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DEGREE FINAL PROJECT

TITLE: Assessing UAM emergency procedures in existing or new heliports

DEGREE: Degree in Aerospace Systems Engineering

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Resum

Amb el creixent interès dels grans inversors i fabricants per solucions UAM, molts prototips de vehicles i dissenys d'infraestructures terrestres comencen a aparèixer i a provar-se en escenaris reals. Aquest mode de transport aeri podria ser revolucionari si s'assoleixen les diferents fites. Tot i que hi ha molts reptes per cobrir, des de la contaminació acústica fins a la gestió de l'espai aeri, la seguretat és probablement un dels principals elements a avaluar. I tot i que s'ha destinat molt d'esforç en el disseny i la promoció de vehicles UAM, hi ha una mancança d'investigacions sobre consideracions de seguretat.

Aquest estudi proporciona una discussió sobre diferents troballes relacionades amb la seguretat basant-se en una anàlisi de la causa arrel de diversos accidents reportats i documentats amb helicòpters involucrats en entorns i condicions similars als que es preveuen en operacions UAM. Mitjançant l'avaluació d'aquests perills en aeronaus VTOL similars, com els helicòpters, es fa una extrapolació per a diferents tipologies de vehicles UAM, en funció de les seves característiques i capacitats operacionals observades en diversos prototips.
L'anàlisi es divideix en dues parts principals. La primera part se centra en els diferents esdeveniments implicats en els accidents, seguint les definicions estàndard del CICTT per a la notificació d'accidents i incidents d'aviació. A la segona part s'aprofundeix i s'analitzen les causes implicades que condueixen a aquests esdeveniments, i com poden aplicar-se als vehicles UAM. La discussió considera els perills identificats en diferents nivells, en funció de factors com la presència humana i l'automatització, i el seu impacte en la criticitat, la prevenció i la mitigació.

Globalment, l'estudi proporciona algunes pautes sobre temes de seguretat que es consideren rellevants per a futures investigacions en l'àmbit de la UAM, així com per a la futura estandardització dels elements necessaris per implantar i regular aquests sistemes als nuclis urbans.

Abstract

With the rising interest from big investors and manufacturers in UAM solutions, many vehicle prototypes and ground infrastructure designs are beginning to appear and being tested in real-world scenarios. This mode of air transportation could be a game-changer if the different milestones are achieved. While there are many challenges to be covered, from noise pollution to airspace management, safety is probably one of the main elements to be assessed. And while much effort has been given into designing and promoting UAM vehicles, little research has been published or conducted about safety considerations.

This study provides with a discussion on different findings related to safety based on a root cause analysis of reported and documented helicopter accidents involving similar environments and conditions to those UAM will face. By assessing these hazards in similar VTOL aircraft such as helicopters, an extrapolation to UAM vehicles is made for different types of vehicles, depending on their characteristics and performance capabilities observed in various prototypes.

The analysis is divided in two main parts. The first part focuses on the different occurrences involved in the accidents, following the CICTT standard definitions for reporting aviation accidents and incidents. The second part goes deeper and analyses the causes involved that lead to those occurrences, and how these could apply to UAM vehicles. The discussion considers the identified hazards in different levels, depending on factors such as human presence and automation, and their impact on criticality, prevention and mitigation.

The overall study provides with some guidelines on safety issues that are considered relevant for future research in the field of UAM, as well as for the future standardization of the necessary elements to implement and regulate these systems in urban centers.

Acknowledgements

The realization of this project has been a journey that would not have been possible without the guidance and expertise of my director, Dr. Jordi Pons-Prats, and my co-director, Dr. Jovana Kuljanin. Their tuition throughout this project, especially on this topic which is still at an early stage of development, has been essential in defining a solid hypothesis. I would also like to thank them for accepting me to take on this research, and for their trust and support.

Many thanks to my family and friends, who have supported me unconditionally along the way. Not only the realization of this TFG but my years of university would not have been the same without their continuous support.

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Abbreviations

AAIB	Air Accidents Investigation Branch
AFCS	Auto Flight Control System
ATSB	Australian Transport Safety Bureau
AOA	Angle Of Attack
CAST	Commercial Aviation Safety Team
CENIPA	Aircraft Accident Investigation and Prevention Center
CICTT	CAST/ICAO Common Taxonomy Team
EASA	European Union Aviation Safety Agency
ETL	Effective Translational Lift
FAA	Federal Aviation Administration
HFACS	Human Factors Analysis and Classification System
HST	High-Speed Train
ICAO	International Civil Aviation Organization
IFR	Instrumental Flight Rules
IMC	Instrumental Meteorological Conditions
LTE	Loss of Tail rotor Effectiveness
NTSB	National Transportation Safety Board
OGE	Out of ground effect
PIC	Pilot In command
RPM	Revolutions per minute
SAS	Stabilization Augmentation System
STOL	Short Take-off and Landing
UAM	Urban Air Mobility
UAV	Unmanned Aerial Vehicle
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VRS	Vortex Ring State
VTOL	Vertical Take-off and Landing

Glossary

UAM	UAM is an air transportation system for passengers in urban environments, projected to complement other existing ground mobility networks. By implementing a network of vertiports and fleets of highly automated small VTOL aircraft, this mode of transportation aims to operate at low altitudes in urban and suburban areas in response to traffic congestion.
VTOL	VTOL and its electric counterpart, eVTOL, refers to aircraft with vertical take-off and landing capabilities, without relying on a traditional runway.
STOL	STOL refer to aircraft that has short runway requirements. Some VTOL aircraft are designed to operate as STOL as well.

According to ICAO Standards and Recommended Practices for Aircraft Accident and Incident Investigation,

Accident	An occurrence associated with the operation of an aircraft which takes place between the time any person boards the aircraft with the intention of flight until such time as all such persons have disembarked, in which (a) a person is fatally or seriously injured while onboard or because of aircraft related factors, (b) the aircraft sustains considerable damage or structural failure which affects structural strength, performance or flight characteristics of the aircraft, or (c) the aircraft is destroyed or becomes completely inaccessible.
Incident	An occurrence, other than an accident, associated with the operation of an aircraft which affects or could affect the safety of operation.
Congested environment	In relation to a city, town or settlement, any area which is substantially used for residential, commercial or recreational purposes.
Congested-hostile environment	A congested environment in which (a) a safe forced landing cannot be accomplished because the surface and surrounding environment are inadequate, (b) the occupants cannot be adequately protected from the elements, (c) search and rescue response/capability is not provided consistent with anticipated exposure, or (d) there is an unacceptable risk of endangering persons or property on the ground.

1. Introduction

1.1. Motivation

Global population is growing, and population density within urban areas is increasing at a much faster rate than the required infrastructure to move this population around. Cities are expanding at a fast pace, and quickly saturate their absorption capacity of the ground traffic before they can adapt. This results in unacceptable traffic congestion levels within urban boundaries, and an impact on commute times that increases exponentially, especially during peak hours. The availability for improved or new ground infrastructures is observed to be very limited, as unbuilt spaces are rare to find in most of the world's major cities, and the disruption that these renovations can cause on the urban layout is delicate and needs deep assessment, as it could be at the expense of neighborhoods division.
While traditional public transit modes have demonstrated to help reduce this traffic footprint, estimated to decrease delays between 38% and 48% (Anderson, 2014), they still rely on the same limited ground infrastructure. UAM is precisely the kind of model that is expected to fill this market gap, and its potential begins to firm up. With an exponential increase in the service frequency until reaching a scale that would make this transport mode accessible for the general public, this transport mode is expected to divert some of the ground impact that commuting causes nowadays.

Many benefits could be obtained from the introduction of UAM networks in major cities. Apart from the pressure alleviation on ground traffic congestion, it can provide new integrated connections inside and outside existing urban structures that are economically impossible to match with ground-based infrastructure. Furthermore, the use of eVTOL vehicles will allow for clean and zero-net-emission journeys, while minimizing the physical space needed to operate.
Major aircraft manufacturers in the rotorcraft industry such as Airbus, Honeywell, Leonardo or Vertical Aerospace, as well as companies such as Uber, Lyft, BLADE or American Airlines, are all investing and researching towards this next mode of transportation (Vertical Aerospace, 2022). While most attention is being focused towards vehicle design, communications or ground and digital infrastructure, there is a lack of research on safety-related topics (Garrow et. al., 2021). Defining operational emergency procedures must be a top priority when assessing this new mean of transportation, as outlining solid operational baselines for these future vehicles will be key to their airworthiness certification. Identifying the main factors that may pose a safety risk and the mitigation actions designed for current aircraft are keys for understanding what can be expected in UAM vehicles and their behavior when encountering emergency situations. Since most of the prototypes proposed for this market share a lot in common with helicopters, analyzing the way they operate and respond to certain situations may help to lay down the operational foundations for these future vehicles.

Some drawbacks, however, can be highlighted in this mode of transportation. The reduced seat capacity observed in many of the prototypes presented, with a payload around 1-5 passengers in average (Lascara et. al., 2018), projects a high scale of investment required that would force this business to operate without any short-term profitability. And because UAM aims to be accessible to the general public, prices should be limited. Therefore, because of this, the economic viability of these projects could delay implementation. Seating capacity could be increased after moving beyond the early stages of UAM's development, but will need to be closely complemented by a high passenger demand and operating frequency. And the latter can only exist after a careful safety evaluation.

There is also a lack of assessment by international entities such as ICAO, which do not describe the requirements and performance standards for either UAM or autonomous vehicles, and would be the most appropriate organization to regulate the safety of such mode of transportation following the work done with similar aviation categories. While Annex 6 (ICAO, 2010) addresses operational recommendations for helicopters, including emergency and contingency procedures, it is not clear these will apply the same way in UAM operations, especially in the case of vehicles that deviate more from current helicopter concepts. Annex 2 (ICAO, 2005), on the other hand, describes general rules for visual and instrumental flight, but does not contain information about how automated or autonomous vehicles should operate. Therefore, a preliminary analysis on vehicle categorization, their respective behavior and the environmental and operational hazards concerning these could be beneficial for future adaptations of these Annexes for eVTOL vehicles.

As commented, previous research on this field is limited. Bauranov et. al., 2019 explores the variability in human workload and the safety risks associated when considering manned and autonomous aerial vehicles. They do emphasize the importance of predicting, controlling and regulating risks and hazards associated with the operation in urban environments, especially when passengers are onboard, as the safety of both the latter as well as that of the other people and property on the ground must be ensured. However, this study focuses on two occurrences, mid-air collisions and ground impact, and does not cover other critical hazards.
Cohen et. al., 2021 compiles historical and current projects on UAM modes in order to find a potential market and indicates, among other aspects, some safety and regulatory issues that need to be covered in order to certify these vehicles and advance in the adoption of this new transportation model. In particular, it addresses six points claimed to be critical, including core system failures (for instance, engine failure), loss of control and unsafe proximity to people or property. Other important hazards include weather-related risks, birds or human factors. While the authors make a first contribution in highlighting relevant safety elements, they do not provide a deeper analysis on these.

1.2. Objectives

This project aims to shed some light in the field of operational safety in UAM vehicles, and propose some hypothesis that may help to identify needed areas of research when designing both the vehicles and its required infrastructure.
Helicopters have been operating in urban environments since the 1950s, and many lessons have been learned during this time. Regulations and procedures have evolved from both research and experience to a degree where this industry has reached a solid operational core. Safety has always been one of the main pillars of aviation, and it is the main reason why certification processes take a long time to be granted. With UAM there will be no difference.

By assessing common safety risks found in helicopters as a reference and analyzing the projected characteristics and behavior of the next generation of UAM vehicles, this project aims to discuss and propose safety elements to be considered when designing these vehicles and its operational procedures around congested-hostile environments, based on previous accidents with helicopters and rotorcrafts in similar environments and conditions to those expected in UAM modes. Experience, accident history and other relevant safety and analysis data may be crucial to help develop the operational regulation in those areas and operations. The resulting requirements may take many forms, such as designation of approved operational areas, routes of flight and obstacle clearance requirements, among others.
While this study is committed to achieving a rigorous and critical overall analysis of the emergency-driving situations and hazards surrounding UAM operations and their impact in performance, an in-depth look at each phenomenon would exceed the goal of this project. The author intends to provide some ideas on necessary safety considerations, rather than an in-depth assessment of individual risks.
This industry is still in its early stages of research, and without the specific characteristics and performance information of the vehicles, it is not possible to propose any specific hazards and ensure its pertinence. Some assumptions have to be made in order to draw valid conclusions, and thus this study takes helicopters as its main reference. Furthermore, hypothesis change as new information and research is presented, and it should be understood that this project presents its conclusions and findings based on the limited technical information available at the time of writing.

2. Historical background and helicopter-based service

In this second chapter, an analysis on previous helicopter-based urban transportation is assessed, observing the conclusions extracted from their successes and failures, as well as the evolution of market growth over time. It serves as a complement to Section 1, discussing how to extrapolate the past, present and future demands on helicopter transportation to the next UAM modes. Observing what can be expected will determine the general characteristics and capabilities to be met by these vehicles.

2.1. Potential market and first operations

To draw the boundaries for this kind of transport mode, Correnti et. al., 2007 proposes to use discrete mode choice models to predict traveler choice behavior when rotorcrafts, both helicopters and tiltrotors, are introduced for short, mid and long-range routes, compared to other means of transportation including commercial aviation and high-speed train (HST). This model considers factors as travel time, including access and egress time to reach and leave the terminal, terminal time for check in and check out operations, and on-board time, as well as other attributes such as comfort and reliability, related to preference for a transport mode.

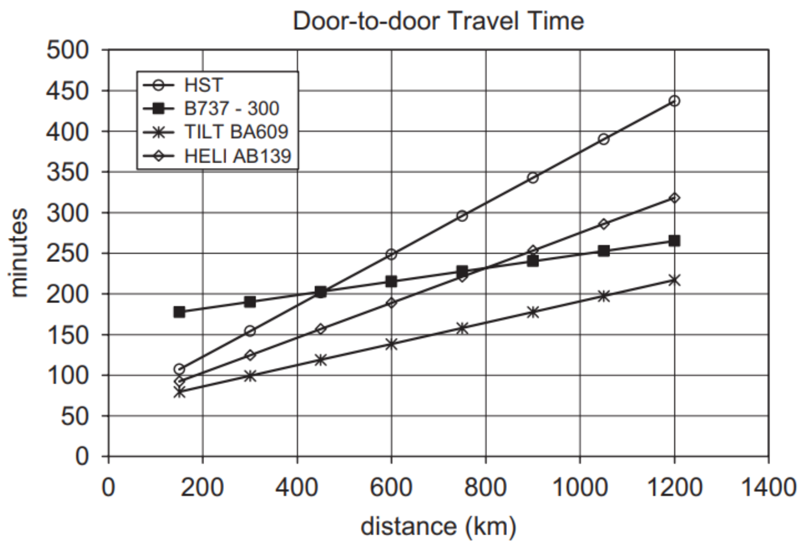

Figure 1.- Door-to-door travel time comparison. Source: Correnti et al., 2007

The results show that, if passenger transport by rotorcraft was introduced, this would be one of the fastest alternatives in terms of door-to-door time. Both HST and helicopter enable quicker journeys over short and medium distances compared to fixed wing aircraft, but rotorcrafts and VTOLs keep the fastest itinerary overall. For journeys over 800 km, the fixed wing aircraft would become the fastest option. However, this applies to low-density traffic demands, when moving small groups of passengers. HST becomes a more optimal and

preferable option for high-intensity traffic markets (European Comission, 1999). Therefore, the service frequency for rotorcraft would have to be escalated considerably in order to compensate for the lack of payload capacity in order to be able to reach the levels achieved by HST or similar mass transportation modes. And, while this study does not succeed on defining a payload threshold, it does offer an estimated market for these means of transportation.
So, with the existing business models and transport systems implemented in most cities, rotorcrafts were estimated to work better when oriented towards a more business travel model rather than leisure.

This market proposal was already identified some decades ago, especially in the United States in the early 1950s, and gained interest throughout the 60's and 70's (Vascik & Hansman, 2017). After World War II, the global population expanded at an increasing rate (Figure 2), leading to a radical growth in metropolitan areas and the incorporation of suburbs into the architecture of many cities, well established in the U.S. The end of the war was preceded by a groundbreaking military, technologic and economic boom that opened a new chapter for the following decades and allowed for the rapid development of turbine-powered commercial helicopters. As the urban landscape expanded and ground congestion increased, so did the need for alternative transport modes. Helicopters allowed the introduction of air taxi services, which were promising solutions.

