Methodology for structuring of collected technical rules, standards and procedures – first release

D2.1

AW-Drones

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AW-Drones

Abstract

This document describes the methodology to systematically structure the collected standards. It is the output of task 2.1 of WP2.

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Acronyms

ARC	Air Risk Class
ATM	air-traffic management
BCG	Boston Consultancy Group
BLOS	Beyond Line-Of-Sight
BVLOS	Beyond Visual Line-Of-Sight
EASA	European Aviation Safety Agency
EC	European Commission
FAA	Federal Aviation Administration
FL	Flight Level
GNSS	Global Navigation Satellite Systems
ICAO	International Civil Aviation Organization
kg	Kilogram
LUC	light UAS operator certificate
MTOM	Maximum Take-Off Mass
RPAS	Remotely Piloted Air System
SORA	Specific Operational Risk Assessment
TMZ	Transponder Mandatory Zones
UKAB	UK Airprox Board
UA	Unmanned Aircraft
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle.

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USD	United States Dollar
VLOS	Visual Line Of Sight.
VTOL	Vertical Take-Off and Landing

1 Introduction

1.1 Purpose of this document

The purpose of this document is to describe the methodology to systematically structure the collected standards in WP3. It is the output of task 2.1.

For clarity a short description of the criteria to assess the standards (to be developed in task 2.2 and to be described in D2.2) is included.

1.2 Validation of methodology

The proposed methodology will be validated with external stakeholders during the first workshop.

1.3 Content of this document

Section 2 describes a high level drone risk model that is used within the methodology
Section 3 describes the methodology for structuring the standards.

Appendix A describes drone events that could result in injuries, fatalities or damage.
Appendix B describes the severities of drone events.
Appendix C describes classes of drones and categories of drone operations.
Appendix D describes the domains used in the EUSCG Rolling Development Plan.

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2 High level drone accident risk model

In this section a high level drone accident risk model is described. This risk model is used within the methodology for structuring the standards described in section 3.

Note: colours are used in the text to enhance readability:

- Drone class related factors are denoted in yellow
- Category of drone operation related factors are denoted in blue
- Functional failures are denoted in pink
- Decision making errors are denoted in green

First drone events that could result in fatalities or injuries to people on the ground or to occupants of manned aircraft, or damage to critical infrastructure / objects, have been identified (see section 2.1).

Then the severities of these drone events have been determined (see section 2.2).

Subsequently for each event, the high-level factors that contribute to the probability of occurrence or the severity of the event have been identified (see section 2.3). These factors include drone class related factors, category of drone operation related factors, functional failures and decision making errors. What these mean is explained in section 2.3,
Finally generic causes of functional failures and decision making errors have been identified (see section 2.4).

2.1 Identification of drone events

Generic drone events that could result in fatalities or injuries to people on the ground or to occupants of manned aircraft, or could results in critical damage to critical infrastructure / objects, have been identified from literature and expert judgement. See Appendix A for details. These events are:

1. A drone hitting people;
2. Debris from a disintegrated drone hitting people;
3. The hand of a person coming into contact with moving rotors;
4. A drone hitting critical infrastructure / objects;
5. Debris from a disintegrated drone hitting critical infrastructure / objects;
6. Collision of a drone with a manned aircraft.

2.2 Identification of severity of drone events

Severities of drone events have been determined from literature. See Appendix B for details. The main findings are listed below.

Drone hitting people

Even a 250 gram drone can cause a fatality when falling down:

- from 150 ft the probability of a fatality when such a drone hits a person is 10%
- from 400 ft the probability of a fatality when such a drone hits a person is 100%

Drone hitting critical infrastructure / objects

No data is available from literature.

Collisions of drone with manned aircraft

Large aircraft (> 5700 kg)

When a drone from the EASA Open Category hits a large aircraft (such as an airliner), a statistical 7% of collisions are against the windshield which is not designed to withstand collisions with high density solid objects. This could results in death of the pilot(s).

A statistical 76% of collisions are against the engine which is not designed to withstand collisions with high density solid objects. This could result in engine failure which is not catastrophic by itself, but reduces the safety level of the remainder of the flight and the safety of air transport in general if it happens frequently.

Collisions against the wing or fuselage could result in loss of fuel, which could be catastrophic if it happens at an unfavourable moment during the flight (e.g. somewhere over the Atlantic). An aircraft is not designed to cope with an arbitrary loss of fuel (for airliners only the loss of fuel from tanks within the engine rotor burst spread zone is considered).
A specific collision against a an engine collector tank in the wing would result in loss of thrust from one engine which is not catastrophic by itself, but reduces the safety level of the remainder of the flight and the safety of air transport in general if it happens frequently.

General Aviation aircraft (< 5700 kg)

When a drone from the EASA Open Category hits a general aviation aircraft, a statistical 56% of collisions are against the windshield which is not designed to withstand collisions with high density objects. This could results in death of the pilot(s).

A statistical 12% of collisions are against the engine which is not designed to withstand collisions with high density solid objects. This could result in engine failure which in case of

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single-engine aircraft could be catastrophic. For twin-engine aircraft engine failure is not catastrophic by itself, but reduces the safety level of the remainder of the flight and the safety of general aviation in general if it happens frequently.

Collisions against the wing or fuselage could result in loss of fuel, which could be catastrophic if it happens at an unfavourable moment during the flight. An general aviation aircraft is not designed to cope with an arbitrary loss of fuel.
A specific collision against an engine collector tank would result in loss of thrust from one engine which in case of single-engine aircraft could be catastrophic. For twin-engine aircraft engine failure is not catastrophic by itself, but reduces the safety level of the remainder of the flight and the safety of general aviation in general if it happens frequently.

2.3 Identification of factors that contribute to probability of occurrence and severity of drone events

Safety risk is the probability of occurrence of an event x the severity of its effect.

For each event identified in section 2.1, the high-level factors that contribute to the probability of occurrence or severity of the event have been identified by expert judgement.
Factors include drone class related factors, category of drone operation related factors, functional failures and decision making errors.

Functions include functions for detecting extreme environmental conditions.
Decision making includes decisions to avoid extreme environmental conditions.
See below for further details about what is included in the various factors.

Event 1: A drone hitting people

For all drones:

The probability that a person (including the remote pilot) gets hit by a drone is determined by:

- Probability of drone crashing due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits
- The drone crash location distribution in case of loss of control (dependent on type of drone, speed, range, measures that reduce the probability of a drone fly-away out of the area of operation)
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation)

For drones that are intended to operate in the vicinity of people:

The probability that a person (including the remote pilot) gets hit by a drone is determined by:

- Probability of a collision course with a person

- Probability of failure of localisation of people due to failure of localisation of people OR failure to detect environmental conditions that those that are required for localisation of people OR failure to avoid environmental conditions that exceed those that are required for localisation of people
- Probability of failure to steer away due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to steer away from person

The severity of a drone hitting people (e.g. injury, serious injury, fatality) is determined by:
- Kinetic energy, frangibility, sharp edges and flammability
- The probability that the drone hits a certain area of the human body (which is also dependent on the size of the drone)

Event 2: Debris from a disintegrated drone hitting people

For all drones:

The probability that a person (including the remote pilot) gets hit by debris is determined by:
- Probability of in-flight break-up due to structural failure (including rotor failure) OR failure to detect environmental conditions that exceed structural limits OR failure to avoid environmental conditions that exceed structural limits
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation)

For drones that operate in U-Space:

The probability that a person (including the remote pilot) gets hit by debris is determined by:
- Probability of a collision course with another drone that has the right of way (dependant on drone traffic density)
- The probability of failure of localisation of other drone due to failure of localisation of other drone OR failure to detect environmental conditions that those that are required for localisation of other drone OR failure to avoid environmental conditions that exceed those that are required for localisation of other drone
- Probability of failure to steer away due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to steer away from drone
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation)

For drones that operate in manned-aircraft airspace:

The probability that a person (including the remote pilot) gets hit by debris is determined by:

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- The probability of collision with another aircraft (see event 6 for details)
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation)

The severity of debris from a disintegrated drone hitting people (e.g. injury, serious injury, fatality) is determined by:

- Kinetic energy, frangibility, sharp edges and flammability
- The probability that the fragments a certain area of the human body (which is also dependent on the size of the drone)

Event 3: The hand of a person coming into contact with moving rotors

For drones that are intended to operate in the vicinity of people:

The probability that a person inadvertently grasps a moving rotor is determined by:

- The time that the drone is in the vicinity of people especially those who are not aware of the risk (e.g. children)
- The specific shielding of the rotors

The severity of a hand coming into contact with moving rotors (e.g. injury, serious injury, fatality) is determined by:

- Kinetic energy of the rotor

Event 4: A drone hitting critical infrastructure / objects

- Similar to event 1

Event 5: Debris from a disintegrated drone hitting critical infrastructure / objects

- Similar to event 2

Event 6: Collision of a drone with a manned aircraft

For drones that operate in U-Space:

The probability of a collision with a manned aircraft is determined by:

- Probability of a manned airspace infringement due to failure of localisation of manned-aircraft airspace OR failure of drone to follow the planned (by decision making) flight trajectory – flyaway failure mode OR failure to steer away from manned-aircraft airspace
- Probability of a collision course with manned aircraft (dependant on manned aircraft traffic density)
- Probability that ATC does not timely detect the drone (e.g. through radar) (in case ATC is responsible for separation from other aircraft):
- Probability that pilot does not does not timely detect drone (e.g. through See and Avoid and/or TCAS)

For drones that operate in manned-aircraft airspace with remote pilot being responsible for separation:

The probability of a collision with a manned aircraft is determined by:

- Probability of a collision course with a manned aircraft that has the right of way (dependant on manned aircraft traffic density)
- Probability of failure of localisation of aircraft - for remain well clear due to failure of localisation of aircraft - for remain well clear OR failure to detect environmental conditions that those that are required for localisation of aircraft – for remain well clear OR failure to avoid environmental conditions that exceed those that are required for localisation of aircraft – for remain well clear
- Probability of failure to perform remain well clear manoeuvre due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to perform remain well clear manoeuvre
- Probability of failure of localisation of aircraft - for collision avoidance due to failure of localisation of aircraft - for collision avoidance OR failure to detect environmental conditions that those that are required for localisation of aircraft – for collision avoidance OR failure to avoid environmental conditions that exceed those that are required for localisation of aircraft – for collision avoidance
- Probability of failure to perform collision avoidance manoeuvre due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to perform collision avoidance manoeuvre
- Probability of failure of collision avoidance of other aircraft

For drones that operate in manned-aircraft airspace with ATC being responsible for separation:

The probability of a collision with a manned aircraft is determined by:

- Probability of a collision course with a manned aircraft that has the right of way (dependant on manned aircraft traffic density)
- Probability of failure to comply with ATC instructions due to failure of communication with ATC or failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to execute ATC instruction
- Probability of failure by ATC to redirect manned aircraft
- Probability of failure of localisation of manned aircraft - for collision avoidance due to failure of localisation of manned aircraft - for collision avoidance OR failure to detect environmental conditions that those that are required for localisation of aircraft – for collision avoidance OR failure to avoid environmental conditions that exceed those that are required for localisation of aircraft – for collision avoidance

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- Probability of failure to perform collision avoidance manoeuvre due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to perform collision avoidance manoeuvre
- Probability of failure of collision avoidance of other aircraft

The severity of the effect of a collision with a manned aircraft (e.g. damage, serious injuries, fatalities) is determined by:

- Kinetic energy and frangibility
- The probability that the drone hits a certain area of the aircraft (which is also dependent on the size of the drone)

2.4 Generic causes of functional failures and decision making errors

Functions are implemented by technical systems or can be performed by the remote pilot.

Decision making tasks are performed by automation (a technical system) or by the remote pilot.

In case a function is (partly) implemented by a technical system, generic causes of functional failures are:

- Technical failures
- Design errors leading to a higher than nominal failure rate
- Maintenance errors leading to a higher than nominal failure rate

And if the technical system needs to be controlled by the remote pilot:

- Remote pilot incapacitation
- Remote pilot system control errors (including exceeding the performance limits of the technical system)
- Technical failures of the system control HMI
- Design errors of the system control HMI leading to a higher than nominal failure rate + inadequate system control HMI design leading to remote pilot system control errors
- Maintenance errors of the system control HMI leading to a higher than nominal failure rate

In case a function is (partly) performed by the remote pilot, generic causes of functional failures are:

- Remote pilot incapacitation
- Remote pilot performance errors

In case a decision making task is (partly) performed by automation (a technical system), generic causes of decision making task errors are:

- Technical failures
- Design errors leading to a higher than nominal failure rate
- Maintenance errors leading to a higher than nominal failure rate

In case a decision making task is (partly) performed by the remote pilot, generic causes of decision making task errors are:

- Remote pilot incapacitation
- Remote pilot perception, decision making or 'take action' errors
- Technical failures of the perception HMI
- Design errors of the perception HMI leading to a higher than nominal failure rate + inadequate perception HMI design leading to remote pilot perception errors
- Maintenance errors of the perception HMI leading to a higher than nominal failure rate

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3 Methodology for structuring the standards

In this section the methodology for structuring the standards is described.
For additional clarification an example of the application of the methodology is given in section 3.1.

Note: colours are used in the text to enhance readability:

- Drone class related factors are denoted in yellow
- Category of drone operation related factors are denoted in blue
- Functional failures are denoted in pink
- Decision making task errors are denoted in green

Step 1:

The applicable sets of factors that contribute to drone accident risks for the category of drone operation at interest will be taken from section 2.3.

Step 2:

For the class of drone at interest the maximum allowable failure rates of the applicable functions and the maximum allowable error rates of the applicable decision making tasks to achieve a certain target level of safety will be calculated. The severities of events identified in section 2.2 will be considered for the calculation.

The determination of a target level of safety is outside the scope of the AW Drones project. Therefore a certain target level of safety will be assumed.

Note for steps 1 and 2:
It has been agreed to initially focus on the EASA Specific Category in terms of class of drone (see Appendix C) and category of drone operation (see Appendix C) to be considered, with a limitation to SAIL IV.

Step 3:

Specific implementations of a function or decision making task will be identified from the standards (standards correspond with a specific implementation of a function or decision making task by technical systems and/or the remote pilot) and by expert judgement.

Step 4:

For a specific implementation of a function or decision making task the causes of failures of the function or errors of the decision making task will be identified using the generic causes from section 2.4.

Step 5:

In order to achieve a maximum allowable failure rate of a function or a maximum allowable error rates of a decision making task, for a specific implementation the probabilities of occurrence of the causes (see step 4) of failures of the function or errors of the decision making task must be below certain levels.

Per specific implementation of a function or decision making task the allowed probabilities of occurrence of the causes of failures of the function or errors of the decision making task will be calculated.

Step 6:

Standards are aimed at preventing the causes of failures of a function or errors of a decision making tasks from occurring too frequently.
Per specific implementation of a function or decision making task the standards that are aimed at ensuring the maximum allowable probabilities of occurrence of the identified (in step 5) causes of failures of the function or of errors of the decision making task will be identified.

Missing standards (gaps) will be identified.

The domains used in the Rolling Development Plan (see 8) will be used to facilitate the search for applicable standards (as agreed during the kick-off meeting, the identified standards will initially be categorised by WP3 according to the domains used in the Rolling Development Plan EUSCG-054 Version 2.0).

When required by the level of detail of the collected technical rules, standards and procedure, standards will be identified specifically for certain drone configurations (such as fixed wing, rotorcraft, aerostats etc.) and control configurations (such as required for VLOS/ BVLOS, level of automation etc.).

Methodology for assessing the standards

For clarity a short description of the methodology for assessing the standards is given below:
The assessment criteria will be developed in task 2.2 and will be described in deliverable D2.2.

Step 7:

The level of compliance of the identified standards with the maximum allowed probabilities of occurrence of the causes of failures of the functions or errors of the decision making tasks (as identified in step 5) will be assessed by using the criteria developed in task 2.2.

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Step 8:

Finally the standards will be assessed using the full set of assessment criteria developed in task 2.2:

- Criteria for assessment of correctness of the standards (e.g. an indication of the stage within the relevant standardisation bodies processes);
- Criteria that take into account the various stakeholders inputs per type of drone operation; Criteria will be inspired by the EASA pre-RIA process. Possible criteria include: safety effectiveness, ease of adoption: economic, regulatory harmonization, social acceptance, global acceptance, environmental impact.

3.1 Example of application of the methodology

In this section an example (covering steps 1 to 6) is given of the application of the methodology for:

Drone Class:
A drone of 2 kg with a maximum attainable height of 120 m

Category of drone operation
- Operation over uninvolved people but not over crowds.
- Operation in U-Space.
- An average number of drone flights over an area of 1 km^2 of 1 per hour.

