 2023 in the US.

Several accidents resulting from bird-strike events in helicopters have been reported over the years. An example was a Bell 206L-1 LongRanger helicopter on a flight from Sydney to St Albans (Australia) that experienced an in-flight break-up of the main rotor blades following an impact with a wedgetail eagle [67].

Despite some similarities with existing rotorcrafts, UAM may have unique features that may lead to aggregate operational risks. One such characteristic is the consideration of DEP in the design of some UAM aircraft. The ICAS explained that the smaller dimension and the greater number of rotors could lead to higher risk of bird strikes, which possibly cause the cascading failure of the adjacent rotors and/or other critical components. The need for the establishment of unique design standards to accommodate the specific features of UAM was also emphasised given the broad range of configurations that have been proposed by distinct UAM manufacturers, which in turn may entail different levels of operational risk [41]. Therefore, it is important to investigate the impact responses of different UAM rotor system configurations under varying impact parameters to assess and compare the resulting risk severity across different scenarios.

3.5. Overview of UAM Rotor Systems Configurations

Numerous studies have been conducted to inform the design and development of UAM prototypes. Customer needs and associated mission and requirement specifications play a major role in various proposed configurations. Refs. [68,69] analysed potential configurations of novel UAM vehicles being used by different companies, including vertical take-off and landing (VTOL), horizontal take-off and landing (HTOL), and hybrid vehicles, as well as the advantages and disadvantages of each configuration based on available data. The HTOL aircraft configuration, although less suitable for urban applications, can still be used for some specific UAM operations due to their ability to carry more passengers, utilising available small airports for low-range transportation. This design follows a conventional fixed-wing configuration, similar to other existing GA aircraft like the Cessna 172 and Cirrus SR22 [69]. A recent example in this category is VoltAero's Cassio, a hybrid-electric fixed-wing aircraft designed for regional transportation, offering seating for five to twelve passengers and a flight endurance of at least 3.5 h [70]. Fixed-wing configurations have advantages in terms of low operating cost, the ability to operate under adverse conditions, and high flight endurance, which is suitable for certain applications. However, the lack of enough space for runways may be a challenge for fixed-wing aircraft in urban operations since they require longer take-off/landing distances. The emergence of VTOL technology and hover capability is expected to allow air taxis to operate from vertiports, such as building rooftops in urban settings, making them more suitable for personal use and short-to-medium distances [5]. However, they have limitations in terms of cruise speed and efficiency, resulting in a shorter range compared to other configurations. Helicopters fall under this category, so these can be used for benchmarking purposes of potential operation scenarios envisaged for UAM aircraft and associated risks. The involvement of electric technologies in UAM has led to the eVTOL aircraft concept, with the expectations to facilitate the integration of automated systems and improved environment operational characteristics, particularly when relying on multirotor configurations. A wingless design configuration has been adopted by several manufacturers to this effect. These vehicles typically possess rotor systems driven by electrical motors, which rely solely on the thrust from their Lift/Thrust Unit (LTUs) for both vertical lift and forward flight [71]. Due to their wingless configuration, they have a simple structure, providing convenient construction and maintenance processes. Numerous companies have embraced a multirotor configuration for metropolitan-based services, including Side-by-Side rotors and quadcopters designs. For example, Johnson et al. proposed concepts for VTOL air

taxis with different passenger capacities, from single to fifteen passenger [72]. Other commercial electric multirotor aircraft include Volocopter VoloCity, Moog SureFly, and Ehang 216 [24,73,74].

In order to increase the efficiency of the HTOL and VTOL configurations, hybrid systems were developed, by combining the advantages of both configurations together, such as vertical take-off capability of VTOLs and high cruise speed and maximum range of fixed-wing aircraft. Popular hybrid designs include dual systems and tilting aircraft. The dual systems aircraft or lift-and-cruise vehicles use separate power systems for take-off and cruise phases, with one system deactivated in each phase [69]. Examples of dual-system aircraft include Eve Air Mobility and Hyundai [75,76]. Tilting mechanisms, like tilt-wing and tilt-rotors, were developed to address efficiency issues of hybrid configurations, allowing for a transition from VTOL to HTOL with vectored-thrust capability. However, tilting design still present challenges due to the limited availability of suitable rotors and engines for both vertical and horizontal flight. These aircraft can also be frequently equipped with ducted rotors or coaxial rotors [69]. Examples of such aircraft include Joby Aviation, Wisk, and Archer [18,20,77].

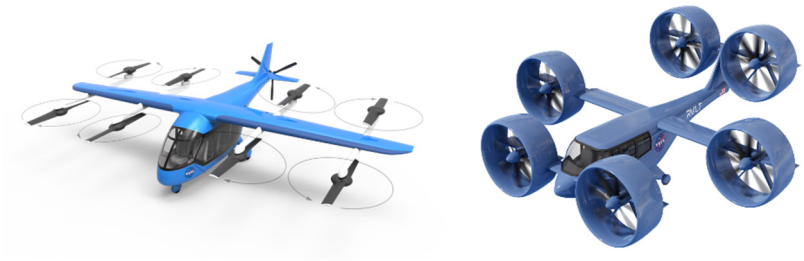
The design of UAM propulsion systems must attend to the intended operational requirements. Ref. [78] presents a good overview of technologies that can be applied to either rotor-based and propeller-based configurations with a view to improve operational characteristics of UAM aircraft, such as low-noise edgewise-flight rotors, stacked propellers/rotors, and ducted propellers The authors of this study have made their analysis based on the assumption the difference between a rotor and propeller is defined by the mode of operation: a rotor is operated predominantly in hover or edgewise flight, whereas a propeller is operated predominantly in axial forward flight [78].

Emerging UAM concepts may be categorised based on their power source (either fully electric or hybrid), the arrangement of their engines, and their control mechanism [5,68,69,71]. This means the features of UAM rotor system will also differ for each configuration. Conventional UAMs rely on a single-main rotor with large blades for quiet operation purposes. Alternatively, multirotor configuration may include side-by-side conceptual design with two overlapping rotors and quadrotor with vertical-separated rotors. The rotor design for the lift-and-cruise aircraft consists of numerous small hybrid-mounted rotors, whereas the tilting systems, such as tilt-wing and tilt-rotor design, incorporate a movable rotor. Moreover, the tilt features have the potential to include ducted rotors in the system, resulting in a "tiltduct" configuration [79]. This design uses a duct to cover mounted propellers, mitigating tip vortices to enhance thrust and reduce noise generated from blade tips. Figure 7 depicts potential UAM configurations for the rotor designs described above.