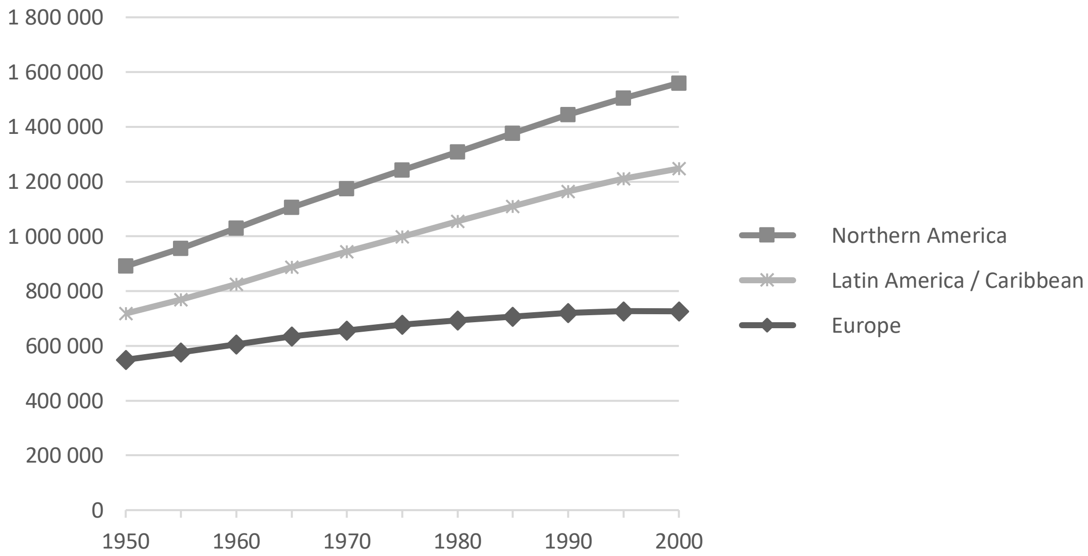

Figure 2.- Total population (In Thousands) between 1950 and 2000. Source: (United Nations, 2019)

The first helicopter airlines began as air mail services in 1947, moving into the passenger market in 1953. By the mid 60's, big cities in the U.S. like Los Angeles, San Francisco, New York and Chicago had between 400.000 and 1,2 million annual passengers, focusing on services between major airports, or between airports and city's downtowns, combined with charter services and private businesses. Operators found that investments in new helipad infrastructure in congested areas increased the demand on these services, with an increase of up to 50% in revenue in the following years. The already occupied city downtowns forced the introduction of rooftop helipads, followed by a rapid growing interest in helicopter-based transportation, and both air taxi and air carriers began to gain force. This study differentiates air taxi from air carrier based on the seat occupancy of the aircraft, referring to air taxi for more private and on-demand itineraries, while air carriers refer to the more accessible helicopter airlines oriented towards a larger public, with greater seat capacity.

Air taxis were focused on intra-city transportation and commuter services networks that could reduce congestion and overcome the geographic constraints of ground mobility modes. They were to operate on a reservation system, allowing customers to request flights in a relative short-notice margin. However, and unlike air carriers, air taxis were more oriented towards business travel for high-income public. And this model has persisted nowadays in cities like São Paulo, New York and Los Angeles. Despite its ability to remain active over the last decades, air carriers were actually the ones to make a bigger breakthrough and move the greatest number of passengers throughout their short lifespan.

In the United States, between the 1920s and 1960s, the number of cars on American roads increased by 600% (Larkin, 2020), especially in commuting routes between cities or between residential suburbs and city downtowns. And even though government studies predicted an unprecedented increase in traffic, the existing road network could not absorb this much.
Furthermore, particularly in the U.S., the lack of a solid public transportation network makes the system fully rely on driving and flying, aggravating both capacity problems. As city populations grow over time, cities lose their capacity to absorb its entire population driving. And then congestion appears, poisoning the entire network. American culture moves around the concept of private vehicles, lacking investment towards public transport modes throughout history, compared to Europe. Currently, most of the metropolitan land is already occupied, leaving very little margin to upgrades, which usually is an expensive and time-consuming option anyway.

By the late 1960s and into the 70s, car ownership in the U.S. increased from 78% of the total population up to 83%. With ground congestion approaching its limit stage in most of the large metropolitan areas, the demand for air transportation as an alternative increased (Helicopter Air Service Program, 1965). This, however, was estimated to result in major airport congestion as well, at an even greater rate, due to the large number of operations between big metropolitan areas.
The increase in demand for air transportation was estimated to be concentrated in geographic areas which already suffered from severe traffic congestion problems. Three regions stood out -New York, Los Angeles and Chicago-, accounting for one-fourth of all scheduled airline passengers. As the projections on the future did not indicate any relief on future demand, it was expected that the capacity of the air transportation would inevitably have to be enlarged, if air traffic was to be handled in the same conventional way. This could be done by either improving air traffic control, designing new methods on operating and clearing the runways, or expanding the number of runways and terminals while investing millions of dollars. Additionally, it was detected that a big factor contributing to this air congestion is related to the inadequacies of having air

traffic operations performed on a system based on airways and runways, costing time, space, and escalating congestion with shared resources.

In order to relieve workload from this congested air network, a new market opened for intercity travel, specifically short-haul segments, that could be operated with vertical-lift aircraft. As airports were usually located considerably far from the metropolitan areas, and still applies today, passengers were forced to make long, time-consuming ground trips. And most of the times, these short-haul routes lost their advantage due to the large handicap that was the time lost on the road. Introducing helicopters to the systems seemed to provide a relatively rapid service between airport and major points in the metropolitan area, and could minimize some of the stress in both ground and air network.

Three carriers introduced their service during the 1950s as a test in those three main cities mentioned before (Helicopter Air Service Program, 1965). New York Airways was the first company that entered into service in 1953, followed by Los Angeles Airways in 1954 and Chicago Helicopter Airways in 1956. All three were to operate between conventional airports and heliports located in business and residential areas. The vertical-lift capabilities (VTOL) provided the capability to approach and operate in selected intracity points, bringing passengers closer to their final destination and creating a serious competition to ground-based transport modes.

Brazil is also a leading world power in the development and implementation of early concepts of UAM transport modes. The chaotic and oversaturated ground traffic in their main cities, such as São Paulo or Rio de Janeiro, opened a new market for intra-city travel. The country's infrastructure has failed to keep pace with its economic development, leading to serious traffic jams during rush hours and exponentially increasing commute times. This, combined with the yearly increasing wave of organized crime and lack of street safety, led the wealthy population to consider other means of transportation to mitigate both issues (Murray, 2004).
Helicopter services were introduced in this country much later than in the United States, by the mid-1990s, as a way of getting around the city without relying on ground infrastructure. However, their business model differed from the one established in the U.S., as it was oriented towards a wealthy and exclusive public. Instead of establishing helicopter airlines, Brazil observed a growing trend in privately-owned helicopter registration, and operation was purely on demand.

2.2. Operations in numbers

The growth in traffic and service of helicopter airlines in the United States during its decade of operation was groundbreaking, increasing year by year at an exponential rate. What began as a modest service of about 1.000 passengers annually with the entry of New York Airways, quickly rose to 29.000 in 1955 when Los Angeles Airways began operations. The first year in which all three carriers operated simultaneously registered up to 64.000 passengers, achieving a tipping point in 1960 with 490.000 passengers in a year.

Table 1.- Scheduled Passengers Originations in the U.S. (In Thousands)

YEAR	TOTAL	CHA	LAA	NYA
1953	1	-	-	1
1954	8	-	-	8
1955	29	-	5	24
1956	64	1	20	43
1957	153	55	30	68
1958	230	109	31	90
1959	366	204	42	120
1960	490	309	39	142
1961	430	245	41	144
1962	358	93	77	188
1963	463	59	149	255

Source: Air Carrier Traffic Statistics

The numbers presented in Table 1 reflect the scale of the operations conducted in the United States, which was achieved by a combination of seating capacity, speed of the aircraft and frequency of service. All three factors were found to be important as means to become a self-sufficient industry. During the operational years, the seating capacity increased at a larger rate than any other air service, as the market expanded and equipment improved. By 1963, the average number of seats available per aircraft operated was 20.7, double than in 1961. However, as seat capacity increased, passenger load factor decreased, dropping from an average of 51.1 in 1959 to 50.5 in 1960, and to 40.7 in 1962 (Helicopter Air Service Program, 1965).

Helicopters also experienced a notable growth in popularity in Brazil short after its introduction in the country. However, due to market share and the type of customer targeted, seating capacity has been much lower. This led to a much higher frequency of operation, reaching world-record traffic levels. By late 2000, the total fleet of private helicopters raised to 800, 400 of which were operating exclusively in São Paulo (Romero, 2000). At peak hour, up to 100 aircraft were overflying the city at the same time, and the number of registered helicopters within the state jumped from 374 to 469 between 1999 and 2008 (Phillips, 2008). This increasing demand for safe and fast inter-city routes led to an unprecedented construction of more than 210 helipads within the city by 2010 (Miracle, 2021), surpassing the figures observed in any U.S. city. Most of these helipads, however, were unregistered and were not monitored by local authorities, leading to a lack of operational data and public statistics available.

While the two business models implemented in both countries differ a lot, these figures reflect the viability of UAM networks in congested and heavy saturated cities.

2.3. Downfall and current operations

After nearly two-decades of air service in the United States, the helicopter airline industry came to a progressively to an end by the late 60s, in part because of both financial challenges and public acceptance.

The helicopter airline concept, as with most modes of air transportation that have been conducted throughout history, was born as an uneconomical service with no indication of when it would become economically self-efficient, and required from federal subsidies in order to thrive. For these to be approved, it was required that the industry was both of public usefulness and competitive, increasing the likelihood of becoming self-sufficient.
By the time the early helicopter industry was born, airlines were at a stage in their economic life cycle where they could survive without external financial assistance. And because of this public perception of the mature stage of general and commercial aviation, the expectations faced into this new industry were higher than what it was capable of delivering. This was directly reflected on the size of the subsidies destined to this purpose, as were similar to those granted to other, more economically sustainable modes of air travel. Furthermore, periodical hearings were conducted before the Civil Aeronautics Board to evaluate whether subsidies were to be continued based on public interest.

Added to the financial challenge, there were critical handicaps that threatened the industry as well, including noise pollution, privacy and safety concerns arising from several accidents and incidents during the decade. The expensive ticket prices that were required as a way to subtract more benefits per operation made this industry slightly more oriented towards business and wealthy customers. This led to the general public to experience the negative traits of operating these services above urban areas. Even though the numbers showed a general growing popularity of these services, this dissatisfaction, added to a series of accidents and reliability issues around these aircrafts, eventually forced the cease of operations for all three companies.

In Brazil, however, the opposite took place. Because the socioeconomic situation has remained almost static throughout the following decades until current times, demand for helicopter transportation has only grown. And because most of the operations have been focused towards wealthy public, financial factors have not been considered a risk to its perpetuation. As of 2021, 574 helipads and helidecks are active just in São Paulo, followed by 145 in Rio de Janeiro (Burgueño, 2021).

However, noise and safety issues are still concerning factors for the general public. Especially with regard to the first factor, the local government proposed new laws in 2007 to regulate operating hours and minimum flight altitudes to reduce the impact of noise (Brähler & Flörke, 2011). São Paulo was also the first city to implement a dedicated air traffic control service for inter-city operations with helicopters, and remains the only one to have implemented it as of this writing, controlling all traffic between 2.000 and 3.500 feet.

As observed, noise and safety are still major factors to be faced when planning an inter-city and intra-city air service like UAM. Whether these new vehicles are capable of resolving them is what will determine their future success.

2.4. UAM expectations and current projects

The interest on urban air mobility is growing back, and projected to scale up to levels not seen since the late 60s. Many private companies, with the support of national aviation agencies and governmental entities, are investing on research to develop the future generation of UAM vehicles and mobility networks, with dedicated ground and navigational infrastructure. And this interest is reaching many countries, aiming to achieve a global network of clean and fast transportation.
For instance, Embraer's partner company, Eve Air Mobility, taking advantage of the strong and consistent demand for alternative mobility modes in Brazil, is working on new air networks between city downtowns and regional airports with eVTOL vehicles and scaling up the frequency of operation in order to achieve a more affordable cost than a conventional helicopter service (Eve Air Mobility, 2021). In Rio de Janeiro, one of the cities with the worst traffic in the world, the first simulations have already been conducted, testing the quality of service and acceptance from the general public.

Chinese company EHang, pioneer on UAM solutions, has invested and tested as well in many countries, including Austria, Canada, Spain and Qatar (CCMA, 2021). So far, they are implementing the first stage of UAM modes by utilizing current infrastructure, such as regional airports, and testing these models in real operating environments.

Honda is also targeting this market by designing eVTOL prototypes with gas turbine hybrid power units, providing greater range and autonomy (Lynch, 2021). Along with vehicle design, they are working towards a full transportation ecosystem, with mobility hubs located in various cities that would coexist with fast ground transportation to achieve a greater level of connectivity.

3. VTOL critical behavior analysis

In this chapter, an analysis and comparison on VTOL behavior when exposed to emergency and extreme situations is conducted, extracted from historical helicopter accidents and incidents. The study of the characteristics of the vehicles, procedures used at the time or the location and environment of the events, among others, are key elements to outline a performance proposal for multi-rotor, UAM vehicles.
Because the design guideline and condition boundaries for the next generation of UAM vehicles is not yet well defined, multiple concepts are arising with a wide variety of performance capabilities and flight systems. Their way of operation, however, is expected to follow a similar path to that of the helicopters, as they will have to adapt to the same environment. Therefore, by analyzing helicopter behavior, some solid conclusions can be extracted on future UAM response requirements.

3.1. Presence of risk in general operations

There are different standards, depending on the country, on how to operate low level flights like the ones present in most helicopter itineraries. For operations within European country members, the regulation stipulates that no aircraft shall be operated in any congested urban environments or any area involving people unless it is conducted at a safe altitude that ensures that, in case of an emergency, the situation could be controlled and mitigated in a safe manner without compromising the safety of those below (Commission Implementing Regulation (EU) No 923/2012, 2012). For IFR operations, this altitude is defined as 300 meters (1.000 feet) above the highest obstacle within a radius of 600 meters (2.000 feet) from the aircraft. Below this threshold, VFR conditions are to be followed, including take-off or landing phases.
Similarly, for U.S. airspace, the FAA specifies that helicopter-like aircrafts over any congested urban area can operate below an altitude of 300 meters above the highest obstacle within a horizontal radius of 600 meters of the aircraft as long as it is conducted without hazard to persons or property on the surface (Code of Federal Regulations, 2011).

Based on both guidelines, it is fair to state that the critical and most vulnerable segment of the flight would be both the take-off and landing phases, as well as air-taxiing to or from the active pad. This concept is backed-up by a recent study on helicopter-related accidents statistics (Alexander et. al., 2021), that showed that, out of 185 cases reviewed, 65 accidents or 35% of the total were produced during take-off (see Figure 3). Another 39 occurred during landing, representing 21% of the total. That makes the combination of the take-off phase and the landing phase account for 104 of the total accidents or 56%. Approach and departure phases, outside the immediate perimeter of the landing zone, were found to be less critical. Out of the 185 cases, 25 occurred during approach, and only 9, less than 10%, during departure.

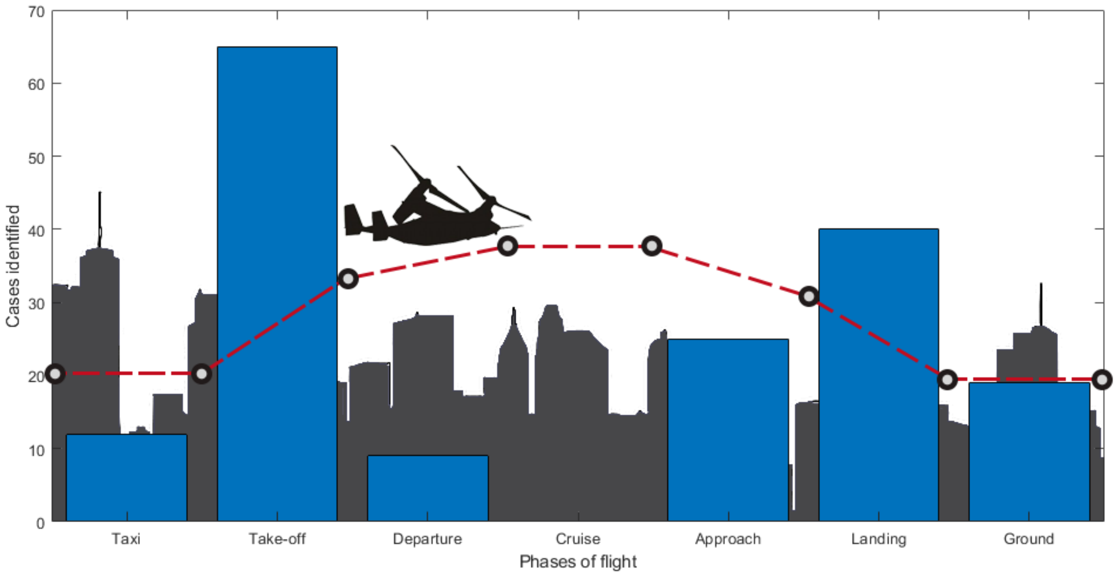

Figure 3.- Cases reported in each phase of flight. Source: own elaboration based on data from Alexander et.al., 2021

The same study identified that location was also a relevant factor. It was reflected that ground-based heliports accounted for the majority of the accident locations at 127 cases or 69%, while rooftop locations accounted for 29 accidents or 16%. The remaining accidents were distributed between offshore sites and other specially designed platforms.