Step 1

The applicable drone events and sets of factors that contribute to drone accident risks that are applicable for this category of drone operation are:

Event 1: Drone hitting people

For all drones:

The probability that a person (including the remote pilot) gets hit by a drone is determined by:
- Probability of drone crashing due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits
- The drone crash location distribution in case of loss of control (dependent on type of drone, speed, range, measures that reduce the probability of a drone fly-away out of the area of operation)
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation)

The severity of a drone hitting people (e.g. injury, serious injury, fatality) is determined by:
- Kinetic energy, frangibility, sharp edges and flammability
- The probability that the drone hits a certain area of the human body (which is also dependent on the size of the drone)

Event 2: Debris from disintegrated drone hitting people

For all drones:

The probability that a person (including the remote pilot) gets hit by debris is determined by:

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- Probability of in-flight break-up due to structural failure (including rotor failure) OR failure to detect environmental conditions that exceed structural limits OR failure to avoid environmental conditions that exceed structural limits
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation)

For drones that operate in U-Space:

The probability that a person (including the remote pilot) gets hit by debris is determined by:
- Probability of a collision course with another drone that has the right of way (dependant on drone traffic density)
- The probability of failure of localisation of other drone due to failure of localisation of other drone OR failure to detect environmental conditions that those that are required for localisation of other drone OR failure to avoid environmental conditions that exceed those that are required for localisation of other drone
- Probability of failure to steer away due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to steer away from drone
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation)

The severity of debris from a disintegrated drone hitting people (e.g. injury, serious injury, fatality) is determined by:
- Kinetic energy, frangibility, sharp edges and flammability
- The probability that the fragments a certain area of the human body (which is also dependent on the size of the drone)

Event 4: Drone hitting critical infrastructure / objects

- Similar to event 1

Event 5: Debris hitting critical infrastructure / objects

- Similar to event 2

Event 6: Collision of drone with manned aircraft

For drones that operate in U-Space:

The probability of a collision with a manned aircraft is determined by:
- Probability of a manned airspace infringement due to failure of localisation of manned-aircraft airspace OR failure of drone to follow the planned (by decision making) flight trajectory – flyaway failure mode OR failure to steer away from manned-aircraft airspace
- Probability of a collision course with manned aircraft (dependant on manned aircraft traffic density)

- Probability that ATC does not timely detect the drone (e.g. through radar) (in case ATC is responsible for separation from other aircraft):
- Probability that pilot does not does not timely detect drone (e.g. through See and Avoid and/or TCAS)

The severity of the effect of a collision with a manned aircraft (e.g. damage, serious injuries, fatalities) is determined by:

- Kinetic energy and frangibility
- The probability that the drone hits a certain area of the aircraft (which is also dependent on the size of the drone)

Step 2

The allowable failure rates of the applicable functions and decision making tasks are calculated.

For this example only the risks for individuals on the ground will be considered. This covers events 1 and event 2.

Assumption for target level of safety for individuals on the ground:

- The probability of getting killed by a drone should be less than 1 per million years per inhabitant of a country.

Additional assumption:

- The horizontal area of person occupies is approximately 0.1 m^2.

Event 1: Drone hitting people

The probability that a person (including the remote pilot) gets hit by a drone is determined by:

- Probability of drone crashing due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits
- The drone crash location distribution in case of loss of control (dependent on type of drone, speed, range, measures that reduce the probability of a drone fly-away out of the area of operation)
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation)

It is assumed that the drone will crash at an arbitrary location in the area.

Given the mass and maximum height of the drone, the severity of the effect is assumed to be fatal (see section 2.2).

For one person in the area the risk per hour of getting killed

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=

[failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability per flight hour] x probability that drone hits the person

=

[failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability per flight hour] x 0.1 m^2 / 1 km^2

=

[failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability per flight hour] x 10^{-7}

For one person in the area the risk per million years of getting killed

=

24 hours x 365 days x 1 million years x [failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability per flight hour] x 10^{-7}

=

10^3 x [failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability per flight hour]

Event 2: Debris from disintegrated drone hitting people

The probability that a person (including the remote pilot) gets hit by debris is determined by:

- Probability of in-flight break-up due to structural failure (including rotor failure) OR failure to detect environmental conditions that exceed structural limits OR failure to avoid environmental conditions that exceed structural limits
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation)

It is assumed that the drone will disintegrate at an arbitrary location in the area.

Given the expected mass of the fragments, the severity of the effect is assumed to be fatal (see section 2.2).

For one person in the area the risk per hour of getting killed

=

[structural failure (including rotor failure) OR failure to detect environmental conditions that exceed structural limits OR failure to avoid environmental conditions that exceed structural limits per flight hour] x probability that drone hits the person

=

[structural failure (including rotor failure) OR failure to detect environmental conditions that exceed structural limits OR failure to avoid environmental conditions that exceed structural limits per flight hour] x 0.1 m^2 / 1 km^2
=
[structural failure (including rotor failure) OR failure to detect environmental conditions that exceed structural limits OR failure to avoid environmental conditions that exceed structural limits per flight hour] x 10^{-7}

For one person in the area the risk per million years of getting killed
=
24 hours x 365 days x 1 million years x [structural failure (including rotor failure) OR failure to detect environmental conditions that exceed structural limits OR failure to avoid environmental conditions that exceed structural limits per flight hour] x 10^{-7}
=
10^3 x [structural failure (including rotor failure) OR failure to detect environmental conditions that exceed structural limits OR failure to avoid environmental conditions that exceed structural limits per flight hour]

The probability that a person (including the remote pilot) gets hit by debris is determined by:

- Probability of a collision course with another drone that has the right of way (dependant on drone traffic density)
- The probability of failure of localisation of other drone OR failure to detect environmental conditions that those that are required for localisation of other drone OR failure to avoid environmental conditions that exceed those that are required for localisation of other drone
- Probability of failure to steer away due to failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to steer away from drone
- Probability of a person present at the location of the drone crash (dependant on population density in the relevant area outside and inside buildings at the time of the drone operation

It is assumed that the drone will collide at an arbitrary location in the area.

Given the mass the drone, the severity of the effect is assumed to be fatal (see section 2.2)

For one person in the area the risk per hour of getting killed
=
Probability of a collision course with another drone that has the right of way x [failure of localisation of other drone OR failure to detect environmental conditions that exceed those that are required for localisation of other drone OR failure to avoid environmental conditions that exceed those that are required for localisation of other drone OR failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that

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exceed drone controllability limits OR failure to steer away from drone per flight hour] x 0.1 m^2 / 1 km^2

For one person in the area the risk per million years of getting killed
=
24 hours x 365 days x 1 million years x probability of a collision course with another drone that has the right of way x [failure of localisation of other drone OR failure to detect environmental conditions that exceed those that are required for localisation of other drone OR failure to detect environmental conditions that exceed those that are required for localisation of other drone OR failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to steer away from drone per flight hour] x 0.1 m^2 / 1 km^2
=
10^3 x probability of a collision course with another drone that has the right of way x [failure of localisation of other drone OR failure to detect environmental conditions that exceed those that are required for localisation of other drone OR failure to avoid environmental conditions that exceed those that are required for localisation of other drone OR failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits OR failure to steer away from drone per flight hour]

Combined risk from events 1 and 2

The combined risk of a person on the ground killed by a drone in 1 million years is:

10^3 x [failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to avoid environmental conditions that exceed drone controllability limits per flight hour]

+

10^3 x [structural failure (including rotor failure) OR failure to detect environmental conditions that exceed structural limits OR failure to avoid environmental conditions that exceed structural limits per flight hour]

+

10^3 x probability of a collision course with another drone that has the right of way x [failure of localisation of other drone OR failure to detect environmental conditions that exceed those that are required for localisation of other drone OR failure to avoid environmental conditions that exceed those that are required for localisation of other drone OR failure of drone to follow the planned (by decision making) flight trajectory OR failure to detect environmental conditions that exceed drone controllability limits OR failure to detect environmental conditions that exceed drone controllability limits OR failure to steer away from drone per flight hour]

The total figure should be less than 1. This determines, depending on the probability of a collision course with another drone that has the right of way, the maximum allowed rates of failure of the applicable functions and decision making tasks.

Step 3

Specific implementations of the applicable functions must be identified.
The applicable functions are:

- Follow the planned (by decision making) flight trajectory
- Detect environmental conditions that exceed drone controllability limits
- Structural integrity
- Detect environmental conditions that exceed structural limits
- Localisation of other drones
- Detect environmental conditions that exceed those that are required for localisation of other drones

Specific implementations of the applicable functions must be identified.
The applicable decision making tasks are:

- Avoid environmental conditions that exceed drone controllability
- Avoid environmental conditions that exceed structural limits
- Avoid environmental conditions that exceed those that are required for localisation of other drones
- Steer away from other drones

As an example:

An implementation of the localisation of other drones function could be

- On-board sensor
- Datalink that sends the drone location to a display on the ground
- Display that provides the drone location
- Remote pilot that gathers the drone location from the display

An implementation of the steer away from other drones decision making task could be:

- Remote pilot who decides to steer away and takes action

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Step 4

Generic causes of functional failures and decision making errors are taken from section 2.4 and applied to the implementation of the localisation of other drones function and steer away from other drones decision making task:

Localisation of other drones function:

- On-board sensor:
    - Technical failures
    - Design errors leading to a higher than nominal failure rate
    - Maintenance errors leading to a higher than nominal failure rate
- Datalink that sends the drone location to a display on the ground
    - Technical failures
    - Design errors leading to a higher than nominal failure rate
    - Maintenance errors leading to a higher than nominal failure rate
- Display that provides the drone location
    - Technical failures
    - Design errors leading to a higher than nominal failure rate
    - Maintenance errors leading to a higher than nominal failure rate
- Remote pilot that gathers the drone location from the display
    - Remote pilot incapacitation
    - Remote pilot performance errors

Steer away from other drones decision making task:

- Remote pilot who decides on the flight path
    - Remote pilot incapacitation
    - Remote pilot decision making or take action errors

Step 5

In order to achieve a maximum allowable failure rates of localisation of other drone function and maximum allowable error rate of steer away from other drones decision making task the probabilities of occurrence of the causes of failures of the function or errors of the decision making task identified in step 4 must be below certain levels.

Assuming a maximum allowable failure rate of localisation of other drone function of 10^{-3} per flight hour and a maximum allowable error rate of the steer away from other drones decision making task of 10^{-3} per flight hour, and dual on-board sensors, the following allowed probabilities of occurrence of the causes would apply:

Localisation of other drone function:

- Dual on-board sensor:
  - A sensor nominal failure rate below 3.3×10^{-2} per flight hour
  - A sensor design process that ensures a sensor failure rate below 10^{-3} per flight hour
  - A sensor maintenance process that ensures a sensor failure rate below 10^{-3} per flight hour
- Datalink that sends the drone location to the remote pilot HMI on the ground
  - A datalink nominal failure rate below 10^{-3} per flight hour
  - A datalink design process that ensures a datalink failure rate below 10^{-3} per flight hour
  - A datalink maintenance process that ensures a datalink failure rate below 10^{-3} per flight hour
- Display that provides the drone location
  - A display nominal failure rate below 10^{-3} per flight hour
  - A display design process that ensures a display failure rate below 10^{-3} per flight hour
  - A display maintenance process that ensures a display failure rate below 10^{-3} per flight hour
- Remote pilot that gathers the drone location from the display
  - Remote pilot medical examination & age restrictions that ensure an incapacitation rate below 10^{-3} per flight hour
  - Remote pilot selection & training that ensure a performance error rate below 10^{-3} per flight hour

Steer away from other drones decision making task:

- Remote pilot who decides on the flight path
  - Remote pilot medical examination & age restrictions that ensure an incapacitation rate below 10^{-3} per flight hour
  - Remote pilot selection & training that ensure a decision making or take action error rate below 10^{-3} per flight hour

Step 6

Now standards that are aimed at ensuring the maximum allowable probabilities of occurrence of the identified (in step 5) causes of failures of the function or of errors of the decision making task must be identified.

The domains used in the Rolling Development Plan (see Appendix D) can be used to facilitate the search for applicable standards. To illustrate this, the domains have been placed in *italics* behind the results from step 5:

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Localisation of other drones function:

- Dual on-board sensor:
  - A sensor nominal failure rate below 3.3 x 10^{-2} per flight hour
    - *Detect and Avoid*
  - A sensor design process that ensures a sensor failure rate below 10^{-3} per flight hour
    - *Manufacturer organisation, Development assurance (software)*
  - A sensor maintenance process that ensures a sensor failure rate below 10^{-3} per flight hour (*Maintenance organisation, Maintenance*)
- Datalink that sends the drone location to the remote pilot HMI on the ground
  - A datalink nominal failure rate below 10^{-3}per flight hour
    - *C3 datalink and communication*
  - A datalink design process that ensures a datalink failure rate below 10^{-3} per flight hour
    - *Manufacturer organisation, Development assurance (software)*
  - A datalink maintenance process that ensures a datalink failure rate below 10^{-3} per *flight hour*
    - *Maintenance organisation, Maintenance*
  - Display that provides the drone location
  - A display nominal failure rate below 10^{-3} per flight hour
    - *Ground control station, Human Machine Interface, Command, control and communication*
  - A display design process that ensures a display failure rate below 10^{-3} per flight hour
    - *Manufacturer organisation, Development assurance (software)*
  - A display maintenance process that ensures a display failure rate below 10^{-3} per flight hour
    - *Maintenance organisation, Maintenance*
- Remote pilot that gathers the drone location from the display
  - Remote pilot medical examination & age restrictions that ensure an incapacitation rate below 10^{-3} per flight hour
  - Remote pilot selection & training that ensure a performance error rate below 10^{-3} per flight hour
    - *Manuals, Remote pilot competence*

Steer away from other drones decision making task:

- Remote pilot who decides on the flight path
  - Remote pilot medical examination & age restrictions that ensure an incapacitation rate below 10^{-3} per flight hour
  - Remote pilot selection & training that ensure a decision making or take action error rate below 10^{-3} per flight hour
    - *Manuals, Remote pilot competence*

4 References

ATSB. (2017). *A safety analysis of remotely piloted aircraft systems.*

B. &. (2018). *Drone Operations: Today & Tomorrow, abridged electronic version.*

BBC. (2015, November 26). *BBC News*. Retrieved February 23, 2019, from https://www.bbc.com/news/uk-england-hereford-worcester-34936739

BBC. (2015, December 23). *BBC Sport*. Retrieved February 25, 2019, from https://www.bbc.com/sport/winter-sports/35164700

BBC. (2018, March 12). Retrieved February 22, 2019, from BBC: https://www.bbc.com/news/technology-43372494

BCG. (2017, April 10). Retrieved from https://www.bcg.com/publications/2017/engineered-products-infrastructure-machinery-components-drones-go-work.aspx

Board, N. T. (2017, December 14). Retrieved February 22, 2019, from https://app.ntsb.gov/pdfgenerator/ReportGeneratorFile.ashx?EventID=20170922X54600&AKey=1&RType=HTML&IType=IA

CAA. (2018). *Drone Safety Risk: An assessment.*

CASA. (2013). *Potential damage assessment of a mid-air collision with a small UAV.*

CBS. (2018, July 13). Retrieved February 22, 2019, from CBS Los Angeles: https://losangeles.cbslocal.com/2018/07/13/dog-attack-causes-pilot-to-crash-drone-and-start-fire/

Center, G. M. (2016). *Do Consumer Drones Endanger the National Airspace?*

Council, R. C. (2000). *Common Risk Criteria for National Test Ranges; Inert Debris.*

Cour-Harbo, A. L. (2017). Mass threshold for ’harmless’ drones. *International Journal of Micro Air Vehicles*.

Dalamagkidis, K., Valavanis, K. P., & Peigl, L. A. (2008). Evaluating the Risk of Unmanned Aircraft Ground Impacts. *16th Mediterranean Conference on Control and Automation.* Ajaccio, France.

DJI. (2019, January 9). *Indemnis Parachute For DJI Drones Meets Stringent New Safety Standard*. Retrieved February 18, 2019, from http://dl.djicdn.com/downloads/dropsafe/en/DJI_Dropsafe_User_Manual_v1.

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION’S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO. 824292.