(**a**) (**b**) (**c**)

Figure 7. *Cont.*



(**d**) (**e**)

Figure 7. Potential UAM rotor system configurations: (**a**) single main-rotor, (**b**) side-by-side, (**c**) quadrotor, (**d**) lift-and-cruise, and (**e**) tiltduct [80].

3.6. Previous Birdstrike Studies on Rotorcraft

Previous studies have been conducted to analyse the damage responses of rotor blades of conventional aircraft under impact loads [81–83]. Tawk et al. (2013) assessed the impact behaviour of helicopter blades using a gas gun to simulate impacts at varying speeds [84]. These authors identified that by increasing the projectile speed, plastic deformation of the stainless-steel protection and greater degradation of the roving front spar can be caused, resulting in delamination and debonding at the skin-roving and skin-foam interfaces. Pascal et al. (2015) analysed oblique impacts on composite skins with foam cores, finding that ply orientation significantly affects fracture patterns and strain distribution, where the out-of-plane stiffness and strain levels were higher for samples with two layers oriented differently [85]. Another study carried out finite element method (FEM) simulations to characterise bird impacts on composite helicopter blades, revealing that blade rotation and bird impact location critically affect stress levels and damage patterns [86]. The results established a higher concentration of effective stress at the root section and some damage on composite skin elements with the localised impact. On the other hand, the inclusion of rubber material at the blade fronts enhanced energy dissipation from the impact mitigating the stress concentration of the solid component in the middle part to not exceeding its critical stress. Another research improved engine blade properties against bird strikes using smoothed particle hydrodynamic (SPH) modelling considering 10% porous gelatine as impactor material [87]. The results highlighted the benefits of blade twist and solid leading edges for impact performance while using a sandwich configuration in other regions helps reduce weight. Wu et al. (2022) also used SPH to simulate bird impacts on aero-engine fan blades [88]. Numerical results were compared against experimental data obtained from impact tests using a real bird (a mallard). These results were in turn validated against Wilbeck's experimental data [89], identifying key factors like impact location and bird orientation that affect deformation and stress. The study identified impacts at blade roots as the most dangerous, generating significant forces and substantial kinetic energy loss. These studies provide a framework for evaluating and enhancing rotorcraft blade design against bird strikes.

3.7. Previous Drone Collision Studies on Rotor Systems of Conventional Aircraft

Besides birds, drones or UAVs pose a significant impact threat to the safety of aircraft flying at lower altitudes. However, research on the criticality of drone collisions on helicopters and potentially on UAMs is still scarce. Some studies have been developed focused on drone ingestion models and impact simulations for larger aircraft engine fan blades [90,91]. Results found that the damage caused by drones was potentially more severe than the one resulting from bird strikes. This was due to the higher density and rigid behaviour of the main components of a drone (most notably motors and batteries), emphasising the necessity of drone impact study on other aircraft. The results also revealed

that drone ingestions at 45° and 90° angles caused greater impact forces, and more damage compared to 0° angles due to reduced blade contact area. Larger drones designed for professional use, particularly those made of carbon fibre, caused severe damage to both titanium and composite fan blades, highlighting their brittle nature. The FAA [92] conducted studies on drone impact models focusing on jet engines with titanium fan blades. They examined the effects of quadcopters and fixed-wing drone at different fan speeds and found that damage severity increased from the centre to the blade periphery. The fixed-wing drone caused more damage than quadcopters, particularly during take-off due to high rotational velocities. Thicker blades showed better resilience to impacts. It was also found that the damage is substantially severe when the fan collides with the rigid components of the drone. Building on these findings, T. Lyons and K. D'Souza conducted a parametric study on drone ingestion into fan assemblies similar in size to those of business jets [93]. They found that the highest fan rotational velocity and impacts farther from the centre resulted in the most severe damage, while thicker fan blades experienced less damage. Liu et al. (2021) used simulations to evaluate drone collisions with aircraft engines, focusing on fan blade damage and thrust loss [94]. They found that the take-off phase caused the most significant risk, followed by approach and climb phases. The study also revealed that collisions around the blade tip did not result in debris ingestion or damage to the compressor core.

Overall, the above-mentioned studies indicate that the impact model has two main distinct elements with different characteristics, i.e., both the impactor and target. Changes in material, geometry, impact angle, and impact speed significantly influence the impact damage outcomes. A comprehensive study entailing all these parameters would contribute to more informed risk assessment criteria associated with impact events, thus leading to more effective ways to reduce the severity of such events.

4. Survey Results and Discussion

In the survey conducted in this research, the participants were asked to prioritise the key hazards potentially posing risk to the UAM vehicles from 1 to 6 (total number of hazard options). The raw data were collected and illustrated as a percentage of the participants voted for such hazards, where the top three responses were highlighted.

In order to assess risks associated with UAM operations, one must start by identifying hazards that may be present in such operations. Risks are often quantified as a combination of the likelihood and the severity of an event, as per the following Equation (1) [95]:

$$\text{Risk} = \text{Likelihood} \times \text{Severity} \quad (1)$$

The likelihood or the probability is the frequency a given event is expected to occur, whereas the severity is the degree of the consequence impacting on the target of interest. The likelihood of an event is normally assessed in semi-quantitative terms using a simple 1 to 6 rating scale (1 = least probability to 6 = highest probability). Similarly, the severity is also quantified on a scale ranging from 1 (least severe) to 6 (most severe) scale. Tables 3 and 4 present a qualitative definition of these terms as per the guidelines of CQE Academy and CASA [95,96].

Table 3. Risk likelihood level definitions.

Ranking	Qualitative Likelihood	Definition
1	Extremely improbable	Almost inconceivable that this event will occur
2	Improbable	Very unlikely to occur
3	Remote	Unlikely to occur, but possible
4	Occasional	Likely to occur sometimes
5	Frequent	Likely to occur many times
6	Often	Likely to occur more than many times

Table 4. Risk severity level definitions.