The scale of current commercial operations in the helicopter industry involving urban environments is hard to specify, as most statistical data are kept classified or are poorly accessible. Differentiating purely urban operations from other typologies and itineraries based on public databases has proven to be a difficult task. While current operation models have been mainly focused on intercity operations, and represent a way bigger portion than intracity ones, the exact portion of the overall operations is not available. However, UAM models project a groundbreaking increase on air traffic and frequency within urban areas, exponentially increasing the chances of incidents happening if special safety factors are not considered on the design of these future vehicles.

3.2. Description of nominal operation procedures

At the time of writing, the way of operation for UAM vehicles is still unclear. Many proposals have been presented over the last years, with a wide range of performance capabilities and maneuverability. However, common general standards can be considered as a theoretical basis for what can be expected, derived directly from what is currently implemented for helicopters.
The most critical phases of flight, as identified previously, are take-off and landing. These are also the most diversified in terms of execution. Depending on the situation, environment and physical properties of the aircraft, both EASA and FAA (EHEST, 2015a; FAA, 2012) define an adequate procedure applicable to all general VTOL vehicles.

3.2.1. Approach and landing

When assessing the approach to a designated landing zone, the environment and the conditions directly around it define the type of path and operation that will have to be conducted in order to safely get to the ground. There are five main categories for approach procedures.

- Normal approach. This is the typical procedure for general, unobstructed landing pads (James, 2021a). These approaches are considered to follow a path of 7º to 10º of steep, while reducing its airspeed. When arriving at a height of 2 to 4 meters from the landing zone, a hover is maintained by pitching up, reducing airspeed to zero. This is made to assess the area before eventually landing.

- Steep approach. When high obstacles are on the way of a normal descent path, a steeper approach is required to avoid any collisions. The angles of descent range from around 13º or 15º all the way to 90º, depending on the power capabilities of the aircraft. This path will directly affect the landing phase, as it will take more time as the aircraft has to move downwards more than it moves forward, while maintaining a controlled descent rate. It is also more power demanding, as most of the approach is performed out of ground effect (OGE), and could affect overall autonomy when operating consecutive itineraries. As the approach is more aggressive than in normal approaches, the control over vertical speed becomes more critical, peaking at the final meters. Additionally, translational lift is lost at a higher altitude than during a normal approach. This will require more power than a normal approach would. For unprepared landing spots or difficult areas, a final hover may be required to evaluate the situation before landing.
  This resource is also effective when avoiding turbulence around pinnacle areas.

- Shallow approach. For high altitude landing spots, where air density and temperature are low, the power required to perform a normal or steep descent might not be available, as both engine and blade capabilities decrease with altitude. Because of this, final high-power maneuvers such as a hover cannot

be considered, as it may end up in a hard landing or accident if the aircraft demands more power than the one available.
To minimize the need for power, these approaches are conducted in a much flatter trajectory, following a path of approximately 3º to 5º, and the decrease on both airspeed and altitude is more gradual while maintaining a constant power configuration. This method is also applied when an emergency situation requires to perform a running landing, being able to quickly be placed onto the ground softly and safely. Shallow approaches have the advantage of requiring much less power supply, as lift is generated by both the air flowing downwards and the one produced by the forward speed component of the aircraft.

Depending on the target landing area, the convenient approach will differ. Two main groups can be found when assessing urban landing sites.

- Confined Area approach. This is the case for landing spots that are completely surrounded by higher obstacles, forcing a two-stage procedure to land. Most urban landing pads located on ground level, surrounded by high buildings, fit into this category. Some roof pads also are included.
  The common method includes a first normal or steep approach until reaching the top of the confined area, or that of the highest obstacle that constitutes the confined area, followed by a complete vertical descent inside the designated area, as to avoid any collisions with the surrounding obstacles.
  Confined environments usually harbor turbulent air due to the obstacles around them, with presence of downdrafts and updrafts. This adds an additional risk to these operations as it may lead to a loss of control of the vehicle.

- Pinnacle Area approach. Opposite to confined areas, pinnacles are considered landing zones higher than the terrain or obstacles of one or all of their sides. Especially in these operations, wind is a major factor in terms of maneuverability of the aircraft. The FAA concluded that the intensity of the wind will determine the steep of the respective approach to avoid turbulent air and downdrafts.

As for the final landing maneuvers, especially on unprepared landing spots or difficult areas, a hover may be required to evaluate the situation before landing. This resource is also effective when avoiding turbulence around pinnacle areas.

- Hover. This is the most common touch-down procedure performed during the final landing phase. The aircraft enters a stable and steady state over the landing spot with zero vertical speed. Usually used as a resource for analysis of the terrain and selection of the most ideal landing point. There are some inconveniences attached to this practice, especially when dealing with areas with dirt or loose objects that could be a risk to both main and tail rotors, and have a negative effect on visibility.

- No Hover. There are some situations where hovering might not be convenient. For instance, when operating on not-pavemented landing zones where dirt or foreign objects may oppose a risk to visibility or the integrity of the rotors, a more direct approach and landing might be more favorable. Other situations such as the ones encountered in shallow approaches might not allow a hover, therefore having to be flown all the way to the landing pad in a continuous descent.

- Running/Roll-on Landing. This technique is also convenient for landing areas with presence of dirt or loose objects, as well as for runway-based pads. It is a maneuver oriented towards larger aircrafts, normally equipped with wheels capable to land this way. As these types of vehicles have bigger rotors, which produce more severe downwash, the risk of kick up dust particles and debris is higher. Given that hovering requires a high-power configuration of the main rotor, a different approach is applied. For instance, the aircraft touches down while following a continuous descent path, keeping a forward component on its airspeed and leaving any dust cloud behind the vehicle, reducing considerably the probability of both visibility loss and debris impact.

  For aircrafts with skids instead of wheels, this method is applied when dealing with emergency situations. Performing this procedure in this case will result in a harder touch down, but will ensure a safe and more controllable landing, improving the chances of mitigation success. In emergency situations where the flight controls get compromised, hovering also gets nearly impossible to be executed as it consists in a series of maneuvers that require a lot of manual effort in case the hydraulic assistance is lost. Running landings are a more preferable option, and reduces human fatigue notably (James, 2021a).

3.2.2. Take-off and departure

Similarly, departing from a landing zone requires a certain climb path depending on the situation and the site properties.

- Normal Take-off. This phase can be executed from a hover or directly from the surface, depending on the properties of the landing site.

- Running Take-off. As its landing counterpart, this method requires wheels to be equipped on the aircraft, as well as a physical runway to perform the take-off. STOL landing zones have to be installed at ground level, and may be more difficult to integrate in an already developed urban environment, where open space is limited, as opposed to traditional VTOL landing which require much less space and can be installed in smaller areas and rooftops with relative ease. However, traditional VTOL landing zones usually do not meet the sufficient characteristics to be able to operate a running take-off or landing in case of emergency, constraining its containment capacity.

- Maximum Performance Take-off. This maneuver is designated for confined area operations, with a steeper initial climb in order to clear near high obstacles such as buildings or power lines. It can be performed by a near-vertical or a full-vertical climb, depending on the surroundings of the platform. Full-vertical take-off is a less efficient but safer way of execution, as it allows for a vertical descent back into the confined area and easily abort. However, this method requires a high-power capability in order to sustain OGE and to avoid losing lift potential.

3.3. Identification of anomaly-causing factors in urban environments

As reflected on previous segments, the most critical phases of flight on which most risks are involved are both take-off and landing. EASA defines that, for these stages, the most common external factors involved in emergency situations are (1) operational procedures, (2) pressure altitude of the aerodrome, (3) temperature, (4) wind, (5) size, slope and condition of the take-off/landing area, and (6) the condition of the airframe, the power plant or the systems, taking into account possible deterioration (EASA, 2008).

As UAM concepts are focused on urban areas, for sake of simplicity this study does not consider sloped landing pads that could cause an impact on performance, as city infrastructure tends to be built in low or non-sloped surfaces. Additionally, airframe integrity and deterioration factors are also neglected, as are complex to model and study their long-term impact on performance. This study assumes no failures or malfunctions on the structure of the aircraft or any of its constituent elements previous to the emergency situation. Pressure altitude has also little relevance in this manner, as the common profiles operated today with helicopters, and the expected ones with UAM vehicles, involve flight levels from 800ft to 5.000ft (Lascara et. al., 2018), and pressure difference should not be a real concern in terms of performance, as long as the aircraft is properly configured to the environmental conditions before flight.

In order to identify these factors in real-world scenarios and their mitigation procedures, a root cause analysis from records of previous helicopter-based failed operations can give an insight on which phenomena are the most recurrent and which contingencies were executed to minimize their consequences, in an effort to identify and extrapolate potential hazards to UAM vehicles. This analysis is focused on congested/congested-hostile environments, involving urban areas or other environments that may experience similar conditions. A total of 37 relevant incidents and accidents have been reviewed from various safety agencies, studying the main factors and causes, and categorizing the occurrences following the proposed ones by the CAST/ICAO Common Taxonomy Team (CICTT, 2014). These include reports from the NTSB (USA), ATSB (Australia), CENIPA (Brazil) and AAIB (United Kingdom), as well as Indonesian and South Korean databases.

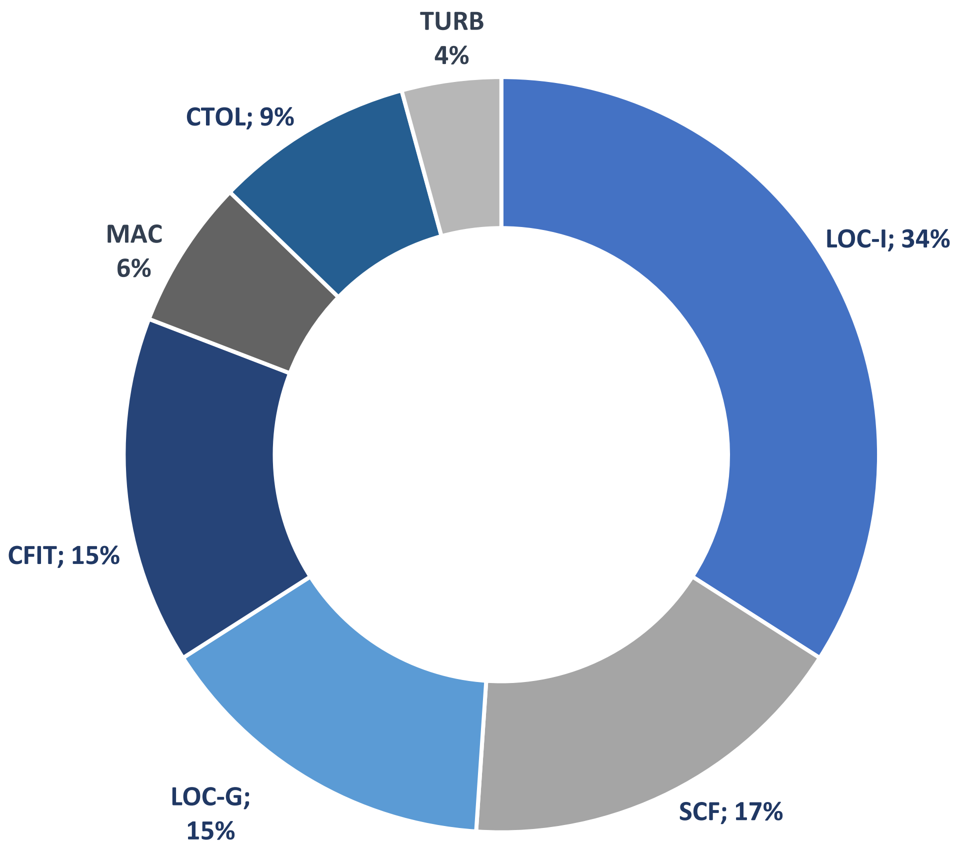

Figure 4.- Significance of the occurrences identified in relevant emergency situations

Based on the main relevant events and the unfolding of the emergency situation, each case was classified in one or more categories that collect the leading causes involved in the accident. As a result, loss of control inflight (LOC-I) is the main occurrence observed in both accidents and incidents by far, with 34% of involvement, followed by system/component failure or malfunction (SCF) and loss of control while on ground (LOC-G), with 17% and 15% of presence, respectively. Controlled flight into or towards terrain (CFIT) has also proved to be a common factor involved during operations around congested environments in 15% of the cases. In a smaller but nonetheless relevant proportion there are collisions with obstacles during take-off or landing (CTOL) and mid-air collisions (MAC), present in 9% and 6% of the total. Other factors derived from turbulent environments (TURB) complete the remaining 4%.

It should be noted that the categorization has been made based on open-access reports published by the respective safety agencies and witness information disclosed to the media, and only considers investigations which have been completed as of the time of writing of this project. The criteria followed to assign a category was based on both the already given occurrence categories, written in the safety reports, and those identified after a deeper analysis. Some cases have been assigned two or more categories considering different factors involved, dependent or independent from each other, in order to address and highlight a wider range of factors likely to appear in these environments.

The aircraft involved in these cases all follow the traditional helicopter structural scheme, with one main rotor and one tail rotor. Though future UAM vehicles may adjust to this design to a greater or lesser degree, this analysis could become a useful tool to draw a valid behavioral baseline, and its extrapolation is discussed later in this project.

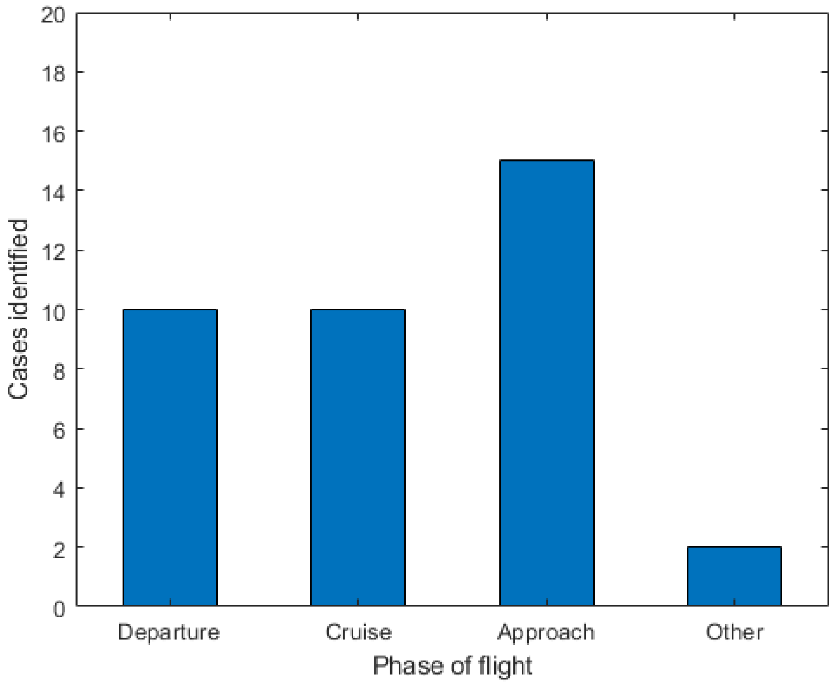

Figure 5.- Presence of emergency situations by phase of flight

Furthermore, Figure 5 reflects the number of accidents that unfolded during each phase of flight. As observed, most occurrences take place during approach, which in this analysis includes both descent and landing maneuvers. Departure, including take-off and climb maneuvers, along with cruise, are slightly below approach in terms of emergency encounters. Still, the numbers reflect a notable degree of relevance, and require as much attention. Other categories include particular ground incidents or unspecified phases of flight.

It makes sense that approach maneuvers are the most prone to encounter anomalies. This phase of flight requires a high level of focus from the PIC, as it combines very slow airspeeds with the need for a high degree of control of the aircraft. Both the flight path and profile narrow and become more constrained as the aircraft reaches the landing site, especially in urban environments.

When comparing these results to the ones found by Alexander et. al., 2021, discussed in Section 3.1, more anomalies are found in the Approach than in the Departure, contrary to Alexander et. al. This could be explained due to the criteria followed when identifying and analyzing emergency encounters. While Alexander et. al. analyzed a wide variety of scenarios, environments and itineraries, this study has focused on a much selective group, looking at cases involving urban environments or which encountered similar conditions or phenomena that could be seen as well in urban operations.

3.3.1. In-depth Analysis of Loss of Control Inflight (LOC-I)

The results reflected this as the most common occurrence in helicopter operations, and is in line with the conclusions drawn by ICAO (RASG-PA, 2013). This category refers to accidents and incidents in which the pilot has temporarily, or completely, lost the ability to maintain control of an aircraft in flight. LOC-I typically results in an extreme deviation from the intended flight path.

Out of the 16 cases that were identified with LOC-I, it was seen that 13 of them were caused directly from undesired aircraft states, involving improper aircraft performance with its environment, incorrect flight execution, negligence or exceeded aircraft capabilities. It is also observed that aircraft malfunction is not the main cause for loss of control while airborne, and that most of the cases involve a perfectly functional aircraft previous to the occurrence. Environmental factors are seen to be secondary elements in these accidents, more catalytic constituents rather than the main causes. In most of the situations (almost 69% of the total), a better execution or awareness would have eluded the respective emergencies. Furthermore, more than 75% of LOC-I cases take place during departure or approach maneuvers. This aligns with the slow speeds that imply these phases of flight, in which the aircraft is more prone to destabilize or suffer from a wind-related anomaly.