EASA. (2014). *Regulation (EU) No 376/2014.*

EASA. (2016). *"Drone Collision" Task Force.*

EASA. (2017). *Annual Safety Review.*

EASA. (2017). *Research Programme On Collisions with Drones: Work Area 1 Final Report.*

EASA. (2018). *Annual Safety Review.*

EASA. (2018). *Proposed Special Condition for small-category VTOL aircraft, Doc. No: SC-VTOL-01 Issue: 1 (proposed).*

EASA. (2018). *Regulation (EU) 2018/1139.*

EASA. (n.d.). *Civil drones (Unmanned aircraft)*. Retrieved March 2019, from https://www.easa.europa.eu/easa-and-you/civil-drones-rpas

EASA. (July 2018). *Regulation (EU) 2018/1139.*

Eurocontrol. (2018). *UAS ATM Airspace Assessment, discussion document.*

European Comission. (2019). *Commission Delegated Regulation on unmanned aircraft intended for the use in the "Open Category, and on third-country operators of unmanned aircraft systems, Draft Version.*

European Comission. (2019). *Commission Implementing Regulation on the rules and procedures for the operation of unmanned aircraft, Draft Version.*

EUSCG. (2018). *Rolling Development Plan, Doc. NO. EUSCG-1054, version 2.0.*

Exponent. (2014). *UAS Safety Analysis.*

FAA. (1997). *Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliar Power Unit Rotor Failure.* Washington DC.

FAA. (2013). *AC 39-8.*

FAA. (2015). *Unmanned Aircraft Systems (UAS) Registration Task Force (RTF) Aviation Rulemaking Committee (ARC).*

FAA. (2016). *'Drone Collision' Task Force.*

FAA. (2017). *FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation.*

FAA. (n.d.). *FAA Near Mid Air Collision System (NMACS)*. Retrieved February 19, 2019, from https://www.asias.faa.gov/apex/f?p=100:33:::NO:::

FAA. (n.d.). *FAA Regulations Policies*. Retrieved February 15, 2015, from https://www.faa.gov/regulations_policies/rulemaking/recently_published/media/2120-AJ60_NPRM_2-15-2015_joint_signature.pdf

FAA. (n.d.). *FAA UAS Sightings Report*. Retrieved February 5, 2019, from https://www.faa.gov/uas/resources/public_records/uas_sightings_report/

Feinstein, D. L., Heugel, W. F., Kardatzke, M. L., & Weinstock, A. (1968). *Personnel Casualty Study.*

Guardian, T. (2015, June 3). Retrieved February 23, 2019, from https://www.theguardian.com/music/2015/jun/03/drone-injury-grounds-enrique-iglesias-for-longer-than-expected

Henderson, J. (2010). *Lethality Criteria for Debris Generated from Accidental Explosions.*

ICAO. (2001). *Doc 4444 Procedures For Air Navigation Services - Air Traffic Management.*

ICAO. (2013). *Safety Management Manual (SMM).*

ICAO. (2016). *Doc 4444 Procedures For Air Navigation Services, 16th Edition.*

ICAO. (2018). *Doc 9859 Safety Management Manual, 4th Edition.*

Janser, P. W. (1982). *Lethality of Unprotected Persons Due to Debris and Fragments.*

JARUS. (2019). *Guidelines on Specific Operations Risk Assessment (SORA), Edition 2.0.*

MAA, B. (2016). *Small Remotely Piloted Aircraft Systems (drones), Mid-Air Collision Study.*

MarketsAndMarkets. (2018, February). Retrieved from MarketsAndMarkets: https://www.marketsandmarkets.com/Market-Reports/commercial-drones-market-195137996.html

NATO. (2017). *STANAG 4671 - Unmaned Aerial Vehicle Systems Airworthiness Requirements (USAR).*

Oberhagemann, D. (2012). *Static and Dynamic Crowd Densities at Major Public Events.* German Fire Protection Association, Technical-scientific advisory.

Payne, A. R., & Patel, S. (n.d.). *Occupant Protection & Egress In Rail Systems project (OPERAS): Injury Mechanisms & Injury Criteria*. Retrieved from http://www.eurailsafe.net/subsites/operas/HTML/Section3/Section3.3frm.htm

Post, T. W. (2015, December 23). *The Washington Post*. Retrieved February 25, 2019, from https://www.washingtonpost.com/news/early-lead/wp/2015/12/23/camera-drones-banned-by-international-ski-federation-after-close-call-with-racer/?utm_term=.8449d7e98724

Raymond, D., Van Ee, C., Crawford, G., & Bir, C. (2009). Tolerance of the skull to blunt ballistic temporo-parietal impact. *42*(15), 2479-2485.

RTCA. (2012). *Software Considerations in Airborne Systems and Equipment Certification, RTCA DO-178C.*

SAE International . (2010). *Guidelines for Development of Civil Aircraft and Systems, SAE ARP 4754A.*

THIS PROJECT HAS RECEIVED FUNDING FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME UNDER GRANT AGREEMENT NO. 824292.

SAE International. (1996). *Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment, SAE ARP4761.*

SESAR Joint Undertaking. (2016). *European Drone Outlook Study.*

SESAR Joint Undertaking. (2017). *U-Space Blueprint.*

Sharma, R. S. (2016). Investigation into Unmanned Aircraft System Incidents in the National Airspace System. *3*(4).

Shelley, A. V. (2016). A Model of Human Harm from a Falling Unammned Aircraft: Implications for UAS Regulation. *3*(3).

Summer, S. M. (2010). *Flammability Assessment of Lithium-Ion and Lithium-Ion Polymer Battery Cells Designed for Aircraft Power Usage.* FAA.

Swisdak, M. (2017). *Procedures for the Collection, Analysis, and Interpretation of Explosion-Produced Debris.*

Thorpe, J. (2012). *100 years of fatalities and destroyed civil aircraft due to bird strikes.* International bird strike committee.

UKAB. (2016). *UKAB AIRPROX findings on cause and risk outside cas - guidelines.*

UKAB. (n.d.). *UK Airprox Board Drones*. Retrieved February 5, 2019, from https://www.airproxboard.org.uk/uploadedFiles/Content/Standard_content/Topical_Issues_and_Themes/Current\%20Drone\%20Airprox\%20Count\%20and\%20Information.xlsx

Wild, G., Murray, J., & Baxter, G. (2016). Exploring Civil Drone Accidents and Incidents to Help Prevent Potential Air Disasters.

Wilde, P. D., & Draper, C. (2010). Aircraft Protection Standards and Implementation Guidelines for Range Safety.

5 Appendix A - Identification of drone events

5.1 Introduction

The aviation world currently faces a rapid development of drone operations as a new challenge (EASA, Annual Safety Review., 2018). In 2017, EASA dedicated a chapter to RPAS/UAS/Drones with the indication that the number of drones within the EU had doubled since 2015 (EASA, Annual Safety Review, 2017).

The limited quantity of data related to drone incidents available, as well as the limited nature of some of this data, hinders the assessment to which extent this increase of drones in circulation poses a risk.

A recent study, (Wild, Murray, & Baxter, 2016), carried out on an extensive ten-year data set of accidents that have occurred worldwide, has pointed out that the failure of technical equipment has played a more significant role for drones than for manned aviation as the cause of accidents and incidents.

This section intends to provide a summary of existing (world-wide) reports on drone related incidents. It aims to identify the main drone-related accidents which have, or could have, resulted in injuries, or damaging or crashing a manned aircraft.

5.2 Methodology

Relevant drone-related incidents over the past years will be identified. From these, the impact of drones will be examined to assess whether there is a common causality in these incidents (for example, height of the drone or location) or even if there exists a direct connection between the expansion of the drone's market and the number of accidents: the number of drones commercialized in mass market is rapidly increasing, is the number of accidents as well?

Although regulatory provisions and voluntary reporting systems are in place to report drone safety events (e.g. (EASA, Regulation (EU) No 376/2014, 2014)), it is uncommon that operators report such events to the Competent Authorities. As a result, the total number of incidents per year cannot yet be assessed with certainty. All the values presented in this report should therefore be taken as an indication. The assumptions in this report are made under a comparison of the reported values over the years. With changing regulations on the reporting of incidents this may change in the future.

There are different kinds of drone-related incidents, and these will be presented in this report in the following order:

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- **Near misses between drones and manned aircraft** (section 5.3): near misses between drones and aircraft represent a risk of collision. These are situations were a drone may have gotten near a manned aircraft and loss of separation may have occurred. In some cases, collision may even have been avoided only due an evasive maneuverer from the manned aircraft. Different severities where considered for these cases, from situations where the risk was easily averted, to situations of imminent collision. ICAO's risk assessment (section 5.3.1) will be used for this categorization.

- **Collisions with manned aircraft** (section 5.4): occurrences where a drone indeed collided with a manned aircraft. The resulting physical damage to the manned aircraft, as well as injuries/fatalities to crew or passengers on-board will be listed. This report will only identify the collision. A more detailed approach of the severity and causality is outside of the scope.

- **Collisions with people** (section 5.5): reports of accidents were a drone collided with a person. These are commonly situations where a drone, flying over a populated location, fell on top of one or a group of people. Possible causes for the uncontrolled fall may be a malfunction or impact against a building or other structure.

The information regarding the previous situations was retrieved from the following sources:

- **UK Airprox Board** (UKAB, UK Airprox Board Drones, n.d.): funded by the UK Civil Aviation Authority (CAA) and the UK Military Aviation Authority (MAA). UKAB collects statistics of drone occurrences with the objective of enhancing air safety. Reports were collected from the pilots and/or controllers involved. After a report submission, further investigation is carried out by UKAB's experts with the intention of evaluating the risk according to ICAO's definitions (section 5.3.1). This report will make use of this expert evaluation.

  All data can be retrieved from the website in excel form making it quite accessible.

- **FAA's UAS Sightings Report** (FAA, FAA UAS Sightings Report, n.d.): reports of unauthorized unmanned aircraft operations collected from pilots, citizens and law enforcement officials. Each report is a direct quote of the words of the reporter. No formal guidelines are followed in the narrative of the report, which may hinder the correct risk assessment of the situation. Given that there are thousands of reports, a computational keyword filter was developed in order to associate each report with the risk evaluation used in this report.

  Several excel sheets can be retrieved from the FAA UAS sightings website. Each sheet tends to contain the reports of about 3 months.

- **FAA's Near Mid-air Collision System** (FAA, FAA Near Mid Air Collision System (NMACS), n.d.): near collisions with drones reported by aviation members. As stated by the FAA, it is the responsibility of pilots and/or flight crew members to determine whether a NMAC actually did occur and, if so, to initiate a NMAC report. These events will be considered in this report as events where a serious risk of collision occurred. However, it should be taken into account that this severity assessment is from the pilot's own experience and perception of danger. As no further expert appreciation was conducted, discretion is advised.

From the website, it is not possible to retrieve the complete dataset. The user may, however, input a narrative keyword search, a date range and the manned aircraft involved. Unfortunately, for many reports there is no narrative. For this reason, for the website search query, only the date range was used. All the results were then transferred from the website and processed. Only occurrences which mentioned the other body involved in the near collision as being a drone, UAV, or RPAS were then considered.

- **News reports**: most collisions between drones and people are divulged through articles in news sources. These were gathered over an internet search. Unfortunately, these articles are often removed from websites a few years after publication, and therefore, most likely, not all the cases could be retrieved. Additionally, regarding injuries, one must trust the publication due to the lack of other sources of information.

Given the risk evaluation of near misses, UK values are considered most trustworthy, as these have been previously evaluated by UKAB. Regarding the FAA reports, it should be considered that reports may not provide sufficient information or that the data analysis performed may not be adequate for every case. The assigned risk categories should therefore be used with caution.

5.3 Aircraft/Drone Near Misses

Attempting to identify the nature and consequences of drone usage world-wide is an interminable task, as reporting of RPAS accidents and incidents are not mandatory, and it therefore scarcely occurs. Consequently, to know for certain the exact number and type of operations conducted through the usage of drones is not possible, especially in the context of mass-market drones which can be bought and operated without record.

The data that does exist is limited to controlled airspace, which is already under a high degree of scrutiny, and for which drone data, although not mandatory, is necessary in order to maintain the desired safety level. The data used in this study was compiled by UKAB (UKAB, UK Airprox Board Drones, n.d.) and FAA (FAA, FAA UAS Sightings Report, n.d.), which monitor UK and USA airspace respectively. These occurrences and sightings come mostly from pilots flying commercial aircraft to and from these countries. In comparison, incoming reports from UAS pilots are not common. Incidents can be reported by all members of the aviation community as long as they have either observed or been involved in an incident. However, there are no legal requirements or regulations which mandate these reports.

The values presented in this report are to be used for an estimation of the evolution of the number of drone-related incidents over the years and not as exact numbers, as it cannot be guaranteed that this assessment includes all occurrences. Additionally, the numbers of the US and UK reports cannot be scaled directly to the rest of world. Most of these reports are believed to be of real drone sightings. However, due to the circumstances of some occurrences, such as poor line of sight, suddenness of the event and human limitations, some reservations must be

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made regarding the total numbers. Some of the events could, in reality, have involved an object other than a drone, such as a balloon, a bird or other non-controlled objects.

5.3.1 Risk Evaluation

To evaluate the risk of the near misses, ICAO's risk assessment is used. ICAO defines a risk situation as "A situation in which, in the opinion of a pilot or air traffic services personnel, the distance between aircraft as well as their relative positions and speed have been such that the safety of the aircraft involved may have been compromised" (ICAO, Doc 4444 Procedures For Air Navigation Services, 16th Edition, 2016) . This assessment related purely to risk of collision, not to what the consequences might have been had the aircraft collided (UKAB, UKAB AIRPROX findings on cause and risk outside cas - guidelines, 2016). The degree of risk is divided into four categories as displayed in Table 1.

Category	Definition
A	Risk of Collision: aircraft proximity in which serious risk of collision has existed.
B	Safety not assured: aircraft proximity in which the safety of the aircraft may have been compromised.
C	No risk of collision: aircraft proximity in which no risk of collision has existed or risk was averted.
D	Risk not determined: aircraft proximity in which insufficient information was available to determine the risk involved, or inconclusive or conflicting evidence precluded such determination.

Table 1: Risk Classification by ICAO (ICAO, Doc 4444 Procedures For Air Navigation Services, 16th Edition, 2016).

5.3.2 UK

The following data was compiled by UKAB (UKAB, UK Airprox Board Drones, n.d.). It indicates the date of the occurrence, the altitude of the manned aircraft when it spotted the drone, as well as the risk classification of the occurrence according to Table 1. It should be noted that this data also contains drone sightings that were later considered to follow normal procedures and safety standards. These were removed from analysis, as this report intends to only evaluate events which violate safety regulations.

The locations referred to in the data are either airport areas or UK regions. In order to determine whether airport areas represent a bigger risk, the former were defined as Airport Area and the latter as Other.

Figure 1 shows that the number of drone related incidents has been growing for the last 5 years. Between 2014 and 2018, incidents have increased by 1666%. All categories have suffered an increase.

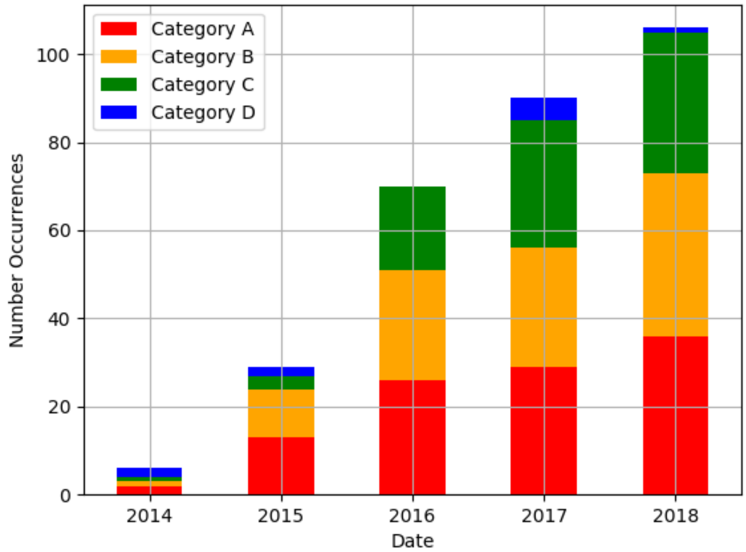

Figure 1: Drone near misses over the years in UK (UKAB, UK Airprox Board Drones, n.d.).

The altitudes at which drones are observed are displayed in Figure 3 and Figure 2. Drones are spotted most frequently in the area of 0-6,000 feet above the ground. This is also the conclusion gathered by EASA (EASA, Annual Safety Review, 2017). More data regarding typical drone flight routes would be necessary in order to conclude whether these values correspond to the more common altitudes at which drones are flown or, instead, if these altitudes are propitious for detection as pilots may be more attentive to drones during take-off and arrival manoeuvres.