Ranking	Qualitative Severity	Definition
1	Negligible	No relevant effect on safety
2	Very minor	Few consequences, no injuries
3	Minor	Low damage, nuisance, operating limitations, use of emergency procedures
4	Moderate	A significant reduction in operation ability, serious incident, injuries possible,
5	Hazardous	Causes a loss primary function, severe damage to major equipment, serious injuries to death
6	Catastrophic	Equipment destroyed, complete unsafe operation, multiple deaths

In the survey questions, the participants were asked to prioritise the potential hazards and corresponding risks specific to UAM operations, ranking these from a score of 1 (highest level) to a score of 6 (lowest level), for both the severity and likelihood of risk. In this sense, a response with a rank of 1 was translated to a risk score of 6 as per the definitions in Tables 3 and 4, representing 'often' (highest probability) and 'catastrophic' (highest severity) in qualitative terms. It should be noted that the level of risk for each category in the survey was calculated in average terms as per Equation (2). For example, Table 5 shows 4 respondents voted the 'Battery Failure' to be the most prevailing hazard potentially occurring during UAM operations, whereas other respondents ranked this hazard differently as per the scores indicated in the table. The average score resulted from the product of the probability scores and corresponding responses over the total number of participants (or responses) as per Equation (2):

$$\text{Average score} = \frac{\sum(\text{Probability Scale} \times \text{Number of responses})}{\text{Total responses}} \quad (2)$$

Table 5. Example of risk score calculation from the obtain survey results.

Probability Rank Probability Scale	1st Rank 6	2nd Rank 5	3rd Rank 4	4th Rank 3	5th Rank 2	6th Rank 1	Total Responses	Average Score
Battery failure	4	1	3	7	5	0	20	3.6

From Equation (2), the average score for the probability of a battery failure event is calculated as follows:

$$\text{Average score} = \frac{(6 \times 4) + (5 \times 1) + (4 \times 3) + (3 \times 7) + (2 \times 5) + (1 \times 0)}{20} = 3.6$$

4.1. Survey Results—Key Findings

In Question (1) and Question (2), participants were asked to prioritise hazards that pose a high risk to UAM vehicles during operation, focusing on both likelihood and severity. The hazards considered included battery failure, control system failures, human errors, foreign object impacts, environmental factors, and others specified by the respondents. Table 6 presents the ranking results based on the percentage of participants' votes, while Figure 8 highlights the percentage of respondents who ranked these hazards in the top three.

The survey data revealed that human errors, battery failure, and foreign object impacts were considered the top probability risks, with 24%, 20%, and 19% of participants, respectively, highlighting these as major concerns. Environmental factors and avionics/navigation system failures were also seen as significant risks, with many respondents ranking them in the second and third categories.

Table 6. Ranking results of hazards posing risks in UAM operation as percentage of participants.

	Key Hazards	**Rank**					
		1st	**2nd**	**3rd**	**4th**	**5th**	**6th**
Probability	Battery failure (electric system and/or propulsion system)	20%	10%	10%	35%	25%	0%
	Avionics, navigation and/or flight control systems failure (e.g., high-level autonomous system, Fly-By-Wire, autopilot, detect and avoid system, etc.)	16%	11%	32%	16%	26%	0%
	Human errors	24%	29%	10%	0%	10%	29%
	Foreign object impacts (e.g., bird strike, drones, obstacles and/or collision with another air vehicle)	19%	19%	24%	29%	5%	5%
	Environmental factors (e.g., wind, turbulence, terrain, and weather)	16%	32%	11%	21%	21%	0%
	Others (disruptive technologies (jammers GPS signals, etc.))	14%	14%	0%	0%	0%	71%
Severity	Battery failure (electric system and/or propulsion system)	28%	17%	6%	33%	6%	11%
	Avionics, navigation and/or flight control systems failure (e.g., high-level autonomous system, Fly-By-Wire, autopilot, detect and avoid system, etc.)	17%	22%	17%	0%	44%	0%
	Human errors	17%	17%	6%	22%	11%	28%
	Foreign object impacts (e.g., bird strike, drones, obstacles and/or collision with another air vehicle)	33%	17%	28%	17%	6%	0%
	Environmental factors (e.g., wind, turbulence, terrain, and weather)	5%	21%	32%	21%	21%	0%
	Others (shot-down, terrorist acts, endurance issues)	0%	33%	0%	0%	33%	33%