The identified elements involved in LOC-I events include loss of tail rotor effectiveness (LTE), vortex ring state (VRS) and loss of engine power as the three main causes.

Concerning the first two phenomena, they are more prone to appear in low-power and low-speed maneuvers, therefore being especially critical during approach and departure, when the aircraft is more vulnerable and when accuracy of movement is essential. Losing control in these phases of flight has significant consequences in most cases. As reflected in the accident analysis, 5 of the cases ended up in a forced landing, while the remaining 11 did not even manage to bring the aircraft safely to the ground. This reflects the seriousness and dangerousness of these situations.

External and meteorological factors do play a relevant role, and have been demonstrated to be conduits to both LTE and VRS. In LTE, the slow airspeeds, combined with some particular wind azimuths, prevent the tail rotor to cancel the natural torque of the main rotor, inducing an unprevented and unintended yaw. It concerns operations at airspeeds lower than ETL, generally around 30 knots, and, because it is exclusively caused by an aerodynamic interaction between the main rotor and tail rotor, and not caused from a mechanical failure, it is usually encountered unnoticed and inadvertently. This phenomenon is pertinent in urban environments, as changing wind conditions are very common when flying around buildings or operating in confined areas.

Depending on the direction of the wind, it can be induced in multiple ways (FAA, 1995). For frontal azimuths, there is a risk of main rotor disk interference, where its vortices and dirty air are pushed into the tail rotor, preventing this from having clean air to propel. In addition, tailwinds interfere with the proper lateral flow of air generated by the anti-torque device, as the winds passing on both sides of the tail rotor make it experience a lot of unpredictable vibrations and lateral oscillations, losing thrust capabilities.

Similarly, VRS also threatens to reduce lift capabilities, and is applicable to both tail and main rotors. It is characteristic for low-power setting operations, such as approach maneuvers, as the upward airflow of air generated by the descent itself may overcome the downwash of the inner section of the rotor, generated as it turns. This would result in the aircraft entering its own turbulent air beneath it, due to the slower speeds of rotation of the inner part of the rotor in comparison with the outer part, generating less downwash. If the approach is steep, or the power setting on the rotor is low enough, this diversity in directions of airflow along the rotor could develop into inner vortices, complementing the already existing tip vortices. This combination of vortices can result in a lot of turbulence and vibrations along the rotor, and downgrade its efficiency and response time.

Like in LTE, this phenomenon is usually generated when airspeed is less than ETL, and when flying steep or near-vertical approaches with great rates of descent (around 30º, with 300 fpm rate of descent). Downwind or tailwind also contribute to generating these inner vortices, as well as OGE-related maneuvers where airspeed is already below ETL.
In tail rotors and anti-torque devices, VRS may also be induced if winds strike laterally and opposite to the wash of air generated by these devices, generating the same effect and losing propulsive capabilities, therefore developing uncommanded yaws if the power setting is not constantly corrected.

In this analysis, those cases in which LTE was perceived or reported on the tail rotor of the respective helicopters have been characterized with this factor, regardless of the way it was induced. VRS refers to cases where this anomaly was detected in their main rotors. Therefore, LTE situations caused by an induced VRS in their tail rotor were still classified as LTE, not VRS.

3.3.2. In-depth Analysis of Controlled Flight Into or Toward Terrain (CFIT) and Collision with Obstacles During Take-off and Landing (CTOL) or Mid-air (MAC).

Accidents involving collisions of the aircraft with obstacles or surfaces can be differentiated by the moment the occurrence took place. In CFIT are included accidents in which a perfectly working aircraft is flown or collides into the ground, man-made obstacles or water. Therefore, no anomalies or loss of control were reported before impact, and the respective PIC were not aware of any dangerous situation or safety violation. This category also includes accidents caused by a collision with obstacles extending above the surface, such as power lines, structures or trees. CTOL and MAC are subcategories of CFIT for those collision occurrences happening during take-off and landing maneuvers, or mid-air encounters with other elements or aircraft. The latter, however, are the result of a previously known loss of control or emergency situation, contrary to what is stipulated for CFIT occurrences.

For events under CFIT category, the results from the analysis showed that 71% of cases in this category were a byproduct of low visibility environments, from IMC conditions such as fog or low cloud ceilings, and night conditions. These environmental factors have shown to be capable of inducing loss of awareness on the surroundings and sudden collision with nearby obstacles. Human factors are especially relevant in these situations, being the cause of accidents in almost all documented cases. However, the capability of the aircraft to fly in IMC conditions is also key to avoid deviations from the expected path, and ensuring a solid network of navigation aids and adequate equipment on the aircraft can prevent inadvertent crashes.

As discussed, causes related to CFIT are mid-air collisions with other airborne bodies, such as birds or UAVs. Categorized as a separate category (MAC) but sharing similar outcomes, these pose a serious risk to safety as cannot be perceived from far, regardless of the visibility conditions, and can inflict critical damage to the aircraft. Current trend projects them as a growing risk in the next years to come, and assessment of airspace regulation is critical to ensure a safe coexistence between both modalities. Redundancy in vulnerable systems, such as power plants, and better composite materials can also provide a better response in case of encounter with these situations.

While CICTT considers bird strikes as a separate category, for practical reasons this study includes them into the MAC category, as they still occur mid-air and fit the description.

Situations involving collisions with nearby obstacles or foreign objects (debris) during take-off and landing phases are classified as CTOL, following CICTT guidelines. While sharing most of the elements and attributes with CFIT occurrences, these accidents are usually the result from a previous anomaly during flight or approach and departure procedures. As this study is based on helicopters, most CTOL cases involve tail strikes with nearby obstacles. This particular occurrence is actually categorized as Abnormal Runway Contact (ARC). However, because UAM vehicles do not seem to follow the same rotor configuration as traditional helicopters and do not incorporate tail booms, it makes sense to englobe all collisions during take-off and landing within CTOL.

In this study, all 4 cases categorized as CTOL involved obstacle collisions near the designated landing zone during these early and final phases of flight. The prevailing causal factors identified were the lack of environmental awareness when executing early and final maneuvers, which are the ones requiring the most focus and precision, as well as aggressive behaviors and maneuvering of the aircraft around the aerodrome. For instance, late or aggressive flares have been observed as a common element in CTOL events, and is usually the result of negligence and misperception.

3.3.3. In-depth Analysis of Loss of Control On Ground (LOC-G)

Not all emergency situations are encountered airborne. Some of the accidents studied experienced an anomaly while on ground, and the factors involved led to a loss of control on the landing pad itself or the respective surface area. However, these types of occurrences are usually a result from another one. For instance, dynamic rollovers have been reported in most of the cases which experienced a loss of control inflight, ending up resting on one side of the fuselage after an abrupt landing contact. These incidents, while not necessarily fatal, may pose a greater risk when operating in elevated landing areas, such as rooftops, where contingency available area is limited, and may pose additional safety risks to ground personnel and passengers. It is crucial to assess this hazard when designing both the landing area and the aircraft in order to secure it within the boundaries of the pad would a loss of control on ground occur.

Heavy winds around the landing field may also induce a LOC-G situation if the aircraft is not properly secured to the ground after touching down or before departure, as seen in 2 cases (CEN15LA288 and ASN151250).

3.3.4. In-depth Analysis of System or Component Malfunction (SCF)

As previously stated, this analysis assumes no failures or malfunctions on the aircraft previous to the emergency situation. However, system failures during flight do happen, and is reflected as one of the main causes of helicopter accidents in helicopters, with direct involvement in 17% of cases. In this study, SCF includes both powerplant and non-powerplant related occurrences, for analytical simplicity.

Loss of engine power appears to be a more common occurrence when compared to other non-powerplant failures, with 62.5% of the total cases categorized as SCF. These results are in line with those found by the FAA, which states that 60.6% of their analyzed accidents caused by aircraft malfunction in air tour helicopters were the result of engine failure (Rigsby, 2011). However, the results also show that a loss of control induced by this occurrence is not as common as one could imagine. Out of the 5 engine failures reviewed, only one suffered an uncontrolled descent into the terrain. In VTOLs, some practices, such as autorotation, allow for a controlled emergency descent without any engine power, and the aircraft can be safely flown to the ground as long as the flight control surfaces and the PIC are performing as expected. This maneuver may be executed when experiencing an engine failure but also for a tail rotor failure or a loss of tail-rotor effectiveness, as autorotation does not involve any torque to be compensated. As no more engine power is available to overcome the drag forces on the blades, airflow is now the only element providing the energy to overcome drag and turn the rotor.

Structural fatigue is the second most common factor identified in SCF cases and the first in the non-powerplant-related group. A wide spectrum of possibilities is involved in this type of outcome, and the complexity of the aircraft's design and components will determine the degree of risk this factor poses.

These figures reflect the importance of maintaining strict compliance in the frequent checking and maintenance of the aircraft, in order to detect and solve any potential risk to the integrity of the vehicle before it gets irreversible or causes more serious consequences.

3.3.5. Study limitations

The scope of this project was to identify the risk and hazards involved in congested-hostile environments that could help to predict what UAM vehicles will have to face and respond to. Analyzing previous records of accidents and incidents gives a solid perspective of actual factors that are relevant in safety assessment. However, in order to be critical in this study, only those cases reported in environments or conditions that involve congested environments, or that closely resemble these, are to be considered as relevant. Many factors are involved during a VTOL operation that could lead to an anomaly or accident, and in order to extract those concerning UAM's operational field, a deep evaluation was conducted to select only those cases that could apply to this subject. This is the reason for the reduced sample of cases considered. However, it is large enough to clearly identify the main trends.

The data extracted comprises different safety agencies, in an effort for having a rich variety of countries involved in the final sample. However, it is inevitable that accidents on U.S. territory represent a larger portion in comparison to the rest of countries, as the United States is the region with the most registered in-service helicopters (28% of the global fleet) (FlightGlobal, 2018), and urban air mobility projects have been widely more spread and explored in this country. As Figure 6 reflects, the U.S. stands out as the top country in terms of registered helicopter airlines. It is clear then that their experience in this field may offer more relevant and complete information, and makes them a key figure in the development of future UAM concepts.

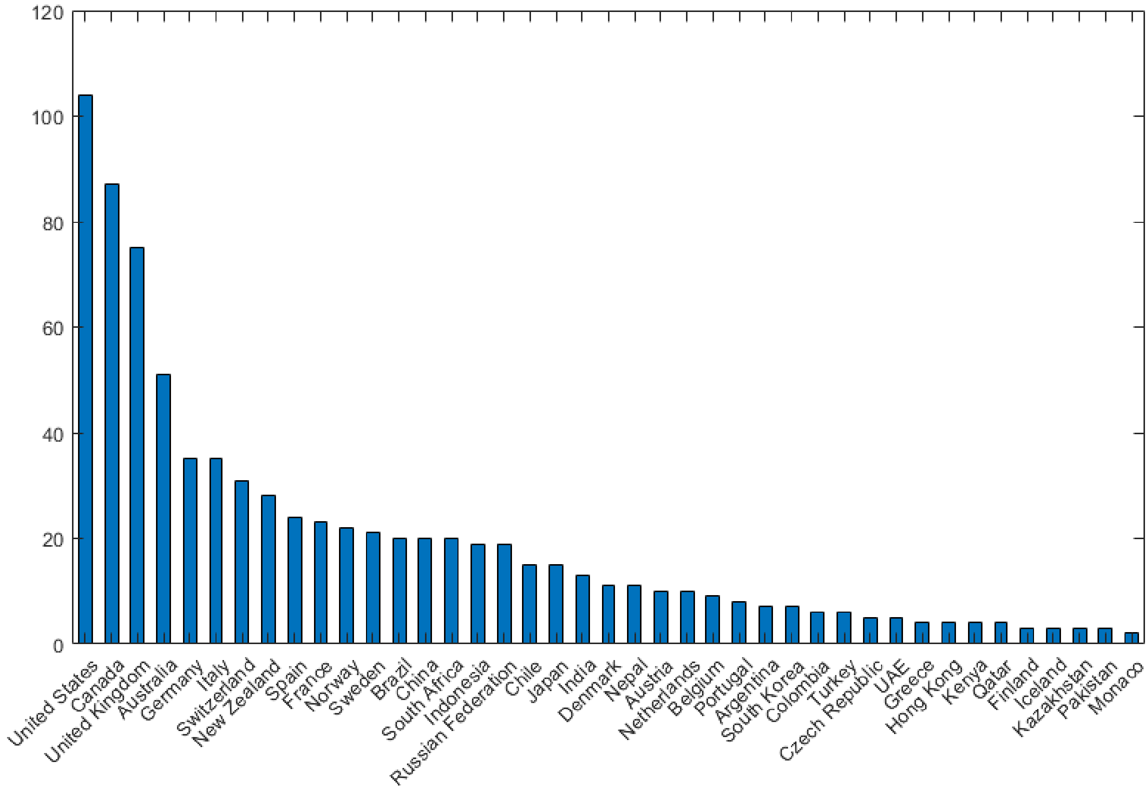

Figure 6.- Historical set (active and defunct) of registered civilian helicopter companies by country. Source: own elaboration based on data from Helicopter History Site.

4. Assessment of performance-related hazards

From the previous results, a further analysis was conducted, aiming to identify the particular phenomena that contributed to these accidents and their stipulated and/or executed mitigation procedures. The main contribution of this work is focused in this segment, in an attempt to find possible safety gaps and tendencies that could be extrapolated to UAM operations as well, based on what has been observed in helicopters.
Because the specific details of each accident could be claimed to be strongly related to the type of aircraft involved, there is no direct way to define or ensure which phenomena or situations will actually apply to future UAM vehicles. Therefore, the approach taken is more focused towards identifying and acknowledging situations and conditions that indicate a tendency to be an operational risk, based on a general vehicle classification.
This chapter is structured with an early definition of both the projected vehicles to be operated in UAM modes and their expected stages of certification, considering human-based and automated stages. A further discussion on identified risks for these vehicles is conducted, focusing on their impact on each type of vehicle. A summary table is provided at the end of the segment as a visual aid to identify the extracted conclusions and proposals.

4.1. UAM vehicle classification

During the recent years, many prototypes have been presented as future candidates to operate in UAM modes. Without any standardization existing at the moment, these concepts diverge from one to another in many aspects of their design, operation and maneuverability capabilities. Therefore, in order to suggest safety requirements or guidelines for vehicles that contemplate such a variety of characteristics and design features, a general classification of some kind is needed. This is a topic already identified and developed by some researchers (Shamiyeh et. al., 2017), clustering comparable flight characteristics.

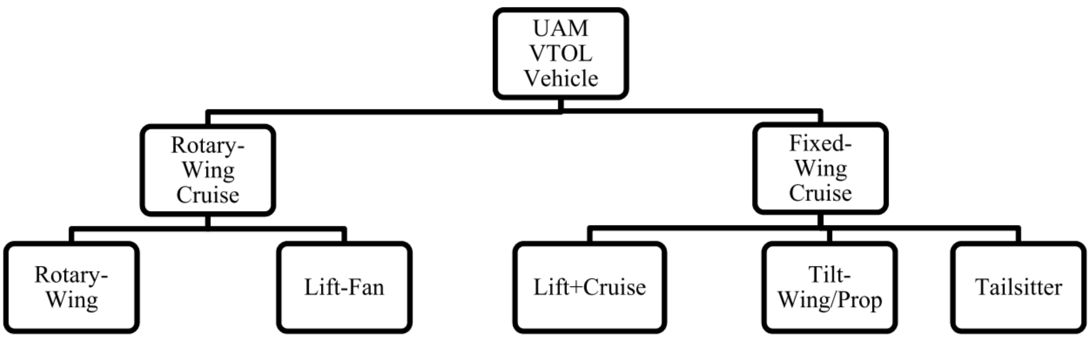

Figure 7.- Two-step classification scheme for VTOL UAM vehicles. Source: Shamiyeh et. al., 2017

Rotary-wing Cruise aircraft are those that generate lift exclusively by rotating airfoil-based wings (Straubinger et. al., 2020). They show less effective cruise capabilities in terms of speed, but show remarkable hover and VTOL controllability compared to the rest of groups.

Prototypes with free rotor-like elements, including multi-copters and traditional helicopters, are given the Rotary-wing subcategory (Figure 8a). Those that rely on encased or ducted fans are considered as Lift-fan vehicles (Figure 8g). The latter are characterized by their compactness as a result of its smaller fans' cross-section, and their safety-related advantages, especially for ground operations and handling of the aircraft. However, their lift-generating elements are less effective during hover and VTOL maneuvers, compared to Rotary-wing aircraft, and their smaller fans force them to produce more downwash, generating much higher noise levels.

Vehicles with fixed wings as main lift generators are categorized as Fixed-Wing Cruise. These compound aircraft have the advantage of allowing both VTOL maneuvers, by combining properties of both rotor-generated thrust for vertical maneuvers, as well as using fixed-wing for efficient cruise like traditional aircraft. This, however, comes at the expense of mechanical complexity. Still, range, speed and cruise efficiency are increased drastically compared to Rotary-wing Cruise vehicles (Zhou et. al., 2020). Some differences are contemplated within this category as well, depending on their transition method from vertical flight to forward cruise.