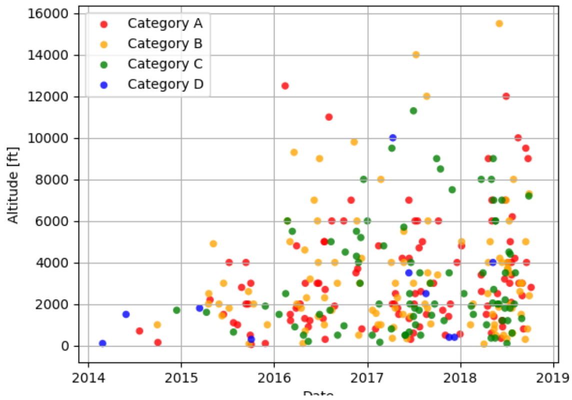

Figure 2: Altitude vs Category in the UK (UKAB, UK Airprox Board Drones, n.d.).

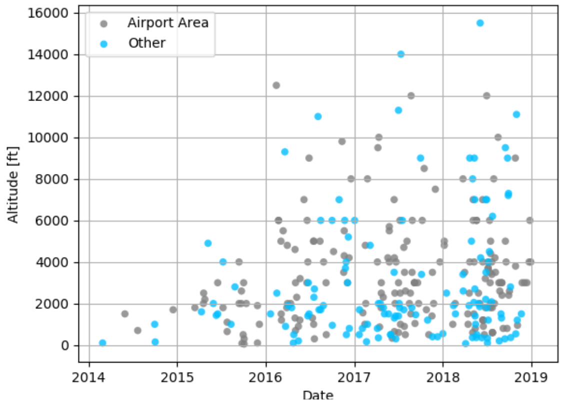

Figure 3: Altitude vs Location in the UK (UKAB, UK Airprox Board Drones, n.d.).

As can be observed in Table 2, incidents in the vicinity of airport are prone to introduce a high risk. This can be expected, given the high number of aircraft arriving and departing from the airports.

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Year	Categories				Location
	Category A	Category B	Category C	Category D	
2018	22	25	14	1	Airport Area
	14	12	18	0	Other
2017	20	19	15	2	Airport Area
	9	8	14	3	Other
2016	14	12	18	0	Airport Area
	10	8	11	0	Other

Table 2: Drone near misses in the UK - Numbers per Location and Category (UKAB, UK Airprox Board Drones, n.d.).

5.3.3 USA

The following data was compiled by FAA in their 'UAS Sightings Report' database (FAA, FAA UAS Sightings Report, n.d.). The data contains the date, city/state of the occurrence and a written summary of the event. This summary does not follow a pre-defined format and is, frequently, a direct quote of the pilot's words. In order to associate this information with the risk categories defined in Table 1, this summary was filtered for specific keywords which identify, for example, whether an avoidance manoeuvre was performed in order to avoid collision or even if the aircraft was struck by the drone. The properties of the filter are as follows:

- Keywords such as Almost Hit, Struck by and similar permutations were classified as Category A, as it represents a serious risk of collision or even an actual collision.
- Keywords such as Evasive action taken, Evasive manoeuvre taken, turn and similar permutations were classified as Category B as it is evidence that an emergency action was performed in order to avoid a likely collision.
- Keywords such as No evasive manoeuvre, No aircraft affected, No Action was required and similar permutations were classified as Category C, as it seems to indicate that no risk of collision existed.
- Summaries which had insufficient data regarding performed manoeuvres or the level of risk to the aircraft were identified as Category D.

As a result of the aforementioned conversions, it cannot be considered that all occurrences are classified correctly as the information available can be insufficient or misleading. However, it allows for a yearly based comparison and an indication for whether these are low or high-risk situations. For example, having an increase of occurrences where an evasive action occurred can indicate that the risk of drone collision in a certain area has increased.

Additionally, regarding the location, as the city/state is not as relevant in an accident context as the proximity to airports or urban areas, certain location-related keywords were also filtered in order to establish proximities:

- Keywords such as Airport, Runway and Arrival/Approach were classified as Airport Area.
- Keywords such as Helicopter were classified as Helicopter.
- When none of the aforementioned keywords are identified, the location is classified as Other.

Proximity to the flight paths of helicopters was added in this analysis given the high number of references to near misses with helicopters. These typically have free flight manoeuvres given that the nature of their operations are mostly directed at law enforcement, search and rescue or construction purposes. It can be a potential source of risk to have these two aerial vehicles, helicopters and drones, in the same area given the unpredictability of their courses.

Figure 4 shows that drone-related incidents have also increased in the USA. Between 2015 and 2017, occurrences increased by 75%. It should be noted that the values for 2018 are not presented, as up until the publish date of this report, data for the complete year of 2018 was yet not available. However, for the first half of 2018, the FAA had already recorded 1235 occurrences, which represents an increase of 17% in comparison with the first half of 2017.

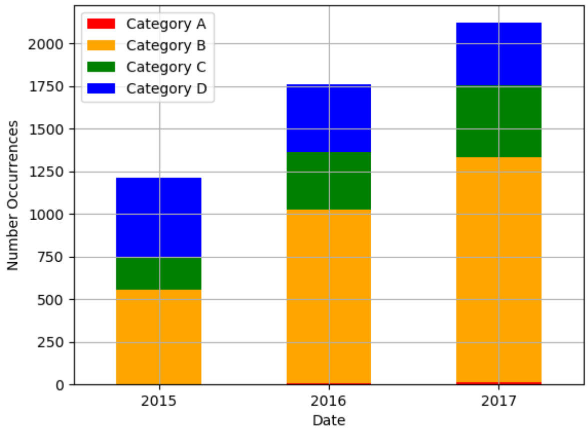

Figure 4: Drone's risk operations over the years in USA (FAA, FAA UAS Sightings Report, n.d.).

In Figure 4, it can be seen that, compared to the UK data, events of Category B are more frequent than events of Category A. A possible reason for this can be the lack of details in order to correctly differentiate between Category A and B. These values should be interpreted as the number of high-risk occurrences.

Another indication for possible values for Category A events is the FAA Near Mid-Air Collision System (NMACS) reporting system. Here, members of the aviation community may

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report an accident which they perceive as having constituted a serious risk of collision. They may have either been involved with or witnessed such event. These reports are not obligatory and are naturally bonded with the reporter's own perception of the event. Additionally, factors such as pilot's experience of even fear of penalties can modify the description of the event and the tendency to report (Sharma, 2016). As a result, these numbers should only be taken as an indication.

Data from the FAA NMACS can be retrieved from the FAA website (FAA, FAA Near Mid Air Collision System (NMACS), n.d.). Events were filtered with the following keywords: UAS, drone, UAV, unmanned. The total number of UAS-related reports obtained is displayed in Table 3.

Year	Number of reported Near Mid-Air Collision
2015	18
2016	62
2017	76

Table 3: UAS related NMACS reported over the years (FAA, FAA Near Mid Air Collision System (NMACS), n.d.).

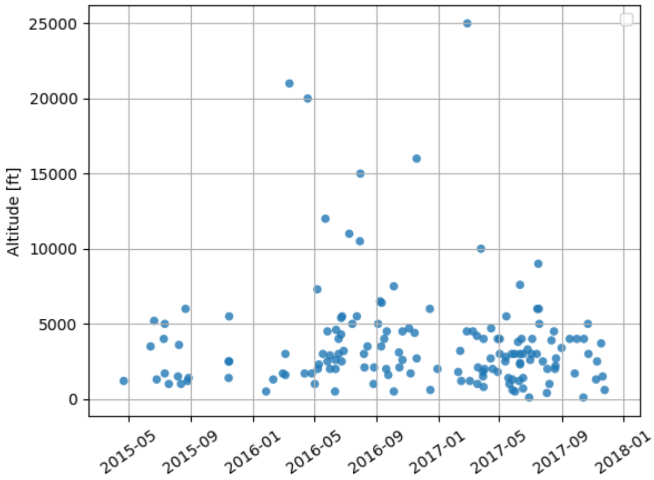

Figure 5: Altitude of NMACS reported over the years (FAA, FAA Near Mid Air Collision System (NMACS), n.d.).

These values are higher than the Category A events retrieved from the FAA UAS Sightings database (Figure 4), which could signify that either the description of events of the latter doesn't correctly identify the high risk of collision, or that some occurrences in the FAA NMACS database should actually be categorized as Category B. More information would be required to make such judgement. As many of the reported FAA NMACS do not contain a narrative, a more detailed analysis cannot be performed on this data.

The altitude of the aircraft at the time of the event is shown in Figure 5. NMACS are mostly reported in the area of 0-5,000 feet above the ground. Combined with the values observed in Figure 3, this could indicate that, indeed, below 6,000 feet is where most of the risk for UAV-related incidents exists.

Additionally, Category D values appear to be decreasing over the years. However, a thorough analysis of the data shows that the summary of events tends to be more detailed as years progress. Such can cause fewer events to be categorized as D and correctly labelled with a higher category.

As observed in Table 4, most of the occurrences tend to be of a higher risk category.

Year	Categories				Location
	Category A	Category B	Category C	Category D	
2017	4	336	109	67	Airport Area
	1	67	27	25	Helicopter
	9	914	286	276	Other
2016	4	273	70	66	Airport Area
	1	66	23	35	Helicopter
	3	679	245	296	Other

Table 4: Drone operation risk in the USA - Location vs Category (FAA, FAA UAS Sightings Report, n.d.).

5.4 Aircraft/Drone Collisions

The number of near misses as well as their severity/risk have increased over the years. However, fortunately, the actual number of collisions is still small in comparison. For example, although there are more than 1 million UAS operating in US airspace (Center, 2016), and thousands of near misses have occurred, to this date only three aircraft-drone collisions were investigated. Regarding EASA Member States, within the period of 2010-2016, three collisions were reported and investigated (FAA, ‘Drone Collision’ Task Force, 2016).

Table 5 presents the verified aircraft-drone collisions worldwide. It should be noted that, although, there is a consensus that all the mentioned events involve collision with a drone, there can only be absolute certainty when the drone, after collision, latches onto the aircraft’s fuselage and can then be retrieved for posterior study. This was the case for the occurrences where the type of the drone is known. In the situations where drone type is not known, the drone could not be retrieved. Assessment of the drone collision was then performed by the description of the pilots, which may report that they’ve seen a drone, and/or expert evaluation of the damages.

From the recorded aircraft-drone collisions, only one resulted in injuries and the crash of the aircraft. The collision in 1997 between a Grob G190b touring motor glider and a radio-controlled model aircraft unfortunately resulted in both crew members on board suffering fatal injuries resulting of the crash.

Date	Location	Airspace	Aircraft	Altitude	Drone Type	Aircraft Damage	Comments
14-10-2018	Driggs, ID, USA	Uncontrolled airspace	Lindstrand Balloons LBL-105	100 ft	---	No Damage	---

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10-10-2018	Petah Tiqwa, Israel	Uncontrolled airspace	Robinson R44 Raven II	100 ft	Phantom 4	No Damage	---
10-10-2018	Hillegom, Netherlands	Uncontrolled airspace	Lange Antares 20E	---	---	Serious delamination	---
2-10-2017	Québec Airport, Canada	Controlled airspace	Beechcraft A100 King Air	2100 ft	---	Dent on the left wing de-icing boots	Final Approach
21-09-2017	Brooklyn, NY, USA	Uncontrolled airspace	Sikorsky UH-60M Black Hawk	300 ft	DJI Phantom 4	Dent on one of the main rotor blades	Temporary Flight Restriction imposed on the area
30-08-2015	Europe	---	Grumman AA-1	2500 ft	---	No Damage	RPAS struck undercarriage
30-04-2015	Near Shoreham Airport, UK	Controlled airspace	Robin DR 400-180	700 ft	SAS Wildthing	Scraping on wing	Final approach
05-04-2015	Worcestershire,UK	Uncontrolled airspace	Pioneer 300	630 ft	Valenta Ray X, S037996	Small hole left wing and surface damage to thewing fabric	---
05-07-2011	Afghanistan	---	Lockheed C-130 Hercules	---	AAI RQ-7 Shadow	Damage to left hand wing	---
14-08-2010	Brighton, CO, USA	Controlled Airspace	Shpakow SA 750	50 ft	AJ Slick model airplane	Lower left wing crushed aft to the main spar	---
03-08-1997	Schopfheim, Germany	Controlled Airspace	Grob G 109B	660 ft	Dingo	Aircraft crashed	2 Fatalities

Table 5: List of known mid-air collisions between manned aircraft and UAS.

5.5 Injuries to people on the ground

Another risk resulting from drone flights is the possibility of a drone hitting (or nearly hitting) a passer-by on the ground. Additionally, a crashed drone may ignite and start a fire, as past events have shown.

5.5.1 Direct collisions

Table 6 displays verified collisions between a drone and a person. Most of the accidents were a result of the drone hitting a building and losing control. Although the number of accidents is still relatively low, it is likely that these are not a complete record. These events are mostly spread through news reports, which tend to be removed from the internet not long after their publication. More accidents can be discerned from internet forums or non-news websites, but these cannot be verified and therefore were not added to this report.

Date	Location	Event
04-07-2018	Las Vegas, USA	A one drone flying over the crowd crashed into a person, injuring her eye
08-06-2016	Quebec	A drone fell, injuring one person
08-04-2016	Cape Town, South Africa	A drone crashed through a building window injuring one person
11-2015	Worcestershire, UK	A drone hit a tree and fell injuring one person
08-10-2015	New York, USA	A drone crashed and exploded, injuring one person
12-09-2015	Pasadena, CA, USA	A drone hit and its debris injured a 11-month old baby
16-06-2015	Albuquerque, NM, USA	A drone hit a building and crashed, causing minor injuries to one person
31-05-2015	Tijuana, Mexico	Singer Enrique Iglesias suffers severe laches on a hand as a result of coming in close contact with the blades of a drone after trying to grab it during a concert.
25-05-2015	Marblehead, MA, USA	A drone hit a building and crashed, causing minor injuries to two people
05-04-2014	Sidney, Australia	A drone hit an athlete during a triathlon
05-09-2013	Brooklyn, USA	A high-powered model helicopter fatally injured its pilot when hit with the high-speed rotating lades.

Table 6: Examples of injuries to people on the ground caused by falling drones.

Another high-profile situation worthy of mentioning, is an incident on September 15th, 2014, where a Parrot AR drone crashed in front of German Chancellor Angela Merkel. No one was harmed, but the situation raised concerns over operations with drones. Additionally, in 2019, during a ski race, a drone crashed into the snow almost hitting an athlete during his run (BBC, BBC Sport, 2015). This led the international ski federation to ban camera drones during races (Post, 2015).

5.5.2 Secondary Impact, Fire

Another way in which drones can induce accidents is by causing a fire, as a result of the battery being punctured during impact.

In 2018, in Arizona, a drone owner was charged with starting a fire. The drone reportedly caught fire after it crashed (BBC, BBC, 2018). In the same year, Springfield, Oregon's Fire Department prevented what could have been a serious situation, by putting down a fire resulting from a drone's crash (CBS, 2018).

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5.6 Concluding Remarks

Information regarding drone incidents/accidents is still very scarce. This is certainly one of the biggest hindrances to correctly identifying the correct magnitude of occurrences and their severity. Additionally, a predefined guideline needs to be created, in order for recorded events to be correctly evaluated.

From the recorded incidents, although near misses resulting from drones approaching manned aircraft have significantly increased in all the retrieved locations, the number of recorded collisions, injuries and fatalities is still considerably slow. However, this may be more correctly attributed to the lack of information as recording is not mandatory and not necessarily to the safety of the operations.

Regarding drone collisions with people, it should be noted that the occurrences presented in this report are not the complete numbers, and likely undervalued. However, either the missing events have not been reported, or this information has already been deleted from websites and is now irretrievable. Nevertheless, the events mentioned in this reported have been reviewed for authenticity.

5.7 Future Work Recommendations

All the information gathered regarding near misses comes from UK and USA. For a better worldwide view, more locations would have been preferred. However, this information is not available. Only these two countries have made this information available to the public. Having more aviation boards making this information public with pre-defined guidelines would definitely increase awareness of the impact of drones in airspace. When possible, it is advised that this report be update with new information from other datasets.

Reporting of the events is naturally influenced by the bias of the pilots or controllers describing the event. More news has recently been spread on the danger of drones. This may induce a negative influence over the appreciation of danger in a drone sighting. Alternatively, these events may often not be reported. As it is not mandatory, when no clear guidelines are in-place for how to report these events, pilots may find it a nuisance to do so instead of an asset for aviation safety. Plus, pilots may be inclined not to report accidents where they believe they may have put a manned aircraft in a position of danger with fear of penalties. It would be of advantage to study possible procedures on how to encourage the reporting of these events and which guidelines should be followed when evaluating and reporting these occurrences. Finally, having a board of experts responsible for following up on an event as to gather more testimonies and proceed with an expert evaluation would certainly make the results more trustworthy.