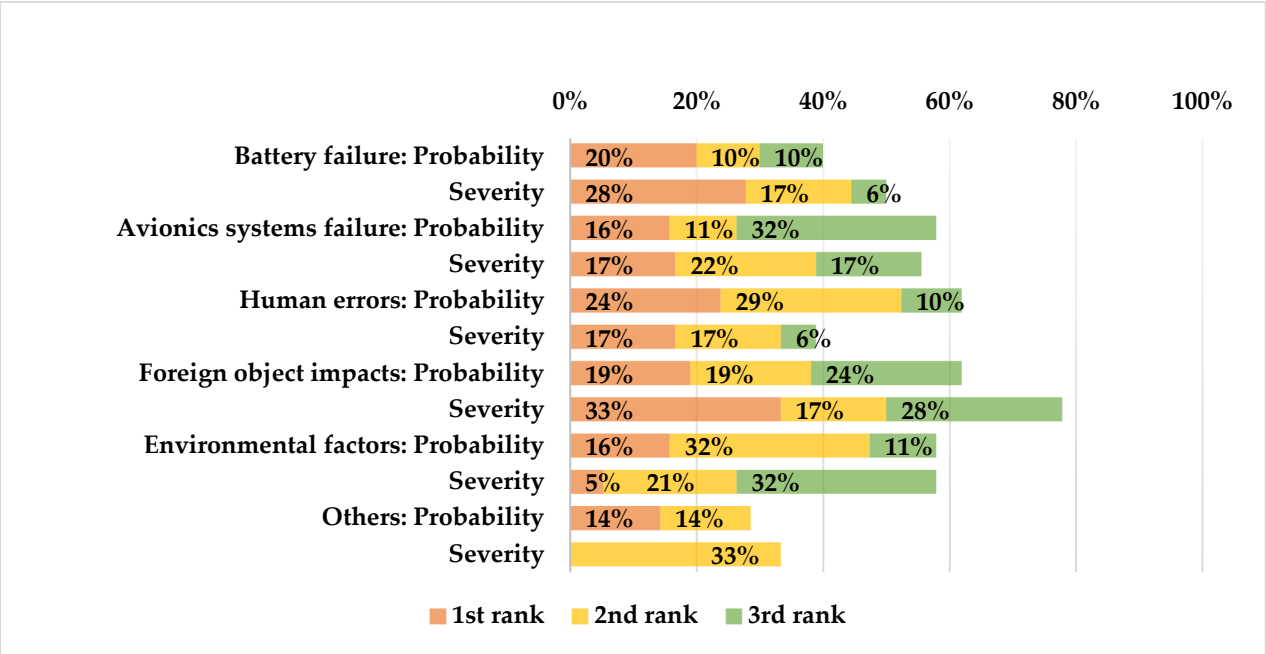


Figure 8. Top three hazards posing risks in UAM operations based on the results of the survey conducted in this research.

In terms of risk severity, foreign object impacts were again rated as the most critical, with 33% of participants ranking them as the top concern and nearly 80% placing them in the top three. Environmental factors remained a major concern, with 60% ranking them in the top three for severity. Battery failures and avionics/navigation system failures were also seen as significant risks, while human errors and other hazards, such as terrorist acts, were ranked lower.

Figure 9 shows the risk level posed by each hazard, revealing that the foreign object impacts were rated the highest across all hazards, with an average score of over 4 out of 6, where 6 indicates the highest risk, for both likelihood and severity dimensions of risk. Environmental factors and battery failures followed closely, with average ratings between 3.5 and 4. The results highlight significant concerns about both technical and operational reliability and the uncertainties associated with UAM operations, with varying levels of agreement on the relative risks resulting from different hazards.

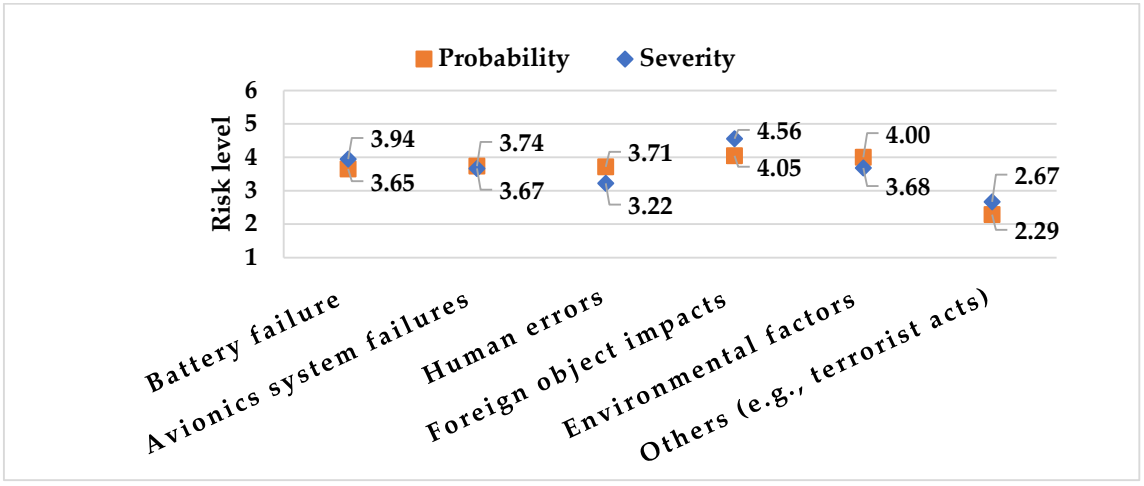


Figure 9. Risk level posed by different hazards in UAM operations as per the results of the survey conducted in this research.

Question (3) and Question (4) both explore potential collision threats to UAM vehicles, focusing on the likelihood and severity of impact from foreign objects. The potential collision threats to the UAM interested in this survey include birds, UAV/drones, other aircraft (excluding drones/UAVs), buildings, and other obstacles (e.g., power lines, antennae/communication towers, etc.). Table 7 provides a ranking summary of participants' perceptions (by percentage) towards different foreign objects that are more likely to pose impact risks to UAM aircraft.

Table 7. Ranking results of hazards posing risks of collision to the UAM as per the results of the survey conducted in this research.

	Key Foreign Objects	Rank					
		1st	**2nd**	**3rd**	**4th**	**5th**	**6th**
Probability	Birds	50%	6%	22%	6%	11%	6%
	UAVs/drones	17%	28%	6%	22%	11%	17%
	Other aircraft (excluding drones/UAVs)	6%	18%	18%	29%	24%	6%
	Buildings	0%	6%	24%	35%	24%	12%
	Other obstacles (e.g., power lines, antennae, etc.)	18%	41%	6%	6%	24%	6%
	Others	6%	0%	0%	0%	0%	0%
Severity	Birds	41%	0%	6%	12%	35%	6%
	UAVs/drones	6%	12%	18%	24%	18%	24%
	Other aircraft (excluding drones/UAVs)	23%	23%	8%	8%	31%	8%
	Buildings	13%	31%	25%	25%	6%	0%
	Other obstacles (e.g., power lines, antennae, etc.)	12%	41%	18%	18%	12%	0%
	Others	0%	0%	0%	0%	0%	0%

For risk probability of the collision event, the bar charts in Figure 10 show that 'birds' are perceived as the most likely hazard, with about 80% of respondents ranking them in the top three, and the highest number considering them the top collision risk. Other obstacles, such as power lines and antennae, and UAVs/drones were also identified as significant risks, with around 65% and 50% of participants ranking them in the top three, though they were more frequently rated as second and third threats. 'Other aircraft' (excluding drones) and 'buildings' were seen as moderate probability risks, with similar rankings in the second and third categories. This suggests that while these are noted concerns, they are not deemed as the most immediate safety risks by the participants in the survey.