Those that have a separated and dedicated power trains for each of the modalities are categorized under Lift + Cruise (Figure 8b). This allows for a mechanically simpler aircraft, with fewer moving parts during flight, reducing fatigue risk and maintenance needs. This allows for a binary modality on main lift generation. As a result, traditional rotors, like the ones used in helicopters, produce lift during vertical maneuvers, delivering hover capabilities, and fixed-wings, producing lift during horizontal and cruise phases.

Tilt-props or tilt-thrust aircraft (Figure 8d, 8e) do have moving rotors that allow for both vertical and forward motion with the same element, while the fuselage and the wing remain horizontal. They are capable of changing their inclination at convenience, redirecting the flow of air, depending on the phase of flight. For take-off and approach, the thrust producers are rotated vertically, and the lift is purely propulsive. For the rest of forward flight phases, they are tilted back to horizontal to allow for the fixed-wings to generate the main lift. This category of vehicles, while requiring less propulsive components as they can provide with both modalities of flight, come with additional dead weight and mechanical complexity to the overall aircraft from the tilting apparatus. Whether this added weight is greater or less than the savings in additional propulsive components is limited to each prototype. However, it can be assured that it is a constraint when designing other aspects of it.

Tilt-wing aircraft (Figure 8c), on the other hand, rotate the entire system of wings and propellers. While achieving similar results, these minimize the thrust interference from the wings when operating VTOL maneuvers, compared to tilt-props. Similarly, the fuselage remains horizontal during all phases as well. A tilt-wing aircraft can begin the transition from helicopter to airplane at zero forward airspeed, contrary to tilt-props which must first fly forwards like a traditional helicopter, building airspeed until the lift generated by the fixed-wings is sufficient to allow the nacelles to begin tilting down. This translates into an improved capability to operate in enclosed areas, as it does not need additional space to begin cruise flight.

Nevertheless, both tilt-props and tilt-wings allow for a cleaner aerodynamic profile of the overall aircraft when compared to Lift + Cruise, and thus achieving a more efficient flight.

Tail-sitters (Figure 8f) apply a similar method but, instead of tilting the propulsion system, is the aircraft itself that tilts, depending on the phase of flight. These vehicles have to take a steep upright position during take-off, and gradually become more horizontal to gain forward speed as altitude is reached. The same sequence is repeated in reverse order for approach and landing. This allows for a fixed rotor system, with less vulnerable moving parts like in Lift + Cruise group, while using the same propulsion system for both modalities. However, safety concerns arise from the poor pilot visibility associated with these types of operation, especially during departure and landing, in which the cabin is in a vertical position. Passenger comfort is also a challenge in these vehicles.

(a) Volocopter 2X

(b) EVE eVTOL

(c) Dufour Aero3

(d) Vertical VX4 (Cruise mode)

(e) Vertical VX4 (VTOL mode)

(f) Opener Backfly

(g) Neva AirQuadOne

Figure 8.- Examples of different UAM concepts

4.2. Stages of automation

The implementation and certification of these vehicles is expected to be escalated in time, as seen with conventional aviation. The expected exponential increase in operations within urban areas demands for a highly accurate network of navigational aids and a change of pattern in the way these vehicles will be operated (Robertson, 2010), in order to ensure safety and decrease or completely remove workload. By transitioning to an automation stage on these vehicles, the human role will decrease in relevance, and both precision and awareness will grow, allowing complex maneuvers, optimization of the airspace, and the creation of a sophisticated network of simultaneously coordinated vehicles. Their ability to operate in an urban air network by themselves will not be seen in action until later on, after perfectioning some intermediate stages in which human presence will have a role. However, their degree of dependence on human interaction will decrease in upper stages, until full automation is reached.

Various approaches exist when assessing automation levels in VTOL aircrafts. This concept is still in early phases of development, as pure automation has yet to be seen in any commercial aircraft. Therefore, different views on how automation should evolve have been raised. EASA currently defines 4 levels of automation for helicopters, based on their navigational equipment and onboard computer aids (EHEST, 2015b).

- No Automation: required continuous pilot control inputs and good surrounding awareness.
- SAS: provides simple short-term stability and damping control inputs to ease aircraft handling. Still requires manual inputs to navigate the aircraft and full surrounding awareness.
- SAS+AFCS 3-axis mode: this adds basic stabilization and long-term attitude retention on pitch, roll and yaw axes. Provides autopilot capabilities in all inputs except blade pitch control (in helicopters, collective pitch), which alters the descent or ascend rate and vertical movement.

- SAS+AFCS 4-axis mode: adds full pitch automation, both blade and fuselage, and vertical speed control, achieving full automation of the aircraft. No manual input is required from the pilot, and higher precision maneuvers can be performed.

In this project, and based on what EASA stipulates for current vehicles, three levels of certification will be considered based on their dependency on human action.

- Manual Flight. This would be the first expected stage of operation for UAM vehicles. The human figure is the primary element in control, requiring a pilot on board to actively navigate through the airspace and there are continuous pilot control inputs. This is what is seen nowadays with helicopters. Navigation systems are expected to be still in the early phase of certification, and could work along with current certified equipment, as seen in helicopters. SAS capabilities can be expected as assistance to the pilot, as it is a common and well-known element to have onboard most current VTOL aircraft.

- Automated Flight. This intermediate stage provides the aircraft with the ability to fly by itself as indicated by some previous input from the pilot or the operator, but will not be able to react to its surroundings. This includes any encounter with obstacles, anomalies or flight plan changes. Human interaction will be required to correct and mitigate the situation. Therefore, the vehicle must be able to be controlled by both a human and the onboard computer, and be able to disengage automated flight in order to take manual control at any moment. This would be equivalent to a SAS+AFCS 4-axis mode.

- Autonomous Flight. The final stage of certification will ensure that the aircraft is capable of flying completely on its own, taking the necessary decisions and actions in real time as it navigates the airspace. With the use of artificial intelligence (AI), the aircraft is provided with advanced surrounding awareness systems and navigational tools, and can detect, process and adapt to any unexpected hazard, deviation or anomaly that the vehicle encounters by its own during the flight, and generate changes in the flight path or flight profile in order to reach its destination without incidents. This phase is yet to be seen in aviation, but is expected to be implemented at some point in time. As UAM will evolve, so will the technology available. Considering this level of autonomation is key to analyzing the long-term performance of this transportation model.

Because the expected behavior of governmental institutions is to certify the onboard equipment before allowing for full-autonomous operations, the automated stage is probably going to be focused on flights with monitoring pilots on board. The equipment, systems and computers needed for autonomous flight will be present, but not fully active, as the human figure will be the one operating during abnormal situations. Automation would have most of the advanced systems of an autonomous vehicle, but used first as a help to the pilot by communicating its intentions, limitations, and warnings to the PIC, as well as other relevant information.

4.3. Human factor

Human factor in UAM operations is a relevant factor, as early stages of certification will very likely rely on a human controlling the aircraft. It is also present during the contingency procedures themselves. Some studies have tried to quantify the type and intensity of the workload experienced by helicopter pilots when facing emergency situations. For instance, when measuring both psychological data and flight control use during these operations (Scarpari et.al., 2021), the results show that, when exposed to an unpredicted event that required to perform an autorotation, the rate of success was generally low, especially among pilots with less experience around these maneuvers. The same trend was seen for reaction times.

The workload, defined as a combination of physical and cognitive demands during a certain operation, was seen to be lower for take-off, as the amount of flight control usage was also lower. The same was reflected for cruise phase, which is less restrictive in comparison with other stages of flight as higher altitudes and larger speeds are considered, and the reaction time required is larger. However, for high-hover and approach maneuvers, both associated with low energy settings, the pilot is required to make more use of flight controls in order to recover RPM and fewer seconds to react, therefore increasing the overall workload.

It is fair to assume from these results that for these two phases, approach and hover maneuvers, the human factor is more likely to have a greater influence on the success of the emergency contingency in terms of workload.

External factors can also contribute to an unsafe resultant derived from human action inflight. When operating in night conditions or under IMC, the dark environment interferes with ground references and general perception of the surroundings (Steele-Perkins, 1976). This leads to a background worry and fear of disorientation, and pilots have to completely rely on instruments. Vibration was also identified as a failure source, as it could cause the instruments to become near-illegible. This factor is usually present in most emergency scenarios, and could bring real struggle when performing the corresponding contingency procedure. Other factors, such as high noise levels, can also contribute to disorientation and decrease the efficiency of acoustic alarms or ground-to-air communications.

Furthermore, a common ground is found around skill-based factors. Studies based on the HFACS framework and NTSB analysis identify this category as the most present one in both minor and fatal accidents, especially during take-off and landing, including failure to maintain control and obstacle clearance (Cline, 2018). This is consistent with the low successes observed when practicing emergency procedures (Scarpari et. al., 2021). It is critical to ensure a solid level of skills during the certification processes and to upgrade the standards, as they might be insufficient for intense operations in congested environments, especially when encountering anomalies that require fast and confident responses from the PIC.

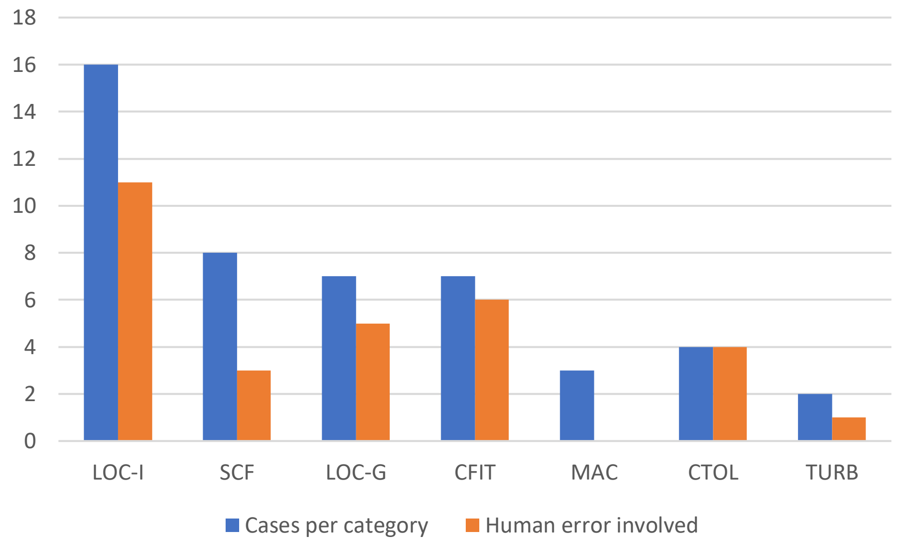

Figure 9.- Human error involvement in each occurrence

For the 37 cases studied, human error was identified as a direct or indirect cause of disaster in 67.6% of the total. The results, however, reveal a rather inconclusive relation between human error and the factors involved in the accident or incident. While it seems to be a larger presence of human error in those that suffered loss of control during flight (68.8% of cases) or a collision with an obstacle or terrain (85.7% in CFIT cases and 100% in CTOL cases), the percentage of cases in which improper execution, reaction or interpretation led to a crash seems to be more linked to a common general trend, regardless of the factors involved. As observed, human action is involved an average of 59.1% in most categories. MAC is not to be included as this is not identified as a main factor but a precursor, and the sample of TURB cases studied is too small to draw any valid conclusions.

Nevertheless, human factors have been proven to be a relevant factor and a main cause of accidents in VTOL operations.

4.4. Discussion on identified risk factors relevant to UAM vehicles

Based on the identified hazards in this study, a series of phenomena arisen as recurrent causes of anomalous situations affecting various phases of flight. Figure 10 shows the different causes identified to have led to an emergency in helicopter operations, sorted by their degree of presence in accidents. In this section, it is discussed the identified factors that may be applicable or expected in the next generation of UAM vehicles.

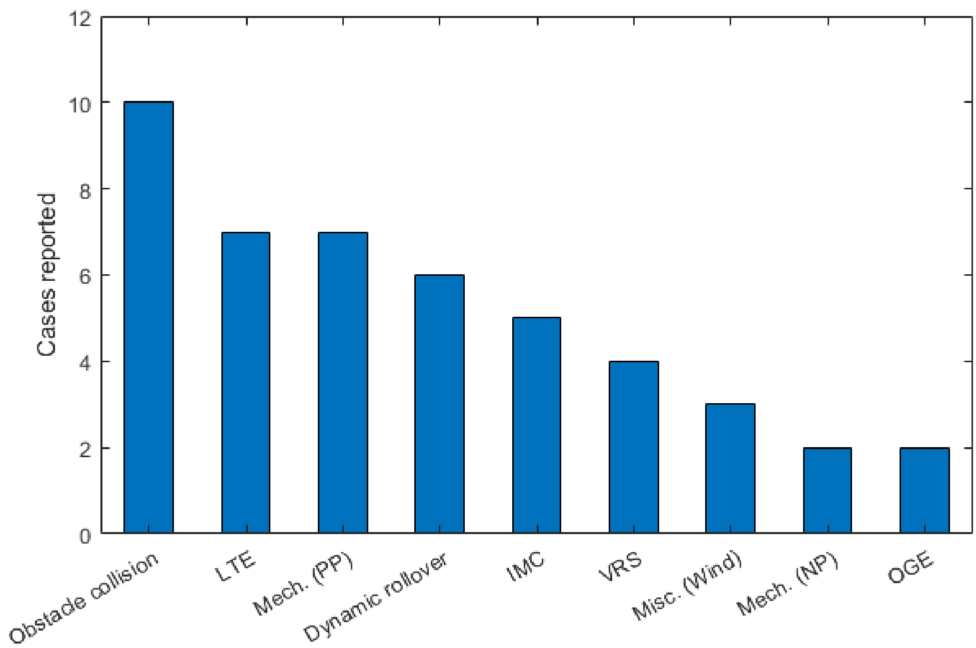

Figure 10.- Identified operational causes of accident in helicopters

4.4.1. Obstacle collision

Obstacle collisions prevails as the most common occurrence found in accidents with helicopters. As explained in Section 3.3.2, this includes strikes with near walls and fences, power wires and adjacent buildings, as well as birds or other airborne bodies or debris. While not sharing many properties, they all pose a risk to the integrity and controllability of the flight. As already seen in helicopters, most of these occurrences lead to a loss of control after impact.

The expected impact of this factor in the next generation of UAM vehicles is evident for a number of reasons. The kind of environment in which they are targeted to operate is the same urban, congested-hostile one in which helicopters have been flying for decades. Even though implementation and certification will be a gradual process, especially for operations in dense urban areas, the projection for these next networks of air mobility is to reach a normalized traffic within the existing infrastructure. High and packed clusters of buildings result in narrow and compacted spaces available for flight maneuvers, which pose a special challenge during the first and final phases of flight. The chances of collision with nearby obstacles increase in these environments, while being more critical as well if the collision results in the partial or total failure of a critical system, such as power systems or flight control surfaces. The reaction time and the margin available to regain control decreases as the aircraft approaches the landing zone, as well as during the first departure maneuvers at low altitudes.

While being a risk regardless of the aircraft category they belong to, the degree of impact it could have in UAM vehicles could vary depending on the vehicle category. For instance, Lift-Fan concepts introduce ducted fans encased and assembled within the fuselage, instead of having its power elements extending beyond the fuselage like in the rest of vehicle categories. This could be one possible path to mitigate critical power failures, as it largely decreases the risk of blade collision and destruction when operating near obstacles or during take-off and landing maneuvers. The risk of a loss of power due to engine damage is reduced compared to other concepts, as well as the risk faced by the ground personnel during ground operations. The rest of vehicle concepts are constituted with exposed rotors, which can pose a greater risk of critical damage by external factors. Therefore, a higher degree of redundancy will have to be implemented in these aircraft.

While a deep assessment on vehicle behavior is not possible due to the lack of public data from current prototypes at the time of writing, it is fair to say that the configuration of the aircraft will determine the degree of maneuverability and stability, and its ability to recover and mitigate from a sudden impact with an object or obstacle before it leads to a more severe situation. The dimensions of the vehicle itself could also be a defining parameter in terms of safety. Larger aircraft, with longer fuselage extensions to accommodate the engines, will also entail a higher risk of collision with nearby structures or obstacles, especially during operations in confined areas and slow speed maneuvers, which have been observed to be more critical and unstable.

Rotary-wing vehicles could be more prone to critical damage, as their rotor configuration is more exposed and extends beyond the fuselage. Lift-fan vehicles, as their rotors are encased or installed within the fuselage, are much more protected, and the probability of critical damage to essential flight elements can be expected to be lower. The same is expected for Tailsitters, as these tend to have a compacted structure.

Lift+Cruise, as well as Tilt-Wing/Prop vehicles, can be expected to be conditioned by the same physical constraints as Rotary-wing vehicles, especially for large wingspan prototypes. These vehicles appear to be larger than Lift-fan vehicles, and have exposed flight controls that make them vulnerable to critical hits with nearby obstacles, especially when approaching narrow roads within urban infrastructure or maneuvering around confined areas.