6 Appendix B - Identification of the severity of drone events

6.1 Introduction

Drones are rapidly increasing in popularity. Their acquisition in large numbers in the mass-market by the general public is becoming a closer reality each day. As a result, the number of near misses and collisions between drones and manned aircraft increases as well.

The aviation world and the general public are naturally concerned about the potential consequences of the increasing number of collisions. However, the risks of material losses or injury to crew and passengers are, to this day, still little understood.

From NATO's Airworthiness requirements (NATO, 2017): "The UAS system must be designed to reduce the risk to people including UAS crew, maintainers and third parties to a level acceptable to the certifying authority. It must also be designed to reduce the risk of material loss or damage to a level acceptable to the certifying authority".

However, in order to reduce the risk of loss, the existing risk must be first be ascertained.

The severity of a drone collision is dependent on several variables, such as the mass and velocity of the drone, presence of high-density components, frangibility, presence of on-board hazardous chemicals, and the type of battery. However, there is currently no consensus on how all the previous elements can be measured against the damage resulting from a collision. Additionally, with the advancement of regulations and technologies these measurements are constantly changing. Situations that, in the past, may have been seen as a worst-case outcome, have now been proven surmountable with the advancement of aviation technology and in-place regulations. For example, bird-strike occurrences have now proven that an engine failure will most likely not cause an immediate risk to crew or passengers.

This study aims to compare the severity of a drone collision based on a literature study of existing research. Several studies are mentioned in this report, which will be compared into a unified definition of a drone-manned aircraft collision severity assessment based on the predicted outcome of such a collision.

6.2 Methodology

The severity of drone events will be categorised. This has the objective of examining which factors, from either drones, manned aircraft or drone operation in populated areas tend to result

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in serious events such as physical damage to the aircraft and injuries/fatalities of members of the crew or people on the ground.

This assessment will be performed based on a literature review. The main documents of this assessment are described in section 6.3. The review will focus mainly on the description of past occurrences and the results of experimental tests performed by other researchers.

From the referenced literature, it is important to mention (EASA, "Drone Collision" Task Force, 2016) as the base for this severity assessment. This document was formulated by studying accident reports and expert judgment. Many of the considerations and assumptions in the current report follow the guidelines defined in (EASA, "Drone Collision" Task Force, 2016).

EASA has defined a physical impact assessment at component level (as described in Table 10). This information should be used for the severity identification of a hit in a specific area of the aircraft when no other information is given. However, if the area of the aircraft is not mentioned in this document, then the impact should be considered as negligible. Many sections of this document attempt to extend the assessment made by EASA by using data from other reports which are either deemed more complete or have experimental results. In these cases, it shall be mentioned in the appropriate section, which taxonomy should be followed for determining the severity. When such a taxonomy does not include all the possible types of damage, the reader should again resort to the information in Table 10.

Drone operations are divided into three categories with an increasing risk level: “Open”, “Specific” and “Certified”. Analogously to (EASA, "Drone Collision" Task Force, 2016), only drones in the “Open” category were considered in this study. “Open” (low risk) is a drone operation category that, considering the risks involved, does not require a prior authorisation by a competent authority before the operation takes place. Mass-market drones are most likely to be employed for operations in the “Open” category. Although the other categories are currently omitted, this scope limitation is considered valid, as during an initial phase of research, the AW-DRONES project focuses primarily on mass-market drones.

This report will base its analysis in drone collision with manned aircraft, and free-falling drones which may hit people on the ground. When data is limited, the characteristics of the impact, such as impact area and angle, are defaulted to the worst possible scenario.

This assessment will not include:

- Factors such as disruption to air traffic or repair costs to the aircraft.
- Secondary impacts, such as parts of the drone bouncing after the first impact and hitting the aircraft a second time.
- In a drone-person collision, it is assumed that the drone is flying above people who are directly exposed to the impact. Obstacles which may diminish the final impact force of the drone or modify its direction are not considered.

The main bottleneck identified was indeed the lack of information. Not many collisions with drones have been reported and some may be missing important details, such as the specifications of the drone involved or conditions prior to collision.

Lastly, it should be considered that the conclusions of this report are directly constrained by the assumptions made. When lacking reports or experimental tests, the impact of the damage was evaluated based on expertise judgment. Naturally, different judgements could result in different conclusions.

6.2.1 Severity scale

Table 7 presents the common severity index which will be used for this report and the description of each as defined per (ICAO, Doc 9859 Safety Management Manual, 4th Edition, 2018).

Severity	Meaning
Catastrophic	• Equipment destroyed • Multiple deaths
Hazardous	• A large reduction in safety margins, physical distress or a workload such that the operators cannot be relied upon to perform their tasks accurately or completely • Serious injury • Major equipment damage
Major	• A significant reduction in safety margins, a reduction in the ability of the operators to cope with adverse operating conditions as a result of an increase in workload or as a result of conditions impairing their efficiency • Serious incident • Injury to persons
Minor	• Nuisance • Operating limitations • Use of emergency procedures • Minor incident
Negligible	• Few consequences

Table 7: Severity index and definitions used in this report. Adapted from (ICAO, Doc 9859 Safety Management Manual, 4th Edition, 2018).

6.3 Literature Review

Not many studies exist, currently, which discuss the impact and severity of drone collisions with manned aircraft. A possible reason is the low number of recorded collisions until today. It should be noted that the record of these collisions is not mandatory.

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Most existing drone-aircraft collision studies cover a specific type of collision, given the limited resources for empirical data. This report attempts to compile information from the following studies and unify it into a single description of drone collision severity:

- **EASA's 'Drone Collision' Task Force** (EASA, "Drone Collision" Task Force, 2016): assesses the risks resulting from collisions between drones of varying masses and different categories of manned aircraft. The results were obtained through engineering judgement from several specialist from EASA and the European aircraft industry. Many of the drone and aircraft classifications will be used in this report as to create a common ground for drone terminology.

- **EASA's Research Programme on Collisions with Drones** (EASA, Research Programme On Collisions with Drones: Work Area 1 Final Report, 2017): research focused on assessing the damage against fixed and rotary wing aircrafts.

- **FAA's UAS Ground Collision Severity Evaluation** (FAA, FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation, 2017): studies the impact of collision between a drone and a person, taking into account criteria developed for human blunt force trauma, penetration and laceration injuries.

- **CASA's mid-air collision assessment** (CASA, 2013): assesses the potential damage of a mid-air collision between a manned aircraft and a small UAV.

- **MAA's and BALPA's Small Remotely Piloted Aircraft Systems Mid-Air Collision Study** (MAA, 2016): uses laboratory collision testing and computer modelling to assess the damage effects of a mid-air collision between small UAVs and manned aircraft through review of exiting experimental data.

- **FAA's UAS Task Force for UAS** (FAA, Unmanned Aircraft Systems (UAS) Registration Task Force (RTF) Aviation Rulemaking Committee (ARC), 2015): recommendation of minimum requirements for UAVs with the objective of limiting risk prone situations.

- **CAA's Drone Safety Risk, An assessment** (CAA, 2018): a drone collision severity assessment as a combination of damage to the manned aircraft and injury or death to those on board the aircraft, or to third parties on the ground.

- **Shelley A., A Model of Human Harm from a Falling Unmanned Aircraft: Implications for UAS Regulation** (Shelley, 2016): study into an UAV induced human harm model. Combines studies of blunt traumas to the human body with the expected impact force of a free-falling drone.

- **Aalborg University's mass threshold study for "harmless" drones** (Cour-Harbo, 2017): journal article proposing a 250-gram threshold for "harmless" drones. This threshold was later used by (EASA, "Drone Collision" Task Force, 2016) and will be used and analysed in this report.

6.4 Drone Classification

The new EASA Basic Regulation (EASA, Regulation (EU) 2018/1139, July 2018) lays down the common requirements for the operation of unmanned aircraft. The regulation divides UAS operations into three categories, corresponding to a growing level of risk, as follows:

- “Open” category (i.e. low risk).
- “Specific” category (i.e. medium risk).
- “Certified” category (i.e. high risk).

In contrast to the “Open” category, operations within the latter categories deal with a higher involvement of the authorities in the operational approval phase.

Operations in the “Specific” Category shall be supported by a safety assessment and will require an authorisation issued by competent authority, unless the operator holds a LUC (Light UAS Certificate) or the operator declares that the envisaged operation is compliant with a recognised standard scenario.

The “Certified” category will cover very high-risk operations, such as passenger carrying drones, transport of dangerous goods or flights over gathering of people employing large drones). The level of risk is comparable to that of traditional manned aviation activities, thus requiring certification of the operator and the aircraft as well as a remote pilot license.

EASA’s ‘Task Force’ (EASA, "Drone Collision" Task Force, 2016) decided to focus its study on drones fitting the “Open” (low risk) category, which does not require a prior authorisation by the competent authority before the operation takes place.

Although limiting the scope of the research and therefore not inferring results for drones outside of the “Open” category, this is a considered a valid limitation given that this category includes the vast majority of drones flying today and expected to fly in the future. Mass-market drones are most likely to be employed for operations in the “Open” category.

This report will follow the scope of work defined by EASA due to the limitation of no literature or experimental data for drones of the other categories (“Specific” and “Certified”). In contrast to the “Open” category, operations within the latter categories require a risk assessment by a competent authority with specific limitations adapted to the operation.

6.4.1 The “Open” Category

As defined in (EASA, Regulation (EU) 2018/1139, July 2018), the “Open” operation category of drones will not require an authorisation by an Aviation Authority in order to flight within the requirements and limitations described in section 7.2.1.

Within the “Open” category, a separation was made into five categories of different maximum take-off mass (MTOM) considered to have different impacts:

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- C0 (MTOM < 0.25kg). These are often referred to as “Harmless” drones.
- C1 (MTOM < 0.9kg).
- C2 (MTOM < 4kg).
- C3 and C4 (MTOM < 25kg).

More detail on the previous categories can be found in section 7.2.1.

Both (EASA, "Drone Collision" Task Force, 2016) and other studies mentioned in this report (CASA, 2013), put more emphasis on drones until category C2. According to (EASA, "Drone Collision" Task Force, 2016), these “represent the vast majority of the drones in this category flying today.” Most studies are limited to “harmless” drones (C0 category) , “small” drones (C1 category), “medium” drones (C2 category until 1.5kg) and “large” drones (C2 category with more than 1.5kg). As a result, there is a lack of experimental data for drones above category C2. However, given that the highest severities are already considered for the higher weight layers of the C2 category, categories C3 and C4 should implicitly be assumed to have the highest severities as well.

Each mass category was assumed to have the components described in Table 8.

Drone Category	**Components**				
	Motor	Battery	FPV camera	Camera	Frame Components
C0	✓	✓	✓		
C1	✓	✓	✓		
C2, C3 and C4	✓	✓		✓	✓

Table 8: Assumed components per drone category. Adapted from (EASA, Research Programme On Collisions with Drones: Work Area 1 Final Report, 2017) and (CASA, 2013).

From the above mentioned drone categories, “Harmless” (or C0 category) will receive the least focus. As the name indicates, these drones are considered harmless to both manned aircraft and people. (FAA, Unmanned Aircraft Systems (UAS) Registration Task Force (RTF) Aviation Rulemaking Committee (ARC), 2015) similarly recommends an exclusion from registration requirements for this category of drones.

6.4.2 Drone Damage Potential

There are several factors which define the level of damage that a drone may impart during a collision. Not all of them are entirely known or studied, but they are typically divided into the categories defined in Figure 6.

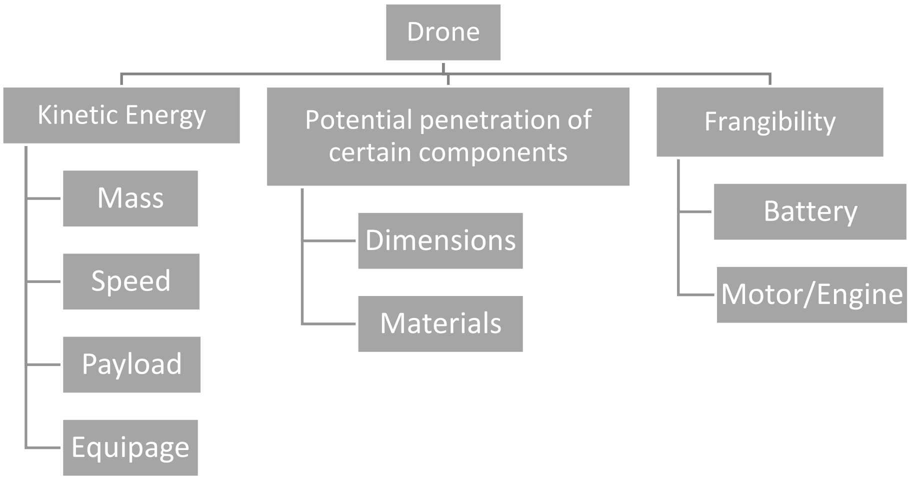

Figure 6: Simplified model of a drone collision severity taxonomy. Adapted from (EASA, "Drone Collision" Task Force, 2016) and (FAA, FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation, 2017).

For the damage assessment the following parameters are considered:

- The **kinetic energy** at the time of the collision is used to estimate the damage of a drone. In a theoretical manner, it is proportional to the mass and velocity of the drone as defined by Equation 1.

  $$KE = \frac{1}{2}mv^2$$

  Equation 1: Kinetic Energy

  In reality, this kinetic energy calculation is not enough to properly assess the impact force. Naturally, it is expected that heavier and fasters drones will cause a bigger impact. However, the rigidity, angle of incidence, and orientation of components also contribute to the outcome of the impact. Notwithstanding, these are difficult to quantify. Additionally, on impact, part of this energy may be dissipated through deformation and fuselage or payload separation. As a result, the impact should be tested experimentally.

- **Potential penetration** refers to the probability of certain components of the drone to penetrate the physical structure of an aircraft, based on size and material. This can be

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especially dangerous when such pieces block the normal movement of rotating parts, such as the propeller.

Frangibility refers to the tendency of the drone to shatter into smaller fragments on collision as to minimize the force of impact. According to FAA's regulations (FAA, FAA Regulations Policies, n.d.): "The unmanned aircraft would be made out of frangible materials that break, distort, or yield on impact so as to present a minimal hazard to any person or object that the unmanned aircraft collides with". The battery (medium dense object) and motor (high dense object) are considered the biggest threats as these do not distort or break so easily on impact.

6.4.3 Drone comparison to bird strikes

Faced with the lack of drone-related data, a common makeshift for existent studies is to resort to information available on bird strikes. Some studies tend to compare a drone with a bird of about 1.8 kg (4 lb) (EASA, "Drone Collision" Task Force, 2016), (Exponent, 2014). However, this comparison does not take into account the differences in density or frangibility between drones and birds.

Both (MAA, 2016) and (CAA, 2018), verified that a drone with denser components caused more damage that a drone with higher mass but with less dense components. For this same reason, the same studies concluded that drones are, in general, more dangerous than a bird of equivalent mass. (EASA, Research Programme On Collisions with Drones: Work Area 1 Final Report, 2017) define that the level and damage that might be expected from an impact with a 4lb bird, which behaves as a fluid upon impact, is significantly different from a drone of the same mass.

Nevertheless, the existing bird strike data can be used to pinpoint the most vulnerable areas on an aircraft and the likelihood of these being hit. These areas are under special scrutiny when evaluating drone impact.

6.4.4 Batteries

Another concern with batteries, apart from their high density, is the risk of ignition on impact.

According to (FAA, FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation, 2017), the vast majority of UAS sold in the US in the "Open" category use Lithium Polymer (LiPo) batteries as a source as power. Unfortunately, collisions with LiPo batteries and the resulting fire hazards test are poorly documented. Is it known that these can ignite if punctured and then exposed to air or water, or if they are poorly maintained. However, precise conditions at which these situations may occur are still not clear.

Results currently available were obtained experimentally with power cells of a capacity higher than normally used in drones of the "Open" category. For example, (FAA, FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation, 2017) reports a burn test conducted with a 7S2P configuration battery where the ignited combustion had an average temperature of 900°C for 5-6 minutes. However, this is a very high capacity LiPo battery and would typically only be used by heavy lift UAS.

Notwithstanding the lack of experimental data, there is evidence of fires started by ignition of the battery once the drone crashed to the ground (BBC, BBC, 2018), (CBS, 2018). Due to the previous occurrences, the risk of combustion on impact will be considered in this severity assessment. The judgment displayed in Figure 8 will be used.