As well as the probability, the risk severity of potential collision damage was also reported in Figure 10. Here, 'birds' were again viewed as the most severe hazard, with 41% ranking them as the top concern. Whereas buildings and other obstacles (e.g., power lines, antennae, etc) gained prominence, with most contributions from second and third positions. Interestingly, 'other aircraft' and 'UAV/drones' were rated lower than expected in terms of severity, despite their potential for high-energy impacts. A possible explanation for this result could be that the participants have interpreted the question as focusing more on natural hazards and urban infrastructure rather than conventional high-risk objects, leading to unexpectedly low concern for some hazards that typically pose substantial risks in UAM operations. Overall, 'birds' were consistently highlighted as both a high-probability and high-severity risk, as well as obstacles like power lines and buildings (Figure 11).

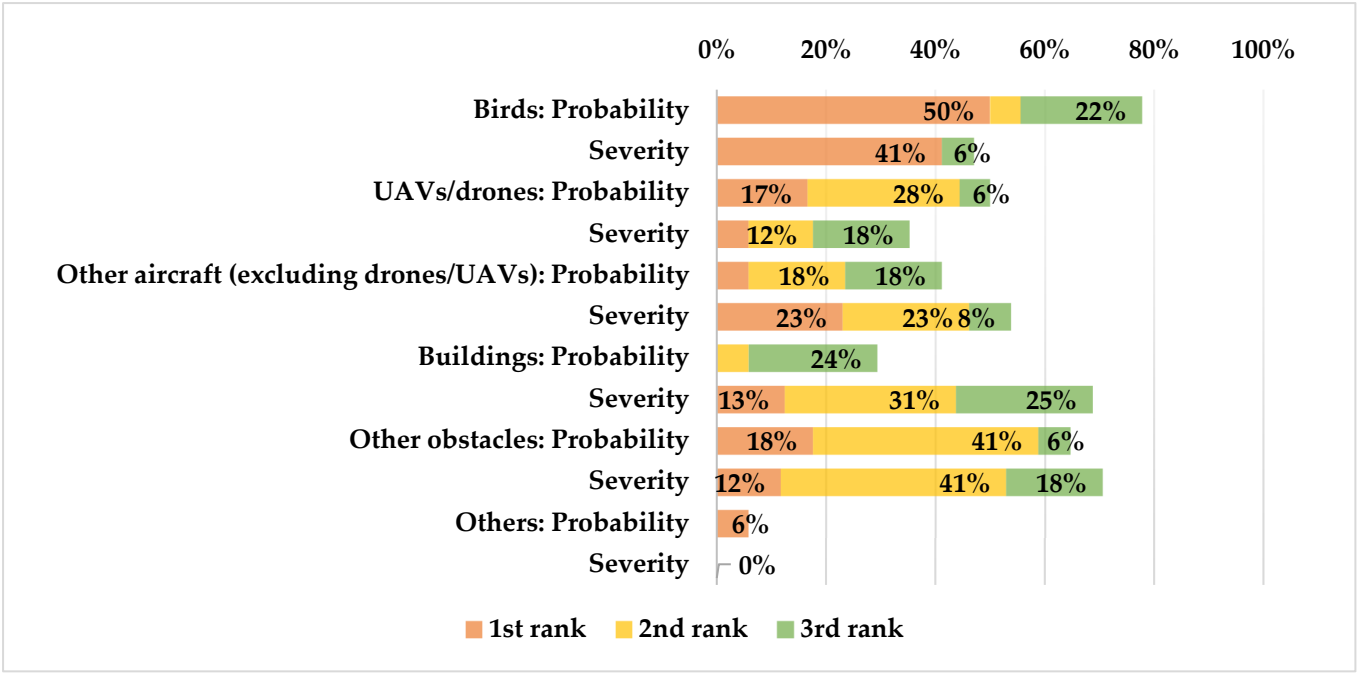


Figure 10. Top three hazards posing risks of collision to the UAM as per the results of the survey conducted in this research.

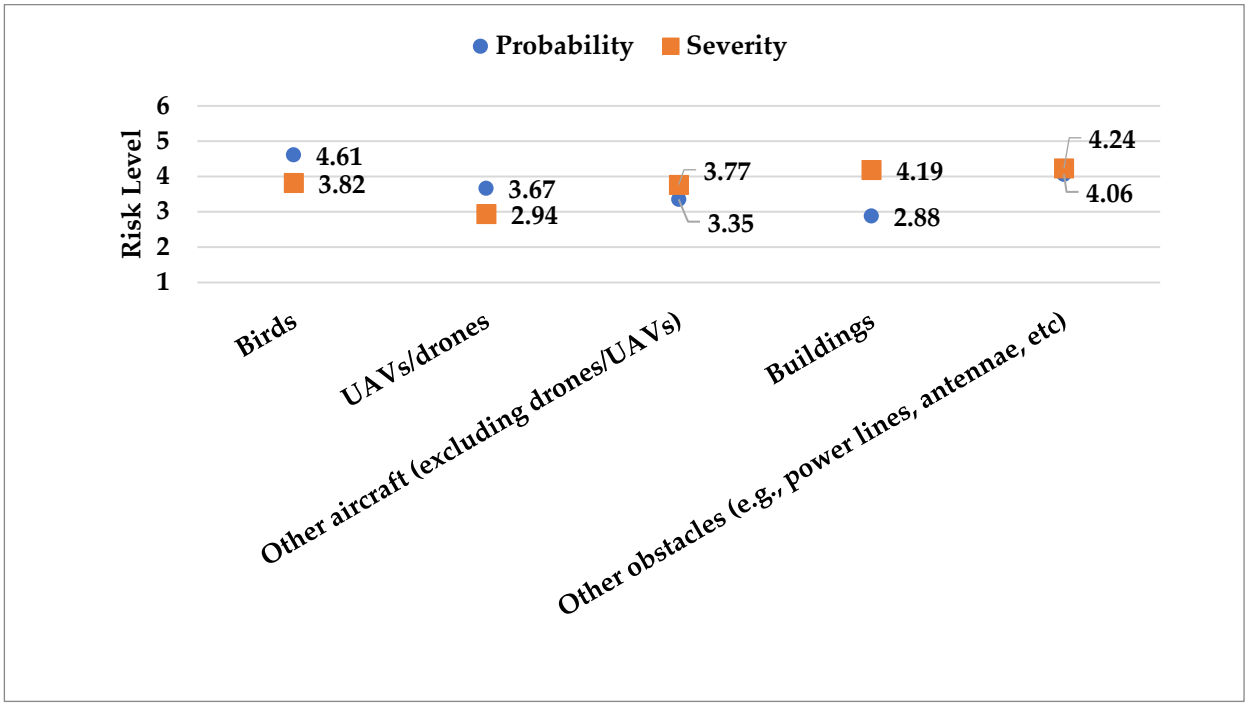


Figure 11. Probability and severity of risk of collision posed by different hazards in UAM operations as per the results of the survey conducted in this research.