On the other hand, onboard navigational equipment and environmental awareness systems will have to be certified for these extreme environments in order to ensure a safe traverse, especially during approach and departure. As IATA and EASA defines, exposed in Section 3.1, there is an existing altitude threshold in which the transition from VFR to IFR is mandatory. And following the same trend, UAM can expect to operate under similar regulations. As automation and autonomation will gain more presence in these vehicles, the technology onboard will have to be sophisticated enough to follow and maintain a very specific flight path, as any deviation or lack of correction could result in serious consequences. And this includes robust environment detection and awareness, sensing and reacting to any nearby object or structure that may overcome a hazard.

As seen in the accident analysis, the existing human-based navigation during these sensitive maneuvers can lead to some lack of awareness by a limited visual contact with the surroundings, leading to inadvertent impacts with adjacent obstacles and path deviations. In 4 of the cases reviewed (NYC08IA145; AO-2017-083; ERA09LA020; A010/CENIPA/2013), the effects of lack of vision and situational awareness are clear, all leading to impacts with close structures, other parked aircraft or the landing pad itself. Furthermore, the requirements expected for the airworthiness certification and implementation of these vehicles in order to operate in congested urban environments will likely demand a near total segregation from human influence in order to avoid or reduce the potential misinterpretations experienced with helicopters.

To reduce the chances of collision, from the operational point of view, a deeper assessment is required of both the aircraft equipment and onboard systems, and the human skills and the proper pilot certification requirements.

Moreover, there is still a lot of investigation to make around their general infrastructure requirements and their way of operation around these environments. Depending on how these infrastructures are developed in relation to the existing urban infrastructure, it will condition and determine the way vehicles and the mobility network operate, and the likelihood of collision. For instance, confined areas may be more prone to a collision when compared to rooftops and elevated pads, as the latter tend to have less buildings or structures in the vicinity, and have a wider clear area.

At the time of writing, there are multiple concepts for aircraft pads developing in parallel, following different approaches. Current ground infrastructure, which revolves around helipads, is not designed for a large mobility mode of transportation, and is just accessible to a small portion of the population. UAM aims to the general public, and with a much higher operating frequency. Therefore, the infrastructure needs to adapt as well. REEF Technology is developing operational terminals in parking rooftops, in cohesion with the existing urban infrastructure. Urban-Air Port, on the other hand, is investigating ground-level modular hubs. These are two different approaches from the operational point of view, and will involve various degrees of risk depending on their location within the urban environment.

As automation, and especially autonomy, is achieved, the greater navigational accuracy available will allow for much safer operation, and the probability of collision can be expected to decrease dramatically. As human factors have been found to be the cause of most of the collisions analyzed, decreasing the role of human presence on board will also decrease the criticality of this hazard.

4.4.2. Loss of tail rotor effectiveness (LTE)

LTE has been observed in 7 of the total cases analyzed, and is one of the main causes of accidents in helicopters. While being a phenomenon related to aircraft with anti-torque systems, it could also affect other modalities of vehicles.

LTE is the result from a pure aerodynamic interaction between a main rotor and an anti-torque rotor, and can affect any single-rotor aircraft that utilizes a tail rotor. This tail rotor relies on a stable clean and undisturbed airflow in order to provide a steady and constant antitorque reaction. As explained in Section 3.3.1, the alteration of this airflow caused by wind disturbance from some azimuths can and will alter the efficiency of these systems, especially during high power demanding phases of flight such as departure and landing, or during hover maneuvers.

The lack of real data and test records poses an obstacle in assessing the degree of relevancy of LTE in the different proposed UAM vehicles. Due to the early stage of development of these prototypes at the time of writing, the conclusions will have to be drawn from simulation models and observations in similar vehicles. So far, none of the presented prototypes to date rely on any anti-torque systems that could reassemble what is observed in helicopter tail rotors, and most are based on a multi-rotor system.

Although lacking a tail rotor, multi-rotors are assembled in a counter-rotating manner, so that they cancel out the overall torque produced by each rotor. This has been demonstrated with similar vehicles such as tandem and dual rotor helicopters, which are the only two types of multi-copters that have actually been implemented into passenger transportation so far. For these aircraft, LTE has not been reported as a hazard.

This fact leads to the claim that LTE will not be applicable to UAM vehicles in the way it affects helicopters. However, symmetry in thrust and lift generation is key for a proper stability and control of these aircrafts. If one of both main rotors stalls or loses its lift capability due to VRS or similar wind-related phenomena, the overall torque would not be canceled and unintended yaw could appear, replicating effects similar to those of LTE.

Moreover, similar phenomena could be experienced in these vehicles related to an aerodynamic interference between rotors. Depending on the forward airspeed of the aircraft, different interferences can overcome and interfere in the performance on Rotary-wing aircraft. In case of multi-rotor prototypes, research has been done around rotor interference depending on the forward airspeed of the vehicle (Ye et. al., 2021).

As this study reflects, for hovering and steady states, interference exists only in the areas of the rotors closest to each other, and is small enough to be negligible. Generally, mutual interference between rotors was demonstrated through simulation to be small enough to be considered negligible, especially for greater forward airspeeds. This effect, however, is more notable between the rear rotors than between the front rotors, and can be particularly complex to analyze for low airspeeds.

For slow forward speeds (10 m/s), the more prominent type of interferences found in multirotor were related to downwash and tip vortices, especially in the rear rotors, which become affected by the disturbances generated by the front rotors. The interference received by the rear rotors mainly comes from front rotor disturbance, combined with fuselage interference as well, to a lesser degree.

As greater forward airspeeds are built (up to 25 m/s), the fuselage becomes the main source of interference. In fact, the wake of the fuselage causes an unequal thrust generation along the rear rotors that becomes more intensive the closer the rear rotors are to the fuselage. However, the overall interference received by these due to fuselage becomes stronger for slow airspeeds of around 5 to 10 m/s, and losses intensity as more airspeed is grown.

Therefore, these results reflect that slow maneuvers are the most prone to observe an unsteady response of the aircraft, changing the aerodynamic forces, pitching moments and thrust capabilities in the aircraft. And could become more critical under wind conditions, which could intensify the interference effects. A clear assessment of this phenomenon is required when designing these vehicles for urban operation, as slow phases of flight, such as take-off and landing, could experience induced loss of control similar to that found in LTE.

It is, however, harder to predict the relevance and impact of this phenomenon on the different vehicle categories, as design and rotor configuration varies wildly even within the same category. Lift-fan vehicles could expect a lower degree of impact compared to the rest of categories, as mutual interference between rotor would be unlikely with encased and isolated rotors. Rotary-wing vehicles might be the ones most affected by it, as they tend to follow a rotor configuration consisting of multiple rotors very close to each other, which could increase the likelihood of aerodynamic interference and disturbance of airflow through them. The ones where there is more uncertainty as to their degree of impact are Lift+Cruise, Tilt Wing/Prop and Tailsitters, and will likely vary depending on their design. Deeper assessment will have to be done by the different manufacturers to ensure minimization of this phenomenon, especially during critical phases of flight.

While, like obstacle collision, this is a phenomenon that won't be eradicated by implementing higher degrees of automation, it could improve the way contingency is executed.

4.4.3. Mechanical Failure (PP/NP)

Accidents caused by mechanical failure can involve either powerplant-related (PP) or non-powerplant (NP) elements. Powerplant or engine-related accidents have been more observed in helicopters when compared to non-powerplant-related ones but, in most cases, both led to a loss of control of the aircraft, and needs to be assessed.

When studying engine-related hazards, the accident analysis on helicopters showed that 5 of the total 7 cases reviewed that experienced a critical engine failure event involved single-engine aircraft, while only 2 occurred when operating dual-engine helicopters. However, the capabilities of these engines may not be enough to operate by themselves if one of them fails during flight. External factors such as density altitude, which depends on air temperature and pressure, the gross weight of the aircraft or the phase of flight, are determining factors to assess if a multi-engine aircraft could keep flying in the event of an engine failure (James, 2021b; FAA, 2012). Therefore, redundancy may not be a definitive solution, and further study has to be conducted in order to certify the different engine prototypes for operation in congested urban environments, and to ensure controllability and capacity of recovery of the aircraft in the event of one or more engine failures. However, redundancy will likely be the determining factor that will grant operational certification as long as the vehicles are proven to be resilient and can sustain safe flight even with a partial or total loss of one or more engines.

In order to operate in dense urban environments, UAM vehicles will require a high degree of engine reliability and mitigation capabilities, minimizing the consequences of any anomaly. These requirements will have to be regulated by the competent authorities, and could be defined based on the vehicle performance, and not focused on its characteristics, in order to be applicable to all vehicle categories regardless of engine configuration or lift generation. ICAO already defines guidelines in this subject for helicopters, by considering a combination of performance classes and characteristics categories to outline aircraft requirements in order to be able to operate in the different environments (ICAO, 2010). Three classes (1, 2 and 3) define the ways the aircraft has to respond or perform at different points of the take-off and landing phases in case of a critical engine failure, and the capability of the vehicle to safely land or continue flight, regardless of the engine configuration of the aircraft, all while maintaining the appropriate minimum flight altitude. Two categories (A and B) define the aircraft characteristics, including equipment, onboard systems and engine configurations. ICAO then combines these two forms of classification, depending on the requirements and constraints of each environment, to create a solid definition for helicopter operation.

For urban flight operations with helicopters, the environments faced are classified as congested/congested-hostile (dense urban environments). Therefore, Performance Class 1 with Category A certifications have to be granted in order to operate. This implies, in general terms, that the aircraft has to be able to reject take-off or continue it while clearing all obstacles by a safe margin, as well as being able to maintain flight until reaching an adequate landing site with the remaining operative engines. The same applies for landing maneuvers. For future UAM vehicles, similar requirements can be expected to be implemented, as the general flight profile, vehicle characteristics and targeted environment are very similar to helicopters.

Rotary-wing vehicles, especially for multi-copters, by having several rotors, the chances of critical loss of control are reduced, as compensation by the other operating rotors is possible. Furthermore, autorotation is also a key feature in these vehicles. As long as the rotors have the capacity to disengage the engine from the rotor shaft, allowing it to spin freely (freewheeling unit), an autorotative emergency descent should be possible. Therefore, from the point of view of criticality, an engine failure should not be as serious as in other vehicles, since their contingency capabilities are greater.

This feature will depend, however, on the number of rotors the vehicle has installed. This is the main drawback that Tilt-rotors or Tilt-wing vehicles, for instance, will have to face. As seen in current prototypes, their rotor configuration typically consists of two main rotors. This, while providing advantages in terms of simplicity in power configuration, does not necessarily provide with sufficient capabilities to perform an autorotation, and should not rely on this technique for a survivable power-out landing. While technically possible, autorotative maneuvers alone have not yet been proven to provide a safe landing in an engine failure scenario. This was seen in the Bell V-22 “Osprey” (MV-22B) aircraft, as its low-inertia rotor system does not provide with much energy storage capacity as compared to Rotary-wing vehicles, and rotor RPM decay very easily with few chances of recovery (Vertical Magazine, 2012). According to U.S. Pentagon officials, in a loss of power situation while hovering below 1.600 feet (490 meters), emergency landings are not likely to be survivable.
To compensate for this lack of autorotation capacity, Tilt Wing/Prop vehicles should be capable of gliding for a controlled running landing (NAVAIR, 2011).
Lift+Cruise vehicles have similar conditions, as only a reduced number of rotors are designed for VTOL maneuvers. Therefore, it has to be assessed the capability of these rotors to perform an autorotation or similar emergency descents when encountering engine failures.

On the other hand, non-powerplant failures found during the root cause analysis were generally identified as fatigue-related issues. The significance of this factor depends on the affected element of the aircraft. Because of the wide variety of parts and elements that can fail due to excessive stress or wear, a detailed assessment exceeds the purpose of this segment. However, the acknowledgement of this hazard is relevant when designing the next generation of vehicles. Using state of the art materials combined with rigorous maintenance checks can help reduce this risk, as observed in current aircrafts.

The most dangerous situations in which fatigue has been observed to have a bigger impact is during landing, as the response margin to allow for autorotation or other mitigation procedures is minimum to nonexistent, depending on the proximity to the ground at the time of failure. This also involves the safety of the ground personnel, as could be harm as a consequence of a loss of control due to fatigue. This is observed in case AAR7709, in which a landing gear failure induced a dynamic rollover short after landing, and the still rotating blades injured or fatally affected many victims. While situations similar to this may be exceptional, it is still necessary to dictate careful procedures for ground operations that ensure a safe environment around the aircraft during maneuvers and turnarounds.

This brings another design flaw on Tilt-wing/Prop vehicles, which is the possibility of a mechanical failure on its tilting mechanism. Should a failure occur during the transition from vertical flight to forward flight, the overall controllability of the aircraft is likely to be lost, which could have critical consequences, especially in Tilt-wing vehicles Airflow over the tilting wings become more turbulent and harder to predict, and special caution must be exercised during these maneuvers to maintain control and stability (Head, 2020). This is more pronounced in maneuvers at low airspeeds, such as approach or departure, rather than at high speeds.

In general, Tilt-rotors and Tilt-wing vehicles show to be more prone to critical impact if a mechanical failure occurs, as fewer contingency options are available and are more vulnerable.

Lift-fan vehicles, as their rotors are usually encased within the fuselage or stacked, tend to be smaller in diameter. This is a factor to be taken into consideration when assessing contingency capabilities of these vehicles, as smaller rotors may not provide the same energy storage during an unpowered autorotative descent when compared to Rotary-wing vehicles with larger rotors.

Nevertheless, it should be considered the capability of the engines for sustaining a controlled flight with one or more inoperative engines, as the ability to drive both rotors with one engine and perform a safe power-out landing is unclear.

As higher automation levels will be reached, it could be expected a decrease in criticality when encountering mechanical failures, as onboard systems are expected to be capable of predicting, reacting and containing these anomalies in a much faster and efficient way than humans can, therefore reducing the risk of disaster. Still, this hazard will remain present even with the most advanced of computers, as it depends on multiple external factors, and can only be improved in contingency rather than eradication.

4.4.4. Instrumental Meteorological Conditions (IMC)

The latter section is closely related to IMC events. In these cases, the loss of visual contact with the surroundings and environmental awareness can also lead to an unintentional collision with nearby obstacles. IMC applies for situations which require instrumental reliance due to poor visibility, including some dark night conditions, low cloud ceilings, fog and rain. In most of the cases analyzed with this occurrence, the accident was directly related to a failed transition between VFR and IFR due to pilot misjudgment, or a lack of IFR certification of the aircraft. An inadvertent encounter with IMC (IIMC), due to a rapid change in the weather conditions while airborne, may cause more prominent human-related factors.

This is an identified relevant phenomenon that acts as a catalyst for other hazards for any of the considered UAM vehicle categories, and will remain so as long as aircraft continue to be manually controlled, or the available technology cannot guarantee complete control and awareness of its surroundings during these events. Therefore, during the first stages of certification, in which the human figure is expected to take an active role during flight, the viability of operation in urban congested-hostile environments during IMC will have to be deeply assessed.

This calls for further regulation and minimum visibility guidelines in order to ensure a safe itinerary, combined with rigorous procedures to ensure that the necessary actions by the pilot and the aircraft are followed, referring to instrumental aids instead of continuing under VFR. Moreover, the human skills and response capability requirements will have to be more precise and must be properly instructed and embedded so that they are applied correctly and immediately in the event of an IMC. As autonomation will be developed, the human factor will be a less active element and the chances of a faulty performance are expected to diminish.

Some solutions include installing extensive flight data monitoring systems onboard that may help identify path deviations when encountering these scenarios (NTSB, 2016). These would provide information regarding pilot performance that could be useful to better understand the nature of any anomaly or path deviation, and take corrective action before an accident occurs or implement mitigation procedures. These systems could be applied for both real-time situation assessment and data-storing for periodic reviews to analyze behavioral trends and take the necessary actions.

Some investigations also reveal the need for advanced sensorial equipment in order to detect and avoid other self-flying vehicles (UAV), near obstacles and pedestrians through fog and mist environments (Tabor, 2022). Most of the sensors present in current helicopters for environmental scanning are based on lidar technology, which might reflect off the water droplets in fog instead of nearby objects and surfaces. For future UAM vehicles, an extended awareness through these environments will be a key factor to ensure a safe and undisrupted operation.

4.4.5. Vortex Ring State (VRS)

Like LTE, VRS is a purely aerodynamic phenomenon. However, this mainly affects horizontal rotors, usually the main rotors that provide the VTOL capabilities to the vehicle. VRS has also been observed in vertical rotors such as tail rotors for some wind azimuths but, as discussed before, because UAM prototypes do not seem to incorporate a conventional tail rotor system like helicopters, only the effects on horizontal rotors are relevant for this study.

VRS is a hazard identified for steep, low-power setting operations, as explained in Section 3.3.1. Therefore, it usually appears during VTOL approaches, in which the rotor's RPM (revolutions per minute) are relatively low compared to other phases of flight, but still critical in order to maintain a controlled descent into the landing zone. When VRS is induced, a notable part of the lift capabilities of the rotors are lost, drastically increasing the rate of descent and leaving a small margin for correction. Its effects are reflected in an uncontrolled sinking, as the aircraft enters its own turbulent air beneath it, therefore causing an unstable lift generation and stall of the rotor blades. Great gross weights will aggravate its effects.