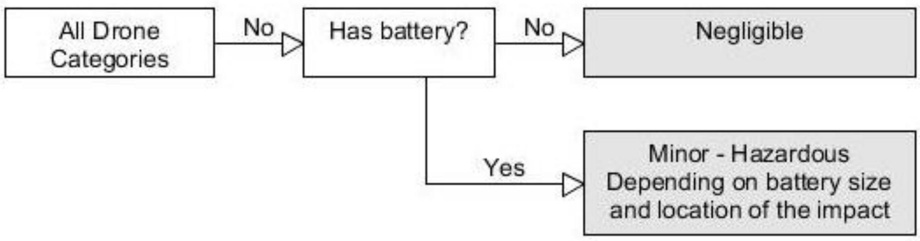

Figure 7: Severity assessment in case of a drone collision when the drone has a battery.

For drones carrying a battery, a severity ranging from Minor to Hazardous will be considered. Although this is a wide severity range, the uncertainty around drone batteries justifies it. It is considered that this severity mainly depends upon the type of battery and the proximity to dangerous goods. Higher-capacity batteries are expected to be more dangerous, as these can combust for longer and at higher temperatures. The proximity of the impact area to combustible materials which may either be on-board of the aircraft, in case of a drone-aircraft collision, or which may be on the ground, in case the drone hits the ground, will naturally increment the severity of a possible combustion.

6.4.5 Aircraft Classification

Similar to drones, aircraft have also been separated into weight categories:

- Large aircraft: take-off weight of more than 5,700 kg.
- Rotorcraft: maximum take-off weight of 3,175 Kg.
- General Aviation: maximum take-off weight of 5,700 kg.

For the three different categories, the typical speeds and fuselage thickness displayed in Table 9 will be assumed.

Aircraft classes	Assumed Speed	Assumed fuselage thickness
Large Airplane	Above 10000 ft: 340 kt Below 10000 ft: 250 kt	1/8“
Rotorcrafts	170 kt	1/16“
General Aviation	120 kts	1/16“

Table 9: Assumed typical speed and fuselage thickness for the different kinds of aircrafts. Adapted from (EASA, "Drone Collision" Task Force, 2016).

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According to (EASA, "Drone Collision" Task Force, 2016), as expected, large aircraft are generally more resilient to collisions with drones than general aviation aircraft. (ATSB, 2017) analysed Australian aviation wildlife strike statics and concluded that the percentage of damaging bird strikes in general aviation is 25%. For high-capacity air transport this is 6%, even though it has more than five times the number of bird strikes of general aviation. (ATSB, 2017) justifies this disparity with a more fragile wing structure employed in general aviation aircraft.

Drones in the “harmless” category are usually considered not a threat. “Smaller”/C1 category drones are typically only a risk for general aviation and rotorcraft.

6.5 High Impact Areas

The damage caused by a collision with a drone depends heavily on the location of the hit. The following high-impact areas displayed in Table 10 were defined in (EASA, "Drone Collision" Task Force, 2016) with resource to engineering judgment and experimental data from bird strike reports. EASA defines which areas, for each type of aircraft, are considered vulnerable to collisions from drones. Outside of these areas, the impact of a drone is considered negligible.

For each area there is a definition of the threshold of damage for each severity level. For most areas, Minor severity corresponds to dents, scratches or limited deformation. Major indicates that performance of aircraft may have been affected, but it is still within safety levels. Lastly, Hazardous severity represents a serious limitation or risk to the normal operation of the aircraft. Safety performance levels will not be guaranteed.

This report will make use of the taxonomy given in Table 10 when no other details are given.

		Hazardous	**Major**	**Minor**
Common				
	Windshields	Penetration or total loss of visibility	No Penetration, partial loss of visibility.	No/limited damage. Loss of external visibility.
	Fuselage areas above and loss of external visibility below windshields			
	Landing gear, and landing gear doors and lights	Damage preventing landing gear safe deployment or affecting essential functions	Damage preventing landing gear safe retraction or other limited damage.	No or limited external damage not affecting operability
	Engines	Significant mechanical damage or detachment of parts.	Non-significant mechanical damage. Reduction of performance. Increase of operating temperatures.	No/limited damage with no effect on integrity and performance.
Specific				

Large Aircraft	Propellers	Significant damage resulting in unsustainable propeller unbalance and instability.	Non-significant damage of the blade(s) resulting in propeller unbalance within sustainable limits.	No effect
	Horizontal & vertical tailplanes/wing heading edges, flaps	Penetration. Significant damage, part detachment.	No penetration but limited deformation	Only dents or scratches
Rotorcraft	Main and Tail Rotor, including blades, hubs, masts and controls	Significant damage resulting in unsustainable rotor unbalance and instability.	Non-significant damage within sustainable limits.	No or limited damage with no effect on performance.
	Nose/radome/large antennas	Penetration. Significant damage, part detachment.	No penetration but limited deformation	Only dents or scratches
	Fairings			
General Aviation	Empennage			

Table 10: High impact Areas per type of aircraft. Adapted from (EASA, "Drone Collision" Task Force, 2016). (EASA, "Drone Collision" Task Force, 2016) uses a *High*, *Medium* and *Low* severity assessment which was adapted to the one used in this report (Table 7).

For heavier aircraft categories, only the fuselage around the windshield, wing/tail leading edges, flaps and spoilers are a source of concern. For general aviation, the whole empennage is considered vulnerable. According to (CAA, 2018), due to the larger relative size of the drone, for a small aircraft any area may be a potential damage area.

In terms of likelihood, statistics on bird strikes show that the engine and windshield are the areas hit more often and, unfortunately, also the most vulnerable. For collisions involving large aircraft, in 76% of the occurrences, the engine was hit and in 7% the windshield (Thorpe, 2012). In comparison, for general aviation, in 56% the collisions the windshield was hit and, in 12%, the engine.

For general aviation, the consequences of hitting the windshield tend to be more severe. As general aviation aircraft do not have a requirement for bird strike certification, the windscreens are usually made of thin acrylic, which is more sensitive to impact. A 40g bird is considered to be enough to penetrate the windscreen (Thorpe, 2012). The great majority of drones will have a bigger mass in comparison. Additionally, according to (CASA, 2013), avoidance manoeuvres from general aviation pilots have led to fatal crashes in the past.

As a side note, landing gear and landing lights are the components predicted to be less vulnerable. This can be attributed to the fact that these are made to endure impact during a landing procedure.

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6.5.1.1 Engine

Given the data available for bird strikes (where 76% of the times the engine was hit), it is fair to predict that a collision between a UAV and a large airplane will most likely result in the ingestion of the UAV into one of the engines. However, according to FAA, modern commercial transport aircraft are actually rather robust with respect to fragment impact damage (Wilde & Draper, 2010). Past experience shows that this class of aircraft tends to land safely even after sustaining substantial damage from fragment impacts.

Additionally, most modern large aircraft are designed to be able to handle total loss of one of the engines and are, therefore, able to perform a safe landing in such a case. (CAA, 2018) indicates that "the current suite of certification requirements for aero-engines provides a very significant degree of protection for any structural integrity issues that might be posed by potential drone ingestion." Equally, (CASA, 2013) has concluded that the ingestion of the UAV into one of the engines of a modern transport aircraft is unlikely to result in a catastrophic outcome.

In this report, the severity judgment displayed in Figure 8 will be used. For large commercial aircraft, loss of a single engine will be considered of non-hazardous severity given the data addressed in this section. For others, EASA's severity definitions from Table 10 should be used.

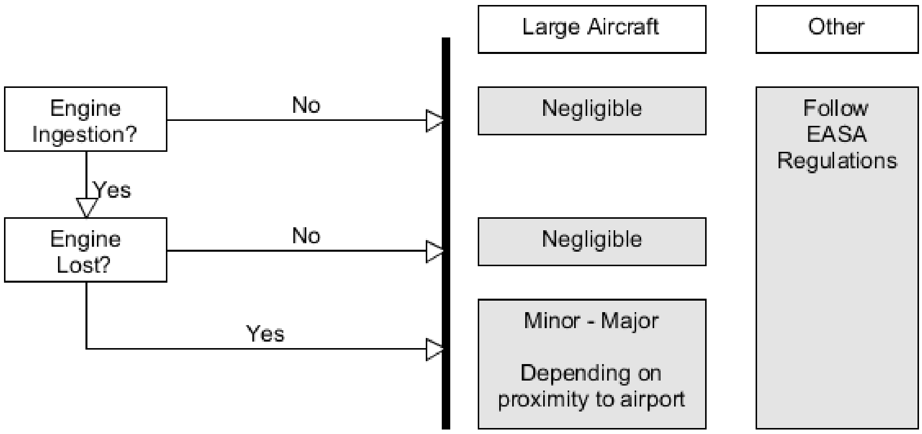

Figure 8: Severity assessment in case of a drone collision which hits the aircraft's engine.

It is considered that the severity of losing an engine is conditioned upon proximity to a runway as to allow for safe landing if needed. It is important to note, however, that commonly large aircraft collide with drones near airports as only during landing or departure will the aircraft travel through lower flight levels where drones can be found.

6.5.1.2 Fuel tank

(CASA, 2013) suggests that, contrary to the previous belief that any debris which penetrates a wing fuel tank would produce a catastrophic event, it may be more reasonable to assume that catastrophic consequences are unlikely due to the current regulations on fuel tanks. These dictate that fuel thanks should be isolated in a way such that "damage from a disc fragment will not result in loss of fuel required to complete the flight" (FAA, Design Considerations for Minimizing Hazards Caused by Uncontained Turbine Engine and Auxiliar Power Unit Rotor Failure, 1997). For reference, bird-strike events which resulted in rapid fuel leak have resulted in no causalities.

Additionally, as defended by (Wilde & Draper, 2010) and (FAA, AC 39-8, 2013): "small penetrations of aircraft fuel lines or aircraft fuel tanks, where the combined penetration areas exceed two square inches (13cm2), is a level 3a classification". A 3a classification only refers to concerns over exhaustion of fuel reserves, i.e., the tank being emptied out as a result of the penetration. This is considered a medium-risk situation and hence a smaller piece will not be deemed a serious situation.

This report will follow the classification on fuel tank impact severity as show in Figure 9.

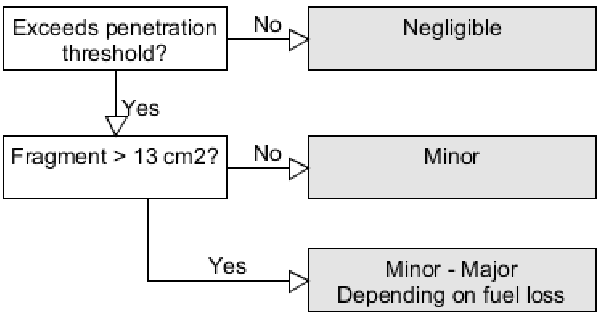

Figure 9: Severity assessment in case of a drone collision which hits the aircraft's fuel tank. Adapted from (Wilde & Draper, 2010)

Severity of penetration to the fuel tank shall be conditioned upon the amount of fuel loss as defined per 3a classification. If the loss rate limits the aircraft's safe approach to a runway, consequences may be major.

6.5.1.3 Fuselage and wings

(CASA, 2013) performed empirical tests on a perpendicular impact of different drones with typical fuselages. The objective was to verify at which velocity the components of the drone were capable of penetrating the fuselage. Table 11 displays the velocity at which penetration occurs. Naturally, for a ticker fuselage, penetration is expected to require a higher velocity.

	UAV - 0.47 kg	UAV - 1.56 kg	UAV - 2.73 kg

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Fuselage thickness	Motor	Battery	Camera	Motor	Battery	Camera	Motor (Single engine)
1/8"	200kts	180kts	150kts	150kts	120kts	120kts	60kts
1/16"	100kts	80kts	70kts	70kts	60kts	60kts	45kts

Table 11: Velocity at which components of a drone penetrate a typical fuselage (CASA, 2013).

During approach with fully extended flaps, for a commercial large aircraft, velocity is typically between 160 kts and 180 kts. As a result, on take-off or landing, all components are expected to penetrate a 1/16" fuselage and all, except for the motor of a small quadcopter, are predicted to penetrate a 1/8" fuselage.

A perfectly perpendicular impact is not the most common case for drone collisions. However, it is the worst-case scenario and therefore accepted as a worst-case severity assessment.

The consequences of fuselage and wing penetration depend on the type of the aircraft. The high-impact areas described in section 6.5 are considered the vulnerable areas. The impact on other areas is considered negligible. As a result, the judgment displayed in Figure 10 will be used.

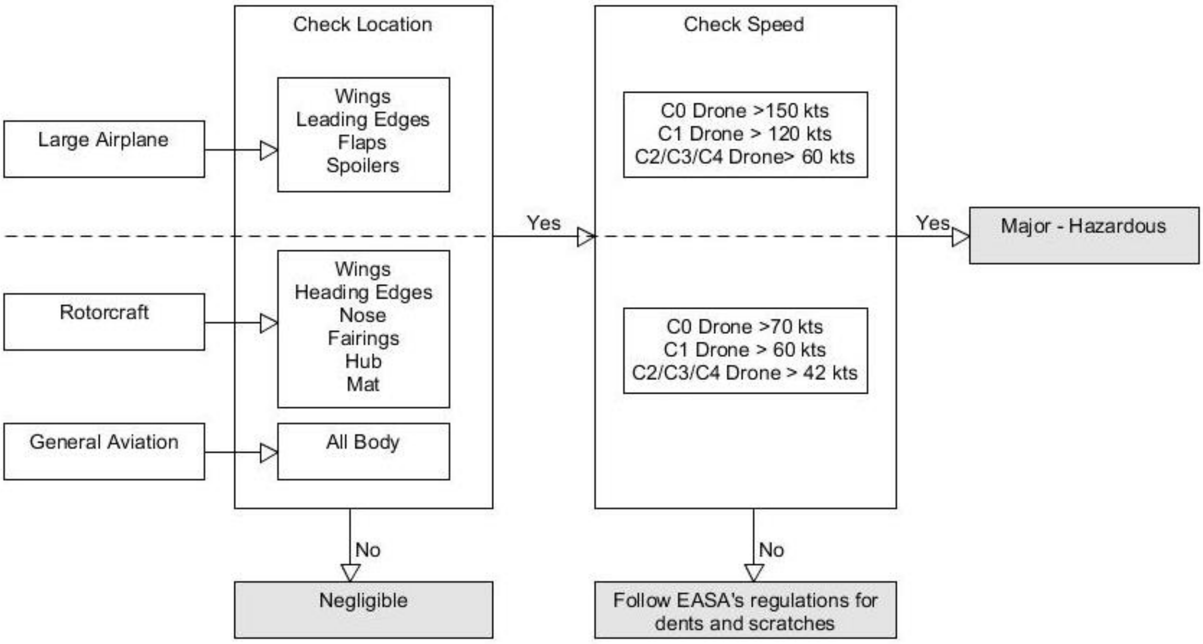

Figure 10: Severity assessment in case of a drone collision which hits the aircraft fuselage.

As defined per (EASA, "Drone Collision" Task Force, 2016), penetration of the high-impact areas is considered of Major impact. It can escalate to a Hazardous severity, especially in rotorcraft and general aviation, when, as a result of the penetration, significant mechanical damage occurs.

In case the speed of the drone is not sufficient to cause penetration, it may still cause serious deformation to the structure and limit its performance. There is no experimental data regarding at which speeds deformations may be an impediment to the operation of an aircraft. As a result, EASA's dents and scratches classification from Table 10 should be used for this case.

For each drone, the minimum speed necessary for one of the components described in Table 11 to penetrate the fuselage was used as threshold. Naturally, for each specific situation one would have to check whether the drone indeed has this component. However, since this is a worst-case scenario it is a valid assumption to assume that the drone would have the considered typical components.

6.5.1.4 Windshield

Windshield penetration is considered critical damage to the aircraft as it may easily reduce/block visibility or cause injuries to the crew in case the drone enters the cockpit.

(CASA, 2013) performed different windshields test for commercial and general aviation. As previously mentioned, the materials used for generation aviation windshields tend to be more sensitive to impact and, therefore, lower speeds necessary for penetration are expected.

Windshield thickness	UAV - 0.47 kg			UAV - 1.56 kg			UAV - 2.73 kg
	Motor	Battery	Camera	Motor	Battery	Camera	Motor (Single engine)
Commercial aviation 1/8“	250kts	200kts	190kts	190kts	140kts	140kts	85kts
General aviation 1/16“	125kts	110kts	90kts	85kts	75kts	75kts	40kts

Table 12: Velocity at which drone components penetrate a typical windshield (CASA, 2013).