Question (5) examined the UAM aircraft components potentially posing higher risk under impact incidents, where the participants were asked to consider both probability and severity risks altogether in this question. The aircraft parts focused on in this survey included windshields, radome/nose cone, rotor/propeller, fuselage, wing leading-edge, empennage, etc. The collected data are presented in Table 8 as a percentage of participants. 'Rotor/propeller' received an obvious highest number of responses among all components, ranking as the first category. Not only did over 50% of the respondents vote it as the top

rank, but also 90% agreed that it was the most critical part within the top three categories. 'Radome/nose cone' was considered as the second aircraft part subject to higher risks, followed by wing-leading edge and windshields. The **'fuselage' and 'empennage'** components show a minimal ranking, suggesting these are of lesser concern in the context of UAM collisions. The prioritization results are confirmed with the risk degrees of 5.2 out of 6 in Figure 12, highlighting the substantial risks of the rotor system of UAM.

Table 8. Ranking results of collision risks of different UAM parts/components as percentage of participants.

	Main Aircraft Parts	Rank					
		1st	2nd	3rd	4th	5th	6th
Probability and Severity	Windshields	7%	33%	7%	27%	13%	13%
	Radome/Nose cone	33%	13%	20%	13%	13%	7%
	Rotor/propeller blades (propulsion system)	53%	20%	20%	7%	0%	0%
	Fuselage	13%	0%	13%	0%	38%	38%
	Wing leading-edge	0%	29%	21%	50%	0%	0%
	Empennage	0%	7%	21%	0%	14%	57%

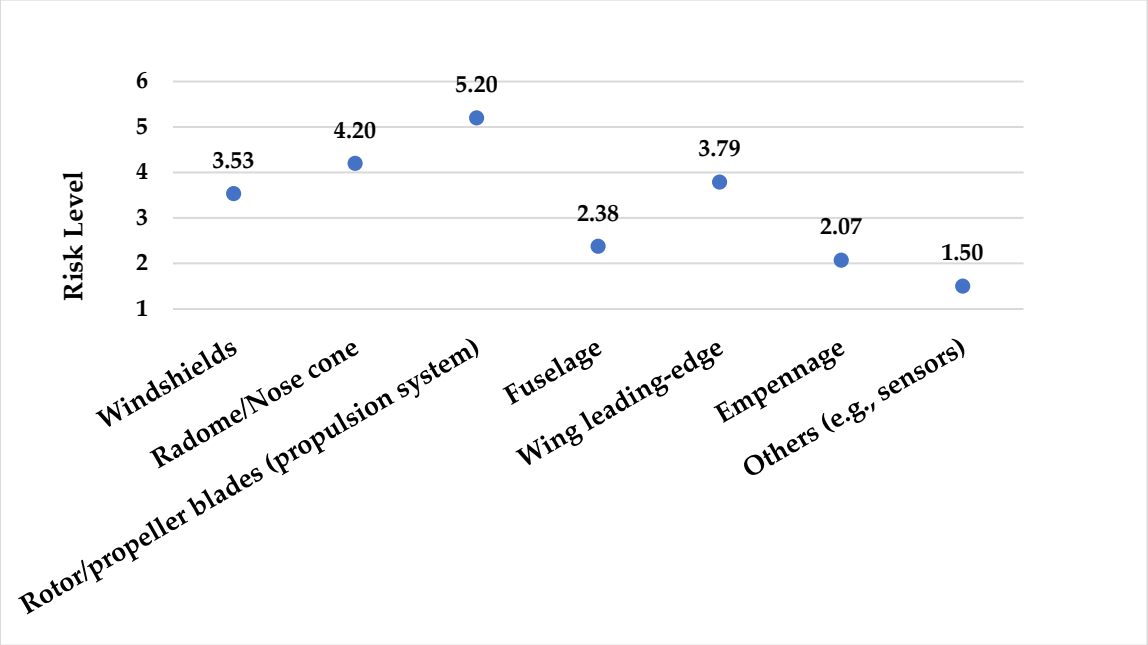


Figure 12. Probability and severity risk levels of different UAM components to impact events.

In Question (6), considering an impact event of the propulsion system (e.g., propeller/rotor blade), the participants were asked to rank different UAM aircraft configurations that could potentially be associated with different levels of risk of impact with foreign objects. As shown in Table 9, more than half of the participants (53%) agreed that 'Single main rotor' (wingless type) has the highest potential to receive critical damage against impact of the foreign objects, with the overall ranking under top three reaching 85%. While 21% of the participants ranked another wingless type 'multirotor' as a secondary top risk configuration, the 'tilting-system' category presented higher overall results within top three ranking, around 20% greater. Figure 13 presents the risk for the different UAM propulsion

system configurations included in the survey, which could be one of the factors of interest to be considered during the design phase of UAM aircraft.

Table 9. Severity risks of different UAM configurations to impact events as per the results of the survey conducted in this research.

	Key Foreign Objects	Rank					
		1st	2nd	3rd	4th	5th	6th
Severity	Single main rotor (wingless)	53%	20%	13%	0%	7%	7%
	Multirotor (wingless)	21%	29%	0%	21%	14%	14%
	Lift-and-cruise (fixed wing)	7%	7%	20%	20%	40%	7%
	Tilting system	14%	21%	36%	21%	7%	0%
	Ducted rotor	0%	14%	29%	21%	21%	14%
	Others	0%	0%	0%	0%	0%	0%

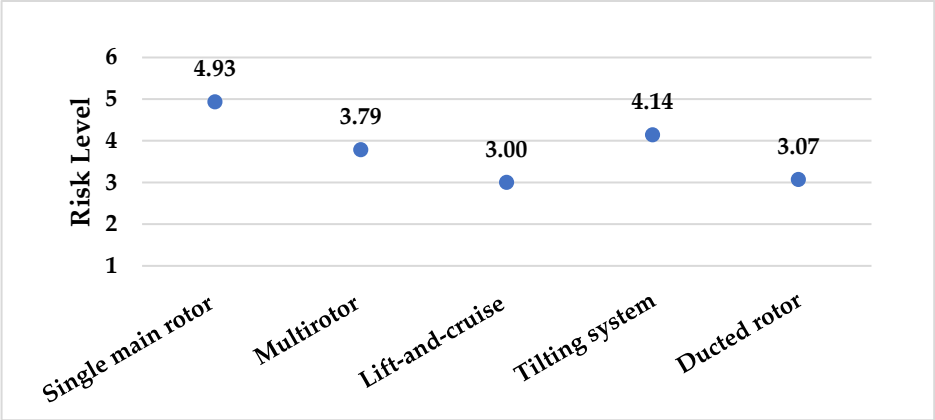


Figure 13. Severity risk levels of different UAM configurations to impact events.