UAM vehicles can be expected to encounter VRS situations based on general trends in rotor configuration seen in most of the vehicle concepts presented in Section 4.1. This argument is reinforced by what has been observed in current similar vehicles, such as the V-22. This tilt-rotor aircraft has been reported to encounter VRS in some of the conducted operations, especially during steep and low speed approaches. This is seen in case ASN56469, and the consequences were reported to be fatal.

While in a VRS state, the mitigation procedures vary depending on the rotor configuration of the aircraft and its navigation control techniques. In general, the supply of more power to the rotors is insufficient to exit the turbulent area, and has to be combined with a pitch angle of the rotors in order to build a forward or lateral speed and regain clean air.

In case of multi-rotors, while some are designed to have rotation capabilities, others achieve roll or pitch control by applying more thrust on one or more rotors. This is seen in current tandem helicopters, which use a configuration of two identical rotors, one located in the forward part of the fuselage and the other in the rear. In these, forward pitch is achieved by increasing thrust in the rear rotor and decreasing it in the front. Tilt-prop aircrafts, such as the MV-22B, work in a similar manner, and roll is achieved by increasing thrust in the left rotor and decreasing thrust in the right. This factor, however, poses a threat when entering VRS, as the additional thrust supply will still not be enough to exit the turbulent area and recover clean air. In case ASN56469, the PIC increased the thrust on the right rotor and decreased it on the left, in an attempt to gain lateral movement. This, however, proved to put the aircraft deeper into VRS, aggravating its effects and causing an uncontrolled and violent descent into the ground.

For UAM vehicles, there is a need to acquire additional data on the different prototypes to assess the degree of influence of VRS, and their convenient contingency procedures. However, previous observations prove that VRS will affect most if not all vehicle categories when operating in VTOL mode if the correct approach maneuvers are not conducted.

A successful avoidance of this phenomenon could be achieved by a combination of a careful landing site location study and proper approach path procedures. Highly confined landing areas imply steeper approach paths, which may be more prone to induce VRS. In addition, these type of landing sites have a much more restrictive space margin to perform mitigation maneuvers, further jeopardizing the flight. In order to perform a safe descent into the landing site, a less steep approach path has to be able to be conducted, while clearing any surrounding obstacles or buildings.

Another element that could vary as well is the ability of recovery or escape from this phenomenon. Each vehicle category has a different degree of maneuverability, which could determine the capacity of quickly correct the trajectory and avoid critical consequences. Rotary-wing aircraft are projected to be the most maneuverable ones, especially within confined spaces, and may have a greater chance of success in escaping VRS encounters. Tilt Wing/Prop vehicles may encounter greater difficulties when faced with this phenomenon, as seen with the V-22. The fact that the relevance of this phenomenon has been proven in these vehicles, combined with their poor capacity of autorotation, especially at low altitudes as presented in Section 4.4.3, decreases their chances of success.

4.4.6. Heavy and Adverse wind

When assessing wind-related factors, a wide spectrum of phenomena, behaviors and outcomes open up. VTOL vehicles thrive on it, and depend on its state and interaction to operate. Rough environments, however, can induce dangerous and unstable situations that may compromise the safety of the flight, as well as that of its near surroundings. Acknowledging the general impact of heavy and adverse wind, the capacity of response and the general maneuverability margin available in VTOL aircraft may help to point out countermeasures to be taken into account when designing these future vehicles to ease contingency measures and reduce safety risks.

For instance, windshear and microbursts are one of the most dangerous situations an aircraft can encounter, especially in low-altitude operations including take-off and landing. Both phenomena involve an area inside which a downward flow of air descents into the ground. As it reaches the ground, the flow translates into a more horizontal direction.

From the performance point of view, encountering these will result in a first stage of increasing headwind as the aircraft reaches the core, followed by a second stage of heavy tailwind. In both cases, a vertical component is present, which adds a risk of unforeseen sinking into the ground. Below 1000 ft, the variation in direction and velocity is even greater. This leads to an important loss of energy in most aircrafts, and could result in an inability to recover if the aircraft already has low energy, as in the case of take-offs and landings.

When avoidance is not an option, escape strategies revolve around gaining altitude while maximizing power delivery in order to maintain a safe airspeed (Elferink & Visser, 2001; Mashman, 1998). The same study also proposes lateral deviation as an alternative to going straight through the core, with improvements in performance, both in climb rates and speed gaining.

Because this is a more generic section with a cluster of different wind-related phenomena identified in Section 3.3, and are not expected to be a main hazard during operations. Therefore, a dedicated assessment for the different vehicle categories would contribute little, and it would not be possible to draw conclusions as solid as those of the other sections. This segment is written as an acknowledgement of possible factors to be considered when designing these vehicles, as their relevance is applicable to all aircraft.

4.5. Analysis summary

This section is destinated to reflect the presented ideas from the latter segments in a visually intuitive way, to facilitate the reader in identifying the main conclusions extracted. By altering the level of automation for each vehicle, the criticality or relevance of each identified hazard varies. To reflect this, a qualitative criterion based on a numerical scale has been implemented to represent the degree of impact in each case, 4 being the most critical and 1 the least.

	Vehicle: **Rotary-wing** Flight: **Manual**	Vehicle: **Rotary-wing** Flight: **Automated**	Vehicle: **Rotary-wing** Flight: **Autonomous**	Vehicle: **Lift-Fan** Flight: **Manual**	Vehicle: **Lift-Fan** Flight: **Automated**	Vehicle: **Lift-Fan** Flight: **Autonomous**
Obstacle collision	4	2	1	3	2	1
LTE/Rotor interference	3	2	2	1	1	1
Mechanical Failure	3	3	3	4	3	3
IMC	4	2	1	4	2	1
VRS	4	3	3	4	3	3

	Vehicle: **Lift+Cruise** Flight: **Manual**	Vehicle: **Lift+Cruise** Flight: **Automated**	Vehicle: **Lift+Cruise** Flight: **Autonomous**	Vehicle: **Tilt Wing/Prop** Flight: **Manual**	Vehicle: **Tilt Wing/Prop** Flight: **Automated**	Vehicle: **Tilt Wing/Prop** Flight: **Autonomous**
Obstacle collision	4	2	1	4	2	1
LTE/Rotor interference	3	2	2	3	2	2
Mechanical Failure	4	3	3	4	3	3
IMC	4	2	1	4	2	1
VRS	4	3	3	4	3	3

	Vehicle: **Tailsitter** Flight: **Manual**	Vehicle: **Tailsitter** Flight: **Automated**	Vehicle: **Tailsitter** Flight: **Autonomous**
Obstacle collision	3	2	1
LTE/Rotor interference	3	2	2
Mechanical Failure	4	3	3
IMC	4	2	1
VRS	4	3	3

5. Conclusions

All the work done during the realization of this project and the accomplishment of the defined objectives are analyzed in this chapter, including its main contribution and the possibilities of future work from now on.

5.1. Main Contribution

This research aimed to identify key elements and factors that could pose a safety concern in the operation with UAM vehicles at a large scale. Based on a quantitative analysis of recorded incidents and accidents with similar vehicles, mainly helicopters, allowed a first insight into the hazardous situations that these future vehicles may encounter depending on the type of vehicle and the degree of automation. The lack of technical data at the time of writing, however, forced to make assumptions when discussing the relevance of the identified hazards in UAM vehicles. Because of this, the level of detail that has been able to consider in this study is relative, and there is a possibility that the conclusions drawn may not apply at the same level as the one presented.

By analyzing previous emergency encounters with helicopters, which should reassemble the next generation of UAM vehicles in many aspects including maneuverability, operational environment and general behavior, this thesis has identified general phenomena and aircraft states that could be considered as potential hazards and that could compromise the safety of the operation. The extensive experience acquired with helicopters makes them a key reference when assessing future UAM vehicles, and have proven useful in providing clear trends in behaviors and interactions with the environment when certain conditions are met.

As the main goal of this thesis, the identification of hazardous situations and emergency-driven factors have been accomplished by applying a root cause analysis of documented accidents and incidents with helicopters. The results have been extrapolated to UAM vehicles utilizing the projected characteristics and main traits of the different clusters of vehicles that share similar features, differentiating five main groups. By doing this, a more global perspective is presented, which proves to be more valuable and convenient than an in-depth analysis in each prototype. The latter, considering the early stage of development in which UAM is at the time of writing, would have been inefficient and give no guarantees it would be relevant in the coming years, as concepts evolve constantly before reaching a more mature and tangible phase of development. This general approach when studying each hazard and occurrence identified has allowed to define safety topics to be considered for these vehicles without focusing on particular elements and regardless of specific design properties. Because most of the prototypes presented to date differ greatly from each other in many aspects, this thesis may have help bringing some light on safety concerns relevant to all of them, to a greater or lesser degree.

This study has also made it possible to visualize the lack of standardization that is being followed in this industry, and the need for the regulatory agencies to implement rules of operation and procedures. Regardless of the economic viability and social acceptance of the UAM model in the near future, the safety area is in need of further assessment from both manufacturers and international regulatory entities. This includes characteristics and aptitudes of the vehicles for operation, especially in congested-hostile environments, as well as performance requirements and capabilities in case of emergency. While this is well established in the area of helicopters, the transition to other UAM modalities will have to be considered in the coming years in order to simplify the certification processes, as well as the design and development processes by the manufacturers themselves. This regulatory uncertainty that is currently present on this market has allowed the manufacturers to present a wide variety of vehicles with different performance capabilities and characteristics. Because of this, prototype tests have been very limited, and have been focused on testing flight capabilities in controlled environments, without any certainty of aspiring to be certified to operate in large-scale urban environments.

Another main highlight that can be extracted from this study is the significance of the human presence in UAM operations, and its critical impact in safety. It has been observed how, excluding mechanical failures, human error appears to be largely involved in accidents with helicopters. The implementation of automated and autonomous phases is projected to decrease drastically the criticality and potential of most of the exposed hazards, and by transitioning to a more passive human role would increase mitigation and avoidance.

5.2. Future work and Missing subjects

As stated in Section 1.2, this project was oriented towards identifying general hazardous occurrences relevant to UAM vehicles, and aiming to extrapolate previously reported anomalies in current VTOL aircraft to these. However, because very little technical information has been released or published concerning performance UAM vehicle prototypes at the time of writing, an in-depth assessment on concrete phenomena or factors for each particular vehicle has not been possible. The fact that only small tests have been conducted with some of these vehicles means that there is no accident history.

During this project, it was identified the need for creating a relationship between the identification of the hazards and the performance of the vehicle itself. This is expected to be possible as research on these vehicles progresses. Deep assessment on concrete hazardous factors and taking them into account during the designing and testing phases of development will be necessary in order to receive their operational certification.

Moreover, as identified in Section 2.3., noise emission is still another major public concern around UAM modes. Research on this topic will also be relevant to gain public interest and acceptance, and therefore obtain the required funding to launch this industry.

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Appendix 1

This appendix collects all the cases considered and referred to in Section 3.3, with a complete description of the events and main factors involved, in order to provide a detailed context for each of them.
For each case, some basic information is indicated, including the severity of the case, whether is considered an accident (indicated as “A”) or an incident (indicated as “I”), and if human factors (HF) were involved.

<table>
<tr><th>Report ID</th><th>Registration</th><th>Date</th><th>Location</th><th>Country</th><th>Severity</th><th colspan="2">CIAAT Categories</th><th>HF</th></tr>
<tr><td>CEN18FA033</td><td>N620PA</td><td>November 19, 2017</td><td>Stuttgart, AR</td><td>United States</td><td>A</td><td>LOC-I</td><td>MAC</td><td>N</td></tr>
<tr><td colspan="9">Bird impact inflight (geese) was identified as the main cause for the loss of control of the aircraft, and likely incapacitated the PIC as well. The aircraft was certificated under 14 CFR Part 27 as a normal category rotorcraft. As such, there are no bird strike safety requirements for the windshield. Transport category rotorcraft do have a requirement under 14 CFR 29.631 to be designed to ensure capability of continued flight and/or landing; however, the design requirement assumed a single 2.2 lbs. bird.</td></tr>
<tr><td>GAA18CA117</td><td>N618SG</td><td>February 1, 2018</td><td>Wrightwood, CA</td><td>United States</td><td>A</td><td>LOC-I</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">The aircraft suffered a loss of tail rotor effectiveness due to a combination of high altitude and high gross weight. This resulted in a demand for tail rotor power larger than the available by the engine.</td></tr>
<tr><td>WPR18MA087</td><td>N155GC</td><td>February 10, 2018</td><td>Peach Springs, AZ</td><td>United States</td><td>A</td><td>LOC-I</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">Loss of tail effectiveness during approach phase, mainly due to intense tail wind combined with the low speeds involved in the final maneuvers. The gusty, turbulent and multidirectional wind of the topography made the operation risky and unpredictable, which eventually led to the accident. A subsequent fire started due to fuel draining, which was the most significant factor in the death of 5 of the 7 occupants. No crash-resistant fuel system was installed on the aircraft.</td></tr>
<tr><td>DCA20MA059</td><td>N72EX</td><td>January 26, 2020</td><td>Washington, DC</td><td>United States</td><td>A</td><td>CFIT</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">This accident involves a loss of control due to an IMC encounter. The aircraft was being flown under visual rules during the entire operation below the cloud base reported for that day. Eventually, the aircraft climbed into the cloud layer, which led to a potential loss of spatial awareness and orientation of the PIC, losing the horizon and visual references. The helicopter began a gradual left turn, unaware of the deviation that the aircraft was taking from the planned path, while losing altitude. The PIC was unaware of this loss of altitude, as he claimed during ATC communications that his intentions were to climb and surpass the cloud ceiling. A witness near the accident site first heard the helicopter then saw it emerge from the bottom of the cloud layer in a left-banked descent mere seconds before impact, leaving no time for the pilot to react. Because no malfunction on the aircraft was detected, human factor was the only element involved in the accident, as refused to switch to instrument navigation given the environmental conditions.</td></tr>
<tr><td>ERA18MA099</td><td>N350LH</td><td>March 11, 2018</td><td>New York, NY</td><td>United States</td><td>A</td><td>SCF</td><td>-</td><td>N</td></tr>
<tr><td colspan="9">The aircraft was faced with an engine power failure caused by an inadvertent loss of fuel flow. The situation led to an autorotative descent to ground level. The procedure performed was a maximum range autorotation, maintaining a low RPM configuration on the main rotor while maximizing both distance covered and time. However, it implied that less energy would be stored for the final flare, so less margin of error remained. The aircraft was put safely to the ground, even though fatal casualties were involved due to other factors.</td></tr>
</table>

<table>
<tr><td>CEN17FA252</td><td>N238BK</td><td>July 1, 2017</td><td>Perryville, MO</td><td>United States</td><td>A</td><td>SCF</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">A dual-engine loss of power caused by fuel starvation due to human error. PIC forgot to activate fuel transfer pumps between main and secondary tanks, and eventually the aircraft decayed once the secondary tanks were emptied. The emergency was mitigated with an autorotation.</td></tr>
<tr><td>CEN18FA259</td><td>N312SA</td><td>July 7, 2018</td><td>Chicago, IL</td><td>United States</td><td>I</td><td>LOC-I</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">An overspeed event on both engines and rotor, caused by human error, led to an unstable flight situation, and a full autorotation was performed. The decrease of the pitch angle on the main rotor blades in order to perform the autorotation, combined with the overspeed, created a high-workload scenario. As the PIC misinterpreted the situation, considering low rotor RPM instead of high rotor RPM, the procedure executed (lowering the collector) was not adequate.</td></tr>
<tr><td>NYC98LA058</td><td>N355DS</td><td>December 31, 1997</td><td>New York, NY</td><td>United States</td><td>A</td><td>LOC-I</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">This accident involved a combined scenario of high tailwind with an uncontrolled VRS during the final approach. The aircraft experienced a fast settle when executing the final flare and pitched up the main rotor AOI. However, because of the unnoticed VRS, no enough power was available to stop the rate of descent. Additionally, no go-around was executed due to the close proximity of the aircraft with the terminal building and others nearby. The aircraft performed a hard landing, followed by a direct impact into the terminal.</td></tr>
<tr><td>NYC08IA145</td><td>N406LH</td><td>March 22, 2008</td><td>New York, NY</td><td>United States</td><td>I</td><td>CTOL</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">The incident occurred during the take-off phase, when one the involved aircraft impacted to the aircraft next to it. The main cause found was a human error concerning a lack of surrounding awareness by the PIC when executing the maneuver. A secondary contributor was the fact that the helipad itself did not follow the recommended spacing between pads by the FAA.</td></tr>
<tr><td>ERA09LA020</td><td>N552J</td><td>October 16, 2008</td><td>New York, NY</td><td>United States</td><td>A</td><td>CTOL</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">The final approach was executed on a confined landing area. A miscontrolled final turn positioned the aircraft outside the confined marked area. Unaware of this situation, the crew descended until impacting the rear tail with the external fence. This led to a loss of directional control and a consequent hard landing.</td></tr>
<tr><td>ERA12MA005</td><td>N63Q</td><td>October 4, 2011</td><td>New York, NY</td><td>United States</td><td>A</td><td>LOC-I</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">An unconsidered overweight of the aircraft, combined with a downwind initial maneuver and the still slow airspeed, led to an LTE and a subsequent crash. Both human error (planning) and weather conditions were factors in this accident.</td></tr>
<tr><td>ERA19LA171</td><td>N26BB</td><td>May 15, 2019</td><td>New York, NY</td><td>United States</td><td>A</td><td>LOC-I</td><td>TURB</td><td>Y</td></tr>
<tr><td colspan="9">The aircraft, operated by the UAM company BLADE, was approaching the helipad with tailwind conditions. The low speed, high-power setting of the procedure contributed to an LTE scenario, experiencing an uncommanded right yaw. After a go-around and second try, same conditions were encountered. The power required to overcome the induced yaw movement due to LTE was larger than the available (pilot applied full pedal to the tail rotor without success), likely due to a loss of translational lift. The aircraft entered an uncontrolled spin, which led to a forced water landing. The failure on controlling and counteract this phenomenon let to an uncontrolled spin and minor crash.</td></tr>
<tr><td>LAX95FA079</td><td>N2209P</td><td>January 14, 1995</td><td>Los Angeles, CA</td><td>United States</td><td>A</td><td>CFIT</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">This flight took place in very poor visibility conditions, involving fog, low overcast ceiling (300 ft AGL) and showers. The PIC executed an inappropriately low departure path for the given conditions, and proceeded to do it so in visual flight rules, instead of following IFR as dictated for IMC type events. This misjudgment of the risks involved led to an impact with some high voltage transmission wires, which damaged critically the main rotor and caused the aircraft to plunge to the ground.</td></tr>
</table>