Tests show that, indeed, the type of windshields used for general aviation are more vulnerable to penetration. (MAA, 2016) achieved similar results in laboratory tests with helicopter windscreens, concluding that these tend to have a low resistance to all different classes of drones. (ATSB, 2017) mentions that there are numerous examples of birds penetrating the windscreen of general aviation aircraft and incapacitating the pilot. However, in comparison, for high capacity transport operations there are no examples of birds penetrating the windscreen.

In this report, the judgment displayed in Figure 11 is used for severity assessment.

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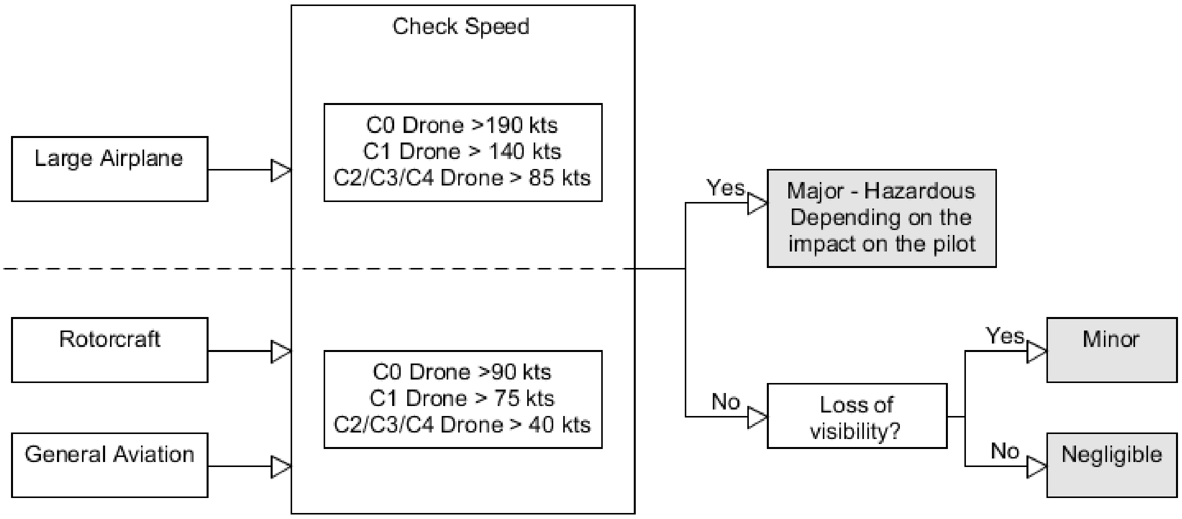

Figure 11: Severity assessment in case of a drone collision which hits the aircraft's windshield.

As defined in (EASA, "Drone Collision" Task Force, 2016), penetration of the windshield is considered of Major impact. It can escalate to a Hazardous severity, especially in rotorcraft and general aviation, when, as a result of the penetration, the pilot is incapacitated.

6.5.1.5 Rotors

(MAA, 2016) performed tests on the impact of drones on helicopter rotors, concluding that, due to the high speed of a rotating blade, these are vulnerable to critical impacts from all types of drones. Even small drones could result in blade failure.

Compared to main rotors, tail rotors are of lighter construction with less substantial leading edges (EASA, Research Programme On Collisions with Drones: Work Area 1 Final Report, 2017). They are, therefore, considered even more susceptible to danger in the event of impact.

Only military helicopters are expected to be able to endure a drone hit to the rotors. A US Army Black Hawk helicopter was able to land safely after a similar accident (Board, 2017). However, these helicopters are a special case of resistance, and this report will, instead consider severities for the majority of the helicopters.

In this report, all hits to rotors will be considered of Hazardous severity.

6.5.2 Impact on crew/occupants

Adding to physical damage, severity of a drone collision must also take into account the resulting impact on the crew, occupants and operations.

(EASA, "Drone Collision" Task Force, 2016) defines the severity levels as shown in Table 13.

	Catastrophic	Hazardous	Major	Minor	Negligible
Occupants	Multiple fatalities	Serious or fatal injury to a small number of passengers or cabin crew	Physical distress, possibly including injuries	Physical discomfo rt	Inconvenience
Flight Crew	Fatalities or incapacitation	Physical distress or excessive workload impairs ability to perform tasks	Physical discomfort or a significant increase in workload	Slight increase in workload	No effect on flight crew

Table 13: Severity classification of a drone collision at crew/operations level. Adapted from (EASA, "Drone Collision" Task Force, 2016). (EASA, "Drone Collision" Task Force, 2016) uses a *High, Medium* and *Low* severity assessment which was adapted to the one used in this report (Table 7).

6.6 Drone/Aircraft Collision

For most collisions, its severity is defined taking into account both the impact on the physical structure of the aircraft as well as the impact on the crew and operations. The assumption made in this report is that the severity can be categorized as the highest impact found on any of the two areas. For example, an aircraft might have suffered non-significant mechanical damage as a result of the collision with the drone. However, if found that it has resulted in fatalities from either the cabin crew or the occupants, the collision must be categorized as High severity. The advantage of this assumption is to be able to gather several risk areas/factors into a single definition of severity. However, the use of a different assumption would possibly have resulted into a different severity categorization. The results of this report should then be kept in context of the assumptions and choices herein made.

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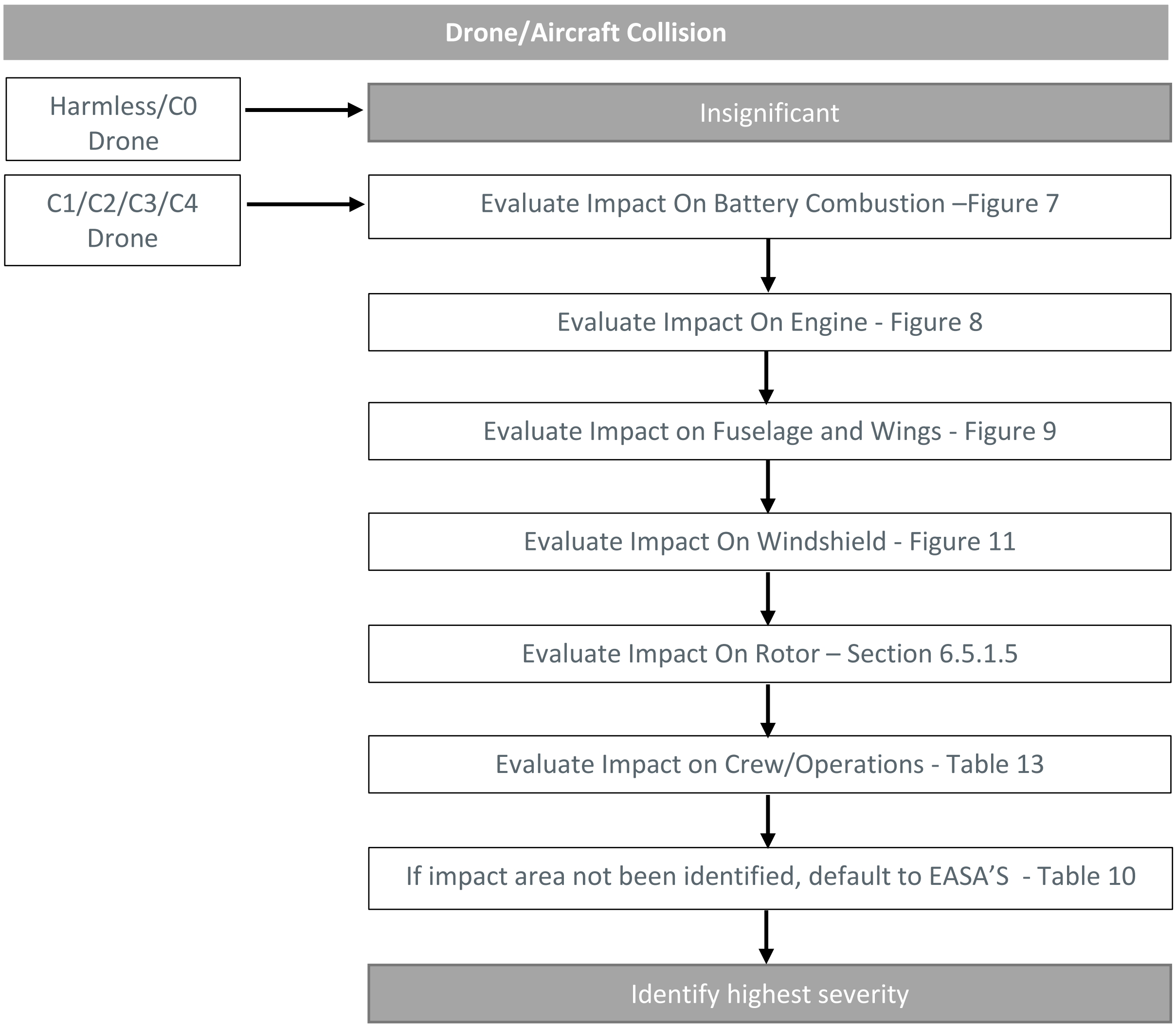
Drone/Aircraft Collision
Harmless/C0 Drone
Insignificant
C1/C2/C3/C4 Drone
Evaluate Impact On Battery Combustion –Figure 7
Evaluate Impact On Engine - Figure 8
Evaluate Impact on Fuselage and Wings - Figure 9
Evaluate Impact On Windshield - Figure 11
Evaluate Impact On Rotor – Section 6.5.1.5
Evaluate Impact on Crew/Operations - Table 13
If impact area not been identified, default to EASA'S - Table 10
Identify highest severity

6.7 Drone/Ground Collision

The severity of a drone hitting the ground will be considered to include two components: possibility of battery igniting once the drone hits the ground, and how fatal the free-fall would be to a person standing directly underneath the drone.

6.7.1 Hitting a person

A collision between a drone and a person will typically occur when a drone falls to the ground and injures a passer-by. For simplicity, it is assumed that a drone is not large enough to injure multiple people simultaneously, so only one person will be considered during free-fall.

Injuries can have different severities, from lacerations (Guardian, 2015), to serious injuries such as losing an eye (BBC, BBC News, 2015), to even fatalities.

No quantification currently exists on the potential for drones causing non-fatal wounds. Risk assessment is, on first analysis, primarily done on fatal injuries as a worst-case scenario.

6.7.1.1 Probability of fatal injuries

In order to identify the risk for a passer-by, the kinetic energy of the drone is associated with the energy capable of harming the human body. This is an oversimplification of the impact of a drone. However it is considered a reasonable measure for an initial analysis.

When analysing the human body, one must keep in mind that different parts of the body react differently to force of impact. Additionally, not all areas are prone to fatal injuries. However, quantifying these different parts is an extensive task.

Both (Shelley, 2016) and (FAA, FAA UAS Center of Excellence Task A4: UAS Ground Collision Severity Evaluation, 2017) use the research conducted by (Henderson, 2010) and (Swisdak, 2017) where the probability for lethality is related to impact force. By combining the latter with the kinetic energy of a free falling drone at a specific height, (Shelley, 2016) concluded the fatality probabilities per drone type as displayed in Figure 12. Naturally, the bigger the mass of drone and the initial height of the drone's free fall, the higher the impact energy will be.

The maximum height was set at 400ft as this is the maximum operation height allowed by FAA's regulation. Most drones that do not have GPS are usually limited to 80-100 feet from the remote control, so it would not be possible to fly up to 400 feet anyway.

(Cour-Harbo, 2017) proposed a mass threshold of 250 gram for "Harmless" drones (which was later used by (EASA, "Drone Collision" Task Force, 2016)), which they found has an expected fatality rate equivalent to that of manned aviation. It should be taken into account that this study considered a "very low person density on the ground", therefore their estimation of drone incidents was not only based on the impact force but also on how likely it would be for a drone that size to actually hit a person on a very low-density location. This was probably an important factor in the decision to set 250 grams as a limit for harmless drones, as, according to Figure

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12, “harmless” drones still have a considerable probability of resulting in a fatality, when hitting a person falling from 150 feet or higher.

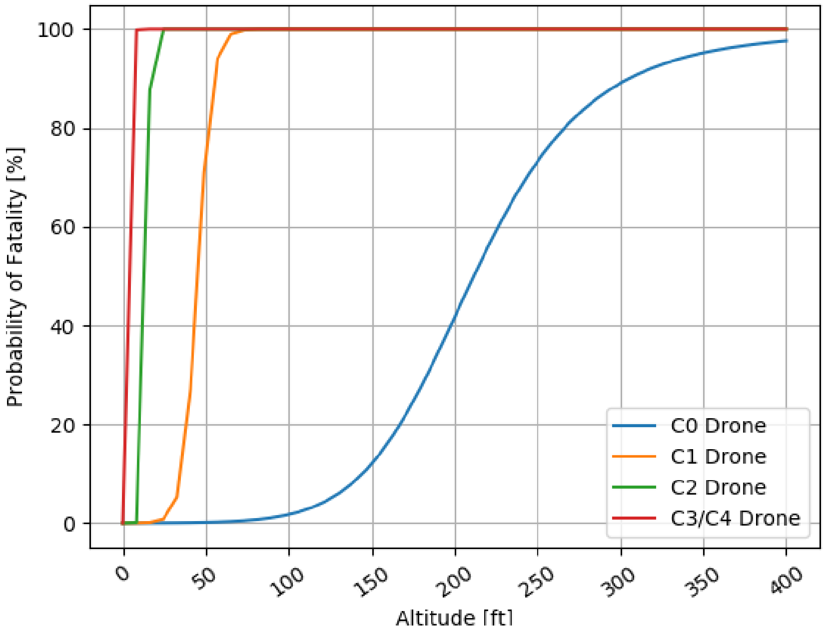


Figure 12: Probability of a Fatality if Impact Occurs, by type of drone and free fall height. Adapted from (Shelley, 2016).

In this report, the judgment displayed in Figure 13 will be used for severity assessment.

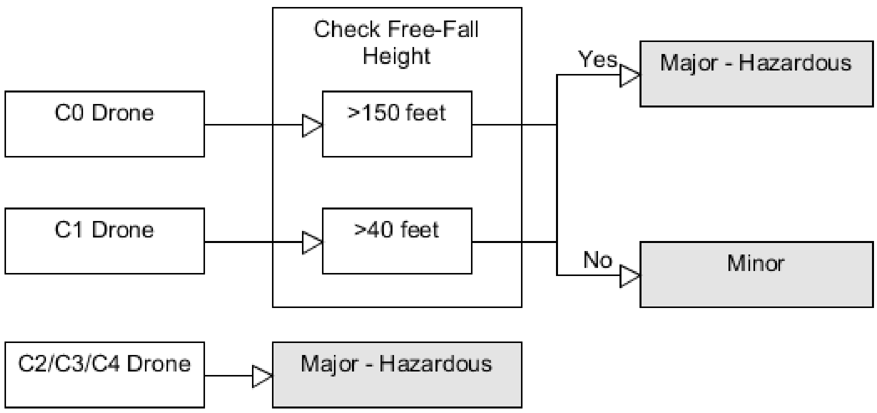


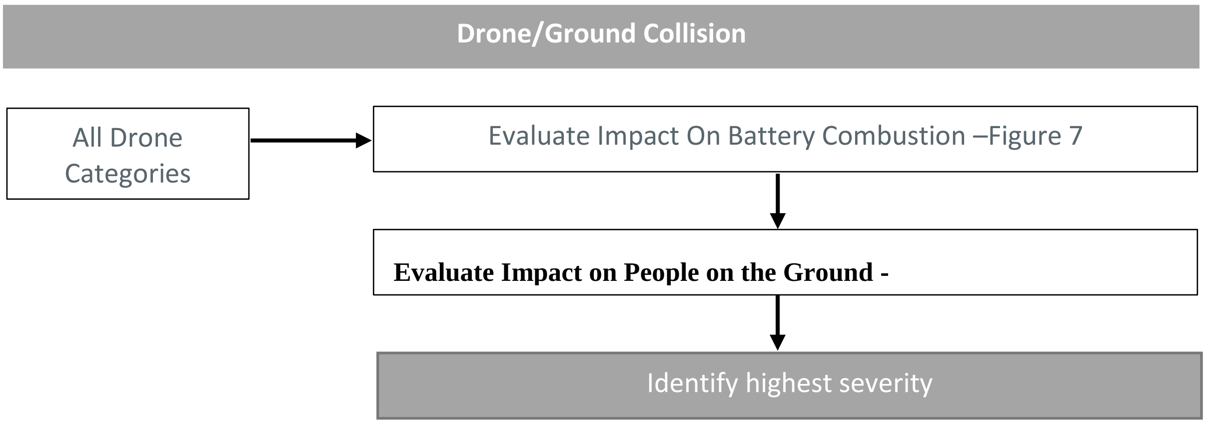
Figure 13: Severity assessment in case of a drone collision with a person. Adapted from (Shelley, 2016).