Finally, Question (7) asks participants how the risks associated with the impact of foreign objects could be mitigated based on their knowledge and/or experience. There were various strategies to improve UAM safety given by a range of expert responses, focusing on bird strike prevention, foreign object management, airspace control, impact resistance, and crash protection.

To reduce bird strikes, one response suggests using bio-acoustic techniques at vertiports and airfields to deter birds from gathering. Similarly, the design and manufacturing sector emphasises the need for take-off and landing areas to be made less hospitable to wildlife, which would lower the risk of animal collisions. Alongside this, they propose enhanced terrain awareness systems and regular FOD patrols to mitigate other risks.

Experts from both the air traffic management and investigation sectors stress the importance of robust airspace control systems, such as Unmanned Traffic Management (UTM/UATM), to manage not only UAM vehicles but also drones and helicopters in crowded urban settings. These sectors also call for advanced onboard detection technologies like Traffic Collision Avoidance Systems (TCAS) and LiDAR to boost traffic safety and prevent collisions, while cybersecurity measures are crucial to prevent unauthorised access to UAM systems.

On the structural integrity front, some participants advocated for the use of advanced composite materials, such as carbon fibre-reinforced polymers, to improve UAM vehi-

cles' impact resistance. This is complemented by non-destructive testing techniques like pulse-echo ultrasonics and wireless sensor networks for early damage detection. Other perspectives also included crash protection through reliable structures, power plants, and CNS systems (communication, navigation, and surveillance), as well as the use of ballistic parachutes and occupant shells for added safety.

From the aeronautical sector, there is a push for stricter standards to ensure failure probabilities remain within the bounds of 10^{-9}, coupled with comprehensive risk failure analyses during certification and operational phases. Aviation accident investigators further highlighted low-altitude risks, including hard-to-detect obstacles like wires and the impact of high wind gusts, which have previously led to helicopter crashes. They suggest incorporating wind modelling around buildings in UAM system designs, particularly in windy cities, to mitigate the risk of collisions with urban infrastructure.

These insights reveal a multi-faceted approach to addressing UAM collision hazards, focusing on a combination of design, material selection, advanced avionics, and regulatory measures. The diverse professional backgrounds of the respondents contributed to a well-rounded understanding of the risk associated with UAM operations, especially collision events associated with foreign objects, offering valuable insights for future research in this area.

4.2. Risk Evaluation Based on the Survey Results

Based on results collected through the survey A, the outcome risk levels for each hazard were tabled on a 6 × 6 risk matrix [95], as depicted in Figure 14. This risk matrix demonstrates the connection between the calculated risk values (shown as numbers within the matrix) and the severity of occurrence (*Y*-axis) along with the likelihood of occurrence (*X*-axis). The risk level increases as either the severity or likelihood increase. This matrix is based on a 6-point scale for both severity and likelihood, where 1 (green) indicates the lowest severity or likelihood and 6 (red) indicates the highest.

Risk Matrix		**Probability**					
		1	**2**	**3**	**4**	**5**	**6**
Severity	**1**	**1**	**2**	**3**	**4**	**5**	**6**
	2	**2**	**4**	**6**	**8**	**10**	**12**
	3	**3**	**6**	**9**	**12**	**15**	**18**
	4	**4**	**8**	**12**	**16**	**20**	**24**
	5	**5**	**10**	**15**	**20**	**25**	**30**
	6	**6**	**12**	**18**	**24**	**30**	**36**

Figure 14. Risk-ranking matrix.

The risk thresholds depend on the risk management policy adopted by main stakeholders. CASA conceptually described the safety risks as acceptable (green zone), tolerable (orange zone) or intolerable (red zone), as shown in Table 10 [96].

The total risk values for each hazard category can be placed against the safety risk zones indicated in Table 10 Since the risk value results from the product of probability and severity scores, the findings from Question (1) and Question (2) were combined, as well as Question (3) and Question (4). In Question (5), the respondents were asked to consider both probability and severity aspects simultaneously, so the risk value resulting from this question was final.

Table 10. Definition of safety risk zones and associated risk mitigation actions by CASA [96].

Safety Risk Zone	Meaning	Recommended Procedure
	Intolerable	Take immediate action to mitigate the safety risk index to the tolerable
	Tolerable	A management decision may require approaching an acceptable risk range
	Acceptable	No further safety risk mitigation necessarily required

- Risks in the operation of UAM aircraft: Question (1) + Question (2)

Table 11 presents the risk levels for the different hazard categories that were identified in the previous sections, represented by different star colours. Figure 15 shows where each risk category falls in the risk matrix by using the same colourstar symbols. The definition of each colour in the risk matrix (green, orange, and red) can be referred to the safety risk regions introduced in Figure 14. If a given risk category sits within the green region, such risk is deemed to be acceptable. On the other hand, those risks which align within the yellow and red regions are considered to require further mitigation actions, especially the ones in the red zone, where immediate procedures are required to prevent catastrophic consequences. For example, the risk of foreign objects impacts posed to UAM operations (yellow star) is located in the red zone (risk score is equal or greater than 18) which is intolerable, meaning mitigation strategies are necessary in order to bring this risk down to acceptable levels. While other operational hazards fall within the tolerable or acceptable risk categories, they would still require ongoing monitoring, and proactive measures so they remain as low as reasonably practicable and do not escalate into more severe threats.

Table 11. Operational risk levels of UAM aircraft associated with different hazards.