<table>
<tr><td>LAX00TA318</td><td>N5758H</td><td>August 29, 2000</td><td>Los Angeles, CA</td><td>United States</td><td>A</td><td>SCF</td><td>LOC-G</td><td>Y</td></tr>
<tr><td colspan="9">The aircraft involved suffered a partial fatigue failure on the main rotor during the departure phase. This situation forced the pilot to turn back to the landing pad, located on a rooftop. The aircraft successfully returned to the base, however the sideward movement executed during the emergency landing led to a dynamic rollover right after touchdown.</td></tr>
<tr><td>LAX08FA052</td><td>N705JJ</td><td>January 25, 2008</td><td>Los Angeles, CA</td><td>United States</td><td>A</td><td>CFIT</td><td>-</td><td>N</td></tr>
<tr><td colspan="9">A leisure night flight was operated under VMC conditions. The PIC was instructed to fly at or below 500 feet AGL to avoid trespassing to restricted LAX airspace. Because the flight was conducted under VFR, and no flight plan was filled, obstacle clearance altitude was not provided. The low visibility due to the dark night conditions and the low-altitude flight profile followed led to an unanticipated mid-air collision with some high voltage transmission wires. This resulted on critical damage to the aircraft's integrity and crashed violently into the ground, claiming the pilot's life.</td></tr>
<tr><td>DCA20IA034</td><td>N71HD</td><td>December 4, 2019</td><td>Los Angeles, CA</td><td>United States</td><td>A</td><td>MAC</td><td>-</td><td>N</td></tr>
<tr><td colspan="9">The flight was being operated without anomalies for most part of the itinerary, when a sudden noise followed by vibrations on the main rotor indicated a possible collision with some object. A precautionary landing was conducted at a nearby helipad, and further analysis revealed a possible mid-air collision with a small unmanned aircraft (sUAS). The dark night conditions added a degree of difficulty at identifying these objects.</td></tr>
<tr><td>LAX01LA243</td><td>N474SF</td><td>July 12, 2001</td><td>San Francisco, CA</td><td>United States</td><td>A</td><td>SCF</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">The aircraft, operated by the San Francisco Helicopter Tours agency, was performing the final descent into the landing zone when a sudden loss of engine power, caused by a malfunction on the gear box, forced the PIC to enter an autorotative descent. In the final flare to kill the forward airspeed in preparation for touch-down, the aircraft experienced an uncontrolled 90º left turn resulting in a tail boom strike with the ground and followed by the main rotor blades. The pilot's failure to maintain directional control during the autorotational flare maneuver was considered a relevant cause of the accident.</td></tr>
<tr><td>CHI06GA174</td><td>N681FD</td><td>June 30, 2006</td><td>Chicago, IL</td><td>United States</td><td>A</td><td>SCF</td><td>LOC-G</td><td>Y</td></tr>
<tr><td colspan="9">The aircraft was operating an emergency response flight when suffered a loss of transmission to the rear rotor caused by fatigue in the tail rotor driveshaft hanger. The consequent unintentional yawing due to loss of tail rotor effectiveness was mitigated by entering an autorotation. As the aircraft entered the final approach and flared, and the AOI increased, it experienced an uncommanded left turn that led to a total rollover on the landing pad.</td></tr>
<tr><td>AO-2017-083</td><td>VH-HBV</td><td>August 15, 2017</td><td>Julatten, Queensland</td><td>Australia</td><td>A</td><td>LOC-G</td><td>CTOL</td><td>Y</td></tr>
<tr><td colspan="9">The aircraft, operating a short ferry flight, experienced a violent landing during a shallow approach operation. While the initial approach was executed correctly, orbiting the landing site at around 500 ft to assess the conditions, the final flare was too aggressive and led to a tail strike. The impact resulted in a tail rotor separation, and the aircraft yawed uncontrolled to the right. The PIC failed to reduce the AOA of the rotor blades (lower collective) in order to reduce the yawing, and the hard landing ended up in a dynamic rollover.</td></tr>
<tr><td>ERA10CA109</td><td>N3275M</td><td>January 6, 2010</td><td>Grantsville, MD</td><td>United States</td><td>A</td><td>LOC-I</td><td>TURB</td><td>N</td></tr>
<tr><td colspan="9">The accident aircraft experimented strong windshear and turbulence during the referred operation through a mountain range, even though these phenomena were not forecasted. This led to sudden unsteady behavior and violent agitation of the aircraft that led to an impact with the ground. These conditions are common in mountainous environments, and can be compared with those encountered in urban areas with a large concentration of high-capacity buildings and skyscrapers.</td></tr>
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<tr><td>CEN15LA288</td><td>N311RL</td><td>June 28, 2015</td><td>South Timbalier 127 Prospect, Offshore LA</td><td>United States</td><td>A</td><td>LOC-G</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">During a routinary departure from an oil rig platform, 1 hour after having landed on the same site, the helicopter experienced major wind forces due to the heavy gust conditions at the moment that pushed the aircraft from the platform and into the sea. At the moment of the incident, the blades were turning freely but the engine had not yet reached enough RPM to even be considered idle speed. The failure on monitoring the windy conditions at the time of departure and failure on deciding to abort were considered the main causes.</td></tr>
<tr><td>ASN151250</td><td>PK-BAT</td><td>March 4, 2003</td><td>Jakarta</td><td>Indonesia</td><td>A</td><td>LOC-G</td><td>-</td><td>N</td></tr>
<tr><td colspan="9">A privately owned helicopter crashed into a swimming pool while attempting to land on the rooftop of a hotel, seventeen floors above. Witnesses claimed wind conditions were strong. The aircraft touched down before a heavy gust of wind destabilized it and rolled over the edge of the platform, plunging into the lower floors.</td></tr>
<tr><td>LAX99LA293</td><td>N59551</td><td>September 1, 1999</td><td>Delhi, CA</td><td>United States</td><td>A</td><td>SCF</td><td>LOC-I</td><td>Y</td></tr>
<tr><td colspan="9">An engine failure during an early stage of departure forced the PIC to perform an autorotative descent at low altitude and with low RPM due to the lack of thrust. Furthermore, the aircraft was overflying a grove of trees when the engine failed, therefore forcing the pilot to alter the angle of descent and loss even more RPM. The overall lack of stored energy led to a hard landing and following rollover.</td></tr>
<tr><td>A010/CENIPA/2013</td><td>PR-JBN</td><td>January 21, 2013</td><td>São Paulo</td><td>Brazil</td><td>A</td><td>CFIT</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">This itinerary was intended to be a low-altitude operation for sightseeing purposes. Eventually, the aircraft flew backwards for inspection of an area of interested, and experienced a combination of an abrupt increase of the angle of attack and a loss of lift. This led to an uncontrolled descent, an impact with a low-tension electric wiring and subsequent crash on the roof of two houses. The investigation revealed that the aircraft was performing a OGE hover before flying rearwards while the incident wind was inside the critical wind quadrant relative to the plane of the main rotor, which increased the induced drag on the main rotor. This, combined with the tendency of OGE to deteriorate lift, led to an unstable situation.</td></tr>
<tr><td>ARAIB/AAR-1307</td><td>HL9294</td><td>November 16, 2013</td><td>Seoul</td><td>South Korea</td><td>A</td><td>CFIT</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">A private company-owned helicopter was operated under conditions, with intense fog and low visibility. The difficult conditions should have been enough to cancel the flight, but it was conducted anyways. Furthermore, the itinerary was conducted following special VFR, which allowed the aircraft to be operated in VFR as long as it was flown following the designated corridor and inside the controlled area. During the descent phase towards the designated heliport, the lack of visibility of the landing pad caused the pilot to loss situational awareness and deviate from the original path, colliding with a high-residential building.</td></tr>
<tr><td>IAD05MA078</td><td>N317MY</td><td>June 17, 2005</td><td>New York, NY</td><td>United States</td><td>A</td><td>LOC-I</td><td>CFIT</td><td>Y</td></tr>
<tr><td colspan="9">The involved helicopter was performing a departure from the helipad, located at ground level. The gusty wind, coming from the west, was initially blocked by the nearby buildings. Unaware, the PIC performed the take-off and turned towards the north. As the aircraft departed and left the influence of the mentioned buildings, it encountered a left quartering tailwind. Because it was still in an early transition from OGE to forward flight, with an airspeed below ETL, the aircraft experienced a settle with power. The loss of lift capability on the main rotor and the low altitude and airspeed at the moment of the accident left no room for recovery, and the aircraft dropped into the water.</td></tr>
<tr><td>LAX93FA093</td><td>N3202A</td><td>January 12, 1993</td><td>Hayward, CA</td><td>United States</td><td>A</td><td>CFIT</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">The helicopter was operated at night under difficult conditions in terms of visibility, including low ceiling and intense fog and rain. Because of the limited ground references available, the aircraft left the planned path multiple times in order to find a known reference to follow. The aircraft was not certified to fly IFR, but the flight was conducted anyway even though the crew was aware of the IMC. The PIC descended too much looking for a ground reference or became disoriented, and eventually struck the water.</td></tr>
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<tr><td>AAR7709</td><td>N619PA</td><td>May 17, 1977</td><td>New York, NY</td><td>United States</td><td>A</td><td>SCF</td><td>LOC-G</td><td>N</td></tr>
<tr><td colspan="9">After successfully landing on the roof pad of the former Pan Am Building, the aircraft flipped over caused by malfunction on side landing gear. The main rotor blade shattered as it touched the ground and directly caused 4 fatalities and 5 injuries. Rotor debris fell to the street level, hitting one facade of the building and another of the adjacent one on its way down and killing one pedestrian. Consequent glass pieces and debris added several more injuries.
First responders and evacuation efforts were delayed due to elevators shutdown on upper floors. The accident happened after finished disembarking and beginning the new boarding. None of the nine persons already aboard were hurt when the aircraft tipped over, and they all got out through emergency exits and doors on the left side, which faced skyward.
Engines were not turned off during the brief three-minute turnaround of the service. It was standard procedure to have the rotors going at their normal 1,000 revolutions-per-minute speed during the turnaround period.
Several struts of the right landing gear snapped. No wind-related factors were believed to be the trigger.</td></tr>
<tr><td>DFW08CA064</td><td>N2364B</td><td>February 8, 2008</td><td>Houston, TX.</td><td>United States</td><td>A</td><td>LOC-I</td><td>LOC-G</td><td>Y</td></tr>
<tr><td colspan="9">The pilot was performing a prolonged hover maneuver when experienced VRS and began to settle uncommanded. The slow reaction and small margin with the ground led to a hard landing and subsequent rollover.</td></tr>
<tr><td>CEN12FA621</td><td>N281RG</td><td>September 10, 2012</td><td>Houston, TX</td><td>United States</td><td>A</td><td>SCF</td><td>-</td><td>N/A</td></tr>
<tr><td colspan="9">The aircraft allegedly experienced a sudden loss of power due to an engine failure of unknown nature. The pilot, flying at 70 to 100 feet above ground at the time of the emergency, could not regain control of the aircraft, and tried to perform an autorotation, unsuccessfully. Witnesses claim main rotor RPM were atypically low and the tail rotor was not spinning during the emergency descent, which leads to the understanding that the pilot was not able to recover RPM and lost vertical control. Weather this was due to pilot misstep or aircraft incapacity to deliver could not be determined.</td></tr>
<tr><td>CEN18FA391</td><td>N907PL</td><td>September 28, 2018</td><td>Gustavus, AK</td><td>United States</td><td>A</td><td>LOC-I</td><td>-</td><td>Y</td></tr>
<tr><td colspan="9">In this case, the aircraft was approaching a coastal shore in a steep path right after a brief hover at around 700 ft. The PIC supposedly decided to perform an autorotation practice maneuver, lowering the thrust lever to IDLE and reducing drastically the main rotor RPM. However, the pitch on the rotor blades was not decreased, therefore not being able to recover and operate inside the safe margins. The aircraft lost uncontrollably and exponentially more power as it lost altitude, and the PIC failed to counteract this situation. The aircraft impacted the water moments later and got destroyed.</td></tr>
<tr><td>CEN16LA168</td><td>N435AE</td><td>April 25, 2016</td><td>Houston, TX</td><td>United States</td><td>I</td><td>LOC-I</td><td>-</td><td>N</td></tr>
<tr><td colspan="9">This aircraft, operating a medical-related flight, departed from a confined landing pad. Wind was blowing from the south-east. As the aircraft overcome the surrounding buildings and translated towards the south to be oriented towards the prevailing wind, it began to yaw and spin to the right uncontrollably. It experienced an induced LTE probably caused by a main rotor disk interference. The wind pushed the dirty air and vortices generated from the main-rotor into the tail-rotor, preventing the tail rotor from having clean air to propel and losing performance. The PIC tried to control the aircraft and stop the spin while moving back to the helipad. A hard but successful landing put an end to this flight, claiming no victims.</td></tr>
<tr><td>LAX02LA161</td><td>N577TA</td><td>May 13, 2002</td><td>Phoenix, AZ</td><td>United States</td><td>I</td><td>LOC-I</td><td>-</td><td>N</td></tr>
<tr><td colspan="9">In this case, the aircraft was performing an autorotation maneuver for practice purposes. The operation consisted in a steep, right turning autorotation with near-zero forward displacement. Starting from a OGE hover, the maneuver was performed without incidents until reaching the last 200 ft, when executing the flare. The aircraft encountered a change in the wind direction, which restrained it from receiving any forward airspeed. This, combined with the still OGE state of flight, led to a VRS and sudden settle of the aircraft to the ground. The investigation reported a failure from the PIC to maintain an adequate airspeed, and identified the high-density altitude as a relevant external factor.</td></tr>
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EW/G2016/07/05	G-VGMG	July 11, 2016	Bideford	United Kingdom	A	LOC-I	LOC-G	Y
During a routinary practice approach, the aircraft was descending following a downwind path. The PIC, however, applied too much cyclic as it reached the touch-down zone, pitching the aircraft beyond the necessary and critically losing airspeed. This led to an LTE situation, which was corrected by applying power to the rotor to counteract and pitching down to regain the necessary speed. However, the aircraft was too close to the ground and impacted the ground. A post-impact loss of control in ground led to an abnormal rest position of the aircraft.								
EW/G2018/05/15	G-RMAA	May 3, 2018	Wolverhampton	United Kingdom	A	CTOL	-	Y
This medical service flight was about to take-off from a parking lot after picking up a patient. As it gained sufficient lift to perform a low hover as an initial departure, and it became light on the skids, the aircraft yawed uncommanded to the left due to a lack of proper adjustment of its anti-torque system. This resulted in a tail impact with a nearby wall, and the partial damage of the aircraft.								
EW/G2015/11/08	G-NWPS	November 25, 2015	Bilsdale	United Kingdom	I	MAC	-	N
On the final approach, while performing a low hover to land, the helicopter's downwash disturbed a metallic foreign object from the pad and threw it into the Fenestron tail rotor. The damage caused, though serious, was not critical, and allowed for the pilot to recover and land safely. Vibrations on the rotor flight controls were reported.								
ASN56469	165436	April 8, 2000	Tucson, AZ	United States	A	LOC-I	-	Y
The tilt-rotor aircraft, property of the United States Marines Corps and operated by the Marine Helicopter Squadron One (HMX-1) during a training exercise, was approaching the landing zone simulating an evacuation operation. An unexpected tail wind of 8-10 kts, added to the aircraft's low forward airspeed at the moment and the great rate of descent and steep approach that was taken into the landing zone, induced a vortex ring state. This resulted in an asymmetrical loss of lift (stall) in the two rotors, resulting in a loss of controlled flight. Four air crew members and 15 passengers were killed when the aircraft impacted the ground.								