Key Hazards	Probability	Severity	Risk
Battery failure (electric system and/or propulsion system)	3.65	3.94	14.40
Avionics, navigation and/or flight control systems failure (e.g., high-level autonomous system, Fly-By-Wire, autopilot, detect and avoid system, etc.)	3.74	3.67	13.70
Human errors	3.71	3.22	11.97
Foreign object impacts (e.g., bird strike, drones, obstacles and/or collision with another air vehicle)	4.05	4.56	18.44
Environmental factors (e.g., wind, turbulence, terrain, and weather)	4.00	3.68	14.74
Others (shot down like MH17, terrorist acts)	2.29	2.67	6.10

- Risks of collision to the UAM aircraft: Question (3) + Question (4)

Similar analysis was also applied to the risk evaluation of Question (3) and Question (4), which focus on the risks associated with collision events of UAM aircraft in urban environments. The risk levels for each hazard category are indicated in Table 12. One can

conclude 'birds' posed the highest risk across all impact threats, closely followed by 'other obstacles', like power lines and buildings. Although both categories do not completely align in the intolerable zone in the risk matrix in Figure 14, their borderline values emphasise the necessity to consider these hazards as critical safety concerns.

Risk Matrix		Probability					
		1	2	3	4	5	6
Severity	1	1	2	3	4	5	6
	2	2	4	6	8	10	12
	3	3	6	9	12	15	18
	4	4	8	12	16	20	24
	5	5	10	15	20	25	30
	6	6	12	18	24	30	36

Figure 15. Evaluation of UAM operational risks associated with the hazard categories identified in Table 11.

Table 12. Hazards and corresponding risk of collision of UAM aircraft operations in urban environments.

Key Hazards	Probability	Severity	Risk
Birds	4.61	3.82	17.63
UAVs/drones	3.67	2.94	10.78
Other aircraft (excluding drones/UAVs)	3.35	3.77	12.64
Buildings	2.88	4.19	12.07
Other obstacles (e.g., power lines, antennae, etc.)	4.06	4.24	17.19
Others	0.00	0.00	0.00

- Risks of impact associated with different UAM components: Question (5)

Table 13 presents the finalised risk outcomes assessing the risk of impact considering the main parts or components of UAM aircraft. Clearly, the rotor/propeller blades are the most concerning issue among all components, highlighting the importance of mitigation strategies to substantially reduce the high-risk level associated with an impact event affecting this component.

Table 13. Impact risk levels for main parts or components of UAM aircraft impact events.

Aircraft Component	Probability	Severity	Risk
Windshield	3.53	3.53	12.48
Radome/Nose cone	4.20	4.20	17.64
Rotor/propeller blades (propulsion system)	5.20	5.20	27.04
Fuselage	2.31	2.31	5.35
Wing leading-edge	3.79	3.79	14.33
Empennage	1.71	1.71	2.94

5. Conclusions

This paper discussed the safety risks associated with the operation of UAM aircraft in urban environments. Due to the specificities of this aviation sector, including the unique design configurations and typologies of UAM aircraft and their operational profile, it was found that there are significant risks of UAM aircraft encountering and colliding with foreign objects, most notably birds and drones.

There are important lessons to be drawn from incidents and accidents that have happened over the years involving conventional aircraft that operate in urban settings, such as helicopters. Additionally, the survey conducted in this paper also contributed to a comprehensive evaluation of risk levels associated with various hazards in UAM operations. These risks were assessed based on both probability and severity of occurrence. A risk matrix was used to categorise the different risks into three zones: green (acceptable), orange (requires attention), and red (intolerable), with mitigation strategies required for the latter. The key outcomes highlight that foreign object impacts, particularly from birds, pose the highest risk, indicating immediate actions are required to address these risks. Other risks are also noted as significant concerns, such as the ones associated with the collision between UAM aircraft and drones. The risk assessment conducted in this paper identified the rotor/propeller blades as the most vulnerable component in a UAM in terms of both the likelihood and severity of an impact event with an object, underscoring the need for mitigation efforts to reduce risks tailored for these components. These findings emphasise the need for a comprehensive risk assessment of impact events with foreign objects to enhance safety in UAM operations.

These findings heighten the importance to consider the development of bespoke risk management strategies to underpin both the design and operation of UAM aircraft. Although previous research has contributed to a more informed knowledge on the effect of impact events resulting from the collision of drones and birds on helicopters and commercial aircraft, the specific risks inherent to UAM aircraft remain uncertain. This knowledge gap raises concerns around critical operational safety concerns for this emerging aviation sector. Further research is required to enhance impact damage tolerance characteristic of UAM rotor systems. Insights from this research would inform the development of new standards and regulatory requirements addressing the unique features of UAM aircraft, contributing to a safer integration of this aircraft category in future airspace system.

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Abbreviations

The following abbreviations are used in this manuscript:

AAM	Advanced Air Mobility
AGL	Above Ground Level
ASN	Aviation Safety Network
ATSB	Australian Transport Safety Bureau
CASA	Australian Civil Aviation Safety Authority
CHEAN	College Human Ethics Advisory Network
CS	Certification Specification
DEP	Distributed Electric Propulsion
EAR	Easy Access Rules
EASA	European Union Aviation Safety Agency

eVTOL	Electrical Vertical Take-Off and Landing
FAA	Federal Aviation Administration
FBW	Fly-By-Wire
FEM	Finite Element Method
FHA	Failure Hazard Analysis
FMECA	Failure Modes and Effects Criticality Analysis
FOD	Foreign Object Debris
FY	Financial Year
GA	General Aviation
HTOL	Horizontal Take-Off and Landing
ICAO	International Civil Aviation Organization
IPP	Integration Pilot Programme
ITS	Intelligent Transportation Systems
LTUs	Lift/Thrust Unit
NASA	National Aeronautics and Space Administration
RPT	Regular Public Transport
SPH	Smoothed Particle Hydrodynamic
TCAS	Traffic Collision Avoidance Systems
UA	Unmanned Aircraft
UAM	Urban Air Mobility
UAS	Unmanned Aircraft System
UAVs	Unmanned Aerial Vehicles
URSA	Unmanned Robotic Systems Analysis
UTM	Unmanned Traffic Management
VTOL	Vertical Take-Off and Landing

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