As the height increases, and the probability of fatality along with it, severity increased from Major to Hazardous. Drones within categories C2, C3 and C4 are expected to have high fatality probabilities starting from very small heights. For C1 category drones, fatality changes are considered negligible before about 40 feet. For C0/harmless drones, this threshold increases to 150 feet.

By only taking into account the probability of the impact of a drone being fatal and not the probability of a drone falling on top of a person, it is clear that starting at 100 feet all masses can be fatal.

6.7.2 Severity calculation

Severity of a drone hitting the ground will take into account both the fact that the battery may ignite as a consequence of a puncture and that it may hit a person. Is it of relevance that the probability of the drone hitting a person in a specific area, given the population density, is not taking into considered, just the fatality of the impact once it happens.



6.7.3 Effect of Parachutes

Other factors may play a part in reducing the height impact of the fall in terms of creating resistance during the fall and, consequently, reducing the force of impact. These effects are, however, not studied sufficiently and therefore were not included in the severity factors. One of these factors is the inclusion of a parachute.

Parachutes can be used as safety devices in order to provide sufficient deceleration to free-falling drones and, therefore, lowering their impact energy.

It is currently being considered that drones may be safe to fly above big crowds in case these carry a parachute which will trigger during descent. The DJI Inspire 2 drone has been certified to legally fly over small groups of people thanks to the result of its parachute descent system (DJI, 2019). Not many studies have been performed in this area apart from the results released by companies attempting to create a new drone with parachute product.

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6.8 Concluding Remarks

A mid-air collision between a large airliner and a drone is not likely to result in a severe situation unless the drone is able to penetrate critical areas. In-place safety regulations have made this category more resistant to situations once considered of high risk.

General aviation and rotorcraft are more vulnerable to collisions due to the quality of materials employed in their manufacturing in case of GA, and the passing velocity of the rotor blades in case of rotorcraft. Penetration of the windshield and impact on the rotor are considered high-risk events which have a history of injuries in events with bird strikes.

Given the results of the severity study of collisions between drones and people, the use of other than C0 or C1 category drones in operations in populated areas may lead to severe safety consequences. Additionally, the proposed analysis also shows that the 250 grams threshold defined for "harmless"/C0 drones only has a low level of risk for operations until 150 feet of altitude. Higher altitudes already present a considerable probability of fatality in case of impact.

As this report illustrates, the severity of a collision depends on several factors, much of which are still not fully investigated. For example, no experimental data exists currently to validate the effect of batteries or materials used in the construction of drones. Once experiments in these areas have been conducted, the conclusions of this report might be modified in accordance.

It would be wise to put focus in the near future, in particular, in general aviation and rotorcrafts which have been identified as being especially vulnerable to drone collisions. As mentioned in (CAA, 2018), the findings of such researches could be used by aircraft certificating authorities in determining whether there is a need to review certification specifications to protect against drone collision.

6.9 Future Work Recommendations

There are still many factors which affect the damage of collision with a drone that have not been included or evaluated in this report due to a lack of information. The following areas are recommended as worthy of attention in the future:

- Assessing the behaviour of lithium batteries on impact with structures. Section 6.4.4 mentioned that many researchers believe that the possibility of ignition of these batteries on impact are a sever source of danger. However, no experimental or theoretical assessment has been made yet on this area.
- On-board of the drone there may be chemicals which may be hazardous. No information could be gathered on this topic.
- Materials used in the construction of drone must be evaluated in terms of frangibility.
- Payload position must be studied in terms of the influence on impact force. It's detachment from the body on collision could help reduce this force. However, nowadays, some types of drones have embedded payloads in order to create a more

aerodynamic shape. It would be of interest to study the disadvantage of these systems on impact force.

- Parachutes can heavily reduce the impact force of a free-falling drone. As mentioned in section 6.7.3, with this innovation drones could reach the safety threshold necessary for operations in populated areas. For now, only data from commercial companies interested in manufacturing these products is available. It would be of interest to have an independent research on this field.

- Human decision-making errors have not yet been assessed in case of collision with a drone. Apart from the fact that not many collisions have been reported as these are not mandatory, members of the aviation world may not be predisposed to report a situation where they may be at fault or receive a penalty for.

- The damage to a person by a drone was made in the worst-case scenario of a direct injury to the head. Cases where the drone would hit other exposed parts of the human body, such as shoulders, arms or hands, may also be considered. The impact to these areas is not expected to be as severe as a direct impact to the head.

The outcome of the previous research could possibly help in creating new regulations or procedures which could reduce the risk and damage resulting from collisions with drones. Additionally, another valuable area of focus would be to identify technology innovations which could lead drones to respect these in-place regulations.

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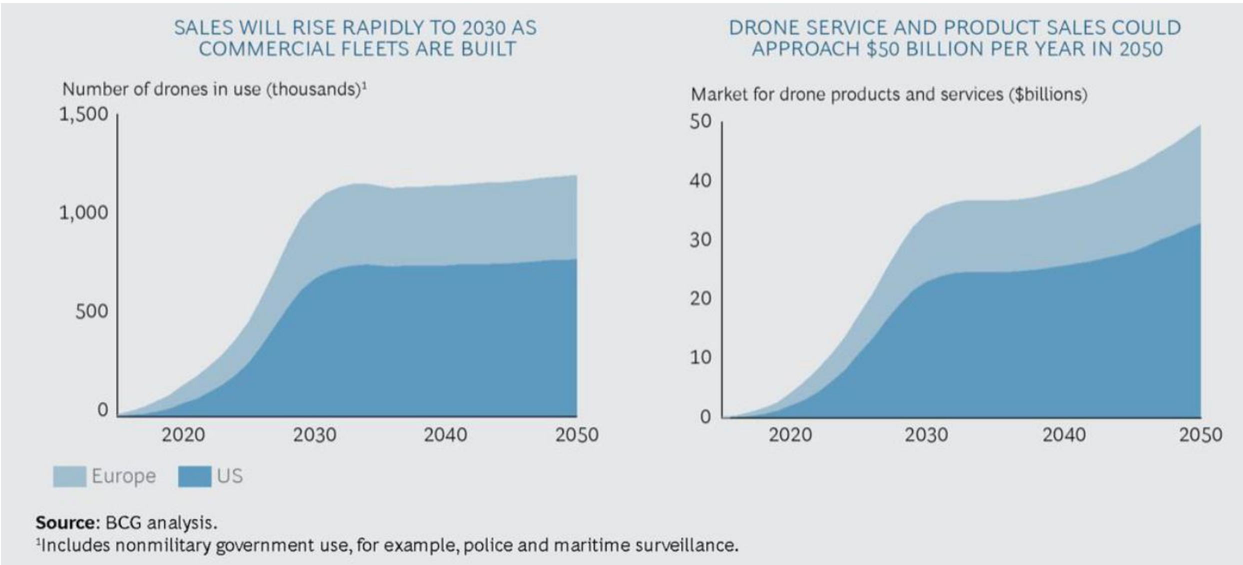
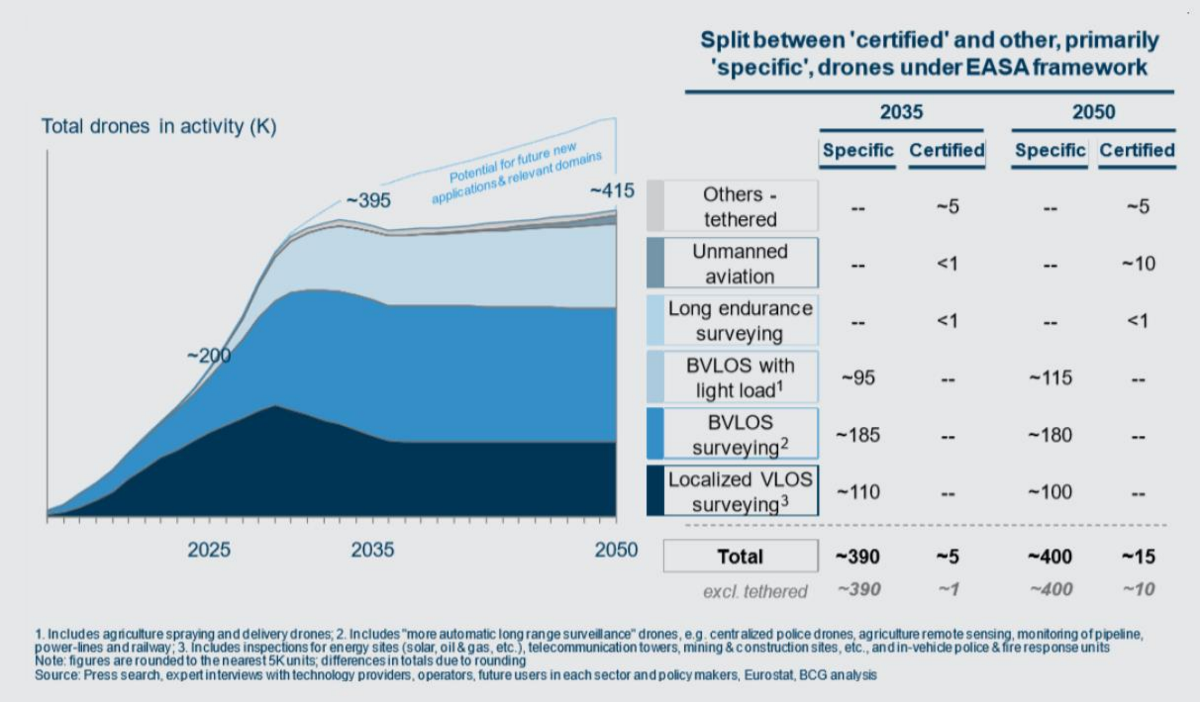
7 Appendix C - Identification of classes of drones and categories of drone operations

7.1 Market outlook and introduction

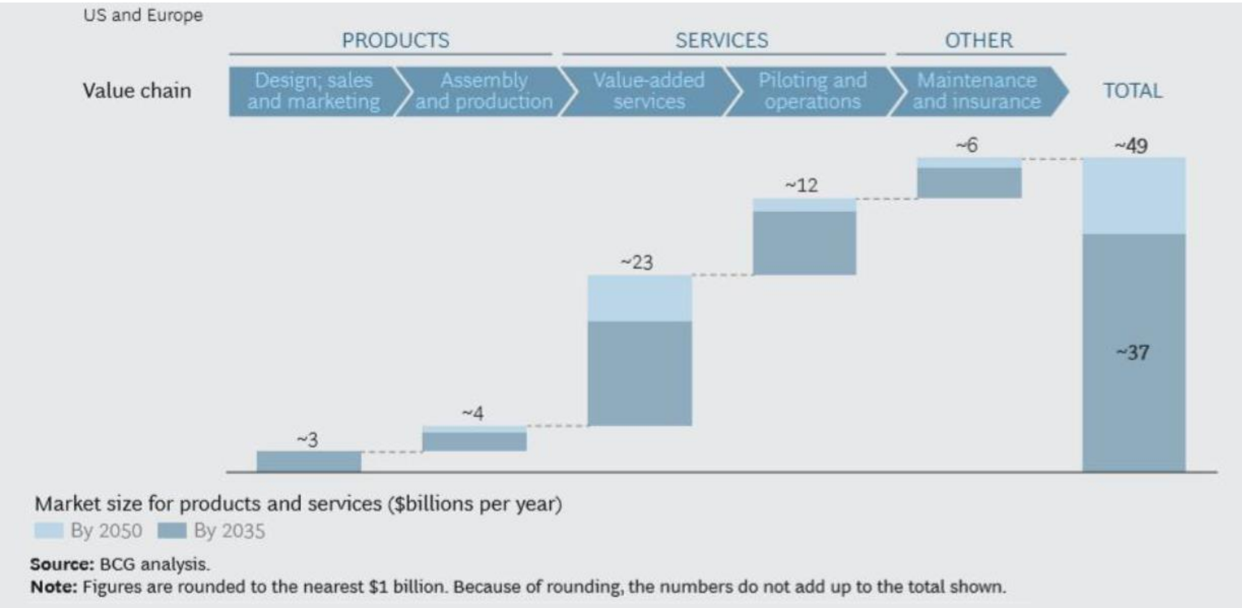
The RPAS/drones technology is considered as a disruptive technology with a (potentially) large market. The worldwide drone market is estimated at 14 billion USD in 2016 with an average annual growth rate of 18% (MarketsAndMarkets, 2018). The Boston Consultancy Group had a lower estimation of the worldwide market in 2016, but shares the estimated market growth up to 2030 as is depicted in the figure below (BCG, 2017).



The SESAR Joint Undertaking conducted a study (SESAR Joint Undertaking, European Drone Outlook Study, 2016) predicting the applications of drones in Europe. The figure below shows the expected growth to 2030 followed by a consolidation. The majority of drone systems are expected to be applied for VLOS and BVLOS operations with a marginal application for long endurance surveying.



The BCG study shows that the highest drone value can be found in the services domain and only for a limited part in the design, production and maintenance of drones.



When looking at the current type of drone applications they are widespread and many more are envisioned for the future (Blyenburgh, 2018). Categorization of drone operations based on their specific application will lead to a huge variety and, with the exception of transporting or drones containing hazardous materials, it is irrelevant in terms of safety risks if application A or application B is performed as long as it’s with the same type of drone in the same area with the

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same operational characteristics. Furthermore a specific type of operation with a specific drone may have a large variety in risks depending on the location. Hence, a different, and more flexible, operational categorization is looked for.

This section identifies the various types of drone operations, in terms of the presence of other aircraft, persons or critical infrastructure on the ground as derived from literature. Starting point is the categorization applied in the regulatory proposals, also referred to as the EASA categories. One of those categories, the Specific category, is further categorised primarily based on the operational characteristics affecting ground and air risks aspects, using a Specific Operational Risk Assessment (SORA) (JARUS, 2019). Eurocontrol (Eurocontrol, 2018) took these as a starting point and derived airspace assessment guidelines to determine which zones of airspace drones may or may not operate in. In addition to the SORA’s ground and air risk this assessment guideline identifies three more considerations (aviation related areas and volumes, non-aviation related areas and volumes, Communication Navigation and Surveillance systems). Next to these aspects, it’s looked for whether or not types of drone operation are affected by the application of U-Space services. All these aspects are further detailed hereunder and concluded with some remarks providing a synthesis on the types of drone operations.

7.2 EASA categories

In accordance with EC (EASA, Regulation (EU) 2018/1139, July 2018), (European Comission, Commission Delegated Regulation on unmanned aircraft intended for the use in the “Open Category, and on third-country operators of unmanned aircraft systems, Draft Version, 2019) and (European Comission, Commission Implementing Regulation on the rules and procedures for the operation of unmanned aircraft, Draft Version, 2019) operations of UAS in Europe will be classified in 3 categories:

- “the 'open’ category is a category of UAS operation that, considering the risks involved, does not require a prior authorisation by the competent authority nor a declaration by the UAS operator before the operation takes place;
- the ‘specific’ category is a category of UAS operation that, considering the risks involved, requires an authorisation by the competent authority before the operation takes place, taking into account the mitigation measures identified in an operational risk assessment, except for certain standard scenarios where a declaration by the operator is sufficient or when the operator holds a light UAS operator certificate (LUC) with the appropriate privileges;
- the ‘certified’ category is a category of UA operation that, considering the risks involved, requires the certification of the UAS, a licensed remote pilot and an operator approved by the competent authority, in order to ensure an appropriate level of safety.”

7.2.1 OPEN category

Several RPAS classes are defined for the OPEN category. Per class an operational limitation is given. The classes are identified by a code C0, C1, C2, C3, C4 or ‘privately built’. The class defines the maximum take-off mass (MTOM) of the UAS, the operational conditions, the remote pilot competency, and requirements and documentation of the UAS.

The OPEN category is for UAS operation with low risk, the UAS has a MTOM less than 25kg and a max height of 120m, VLOS operation and far from aerodromes. The area of operation, the proximity of people, crowd or urban areas, depends on the MTOM of the UAS. If a UAS or kind of the operation cannot meet these requirements the SPECIFIC category is needed.

The open category distinguishes two type drones, those that are privately build and those that are built by a manufacturer.

<u>Privately built UAS</u>

There two classes privately built UAS:

- MTOM <250g
  In this class the UAS may fly over uninvolved people (subcategory A1) and there are no remote pilot competency requirements.
- MTOM <25 kg
  The UAS must fly far from people and urban areas (subcategory A3), the requirements for operator and pilot are the same as for class C2; the UAS operator is registered, the pilot has successfully finished an online training and online test.

For the ‘privately built’ there are no requirements defined for the UA or the UAS manual.

<u>UAS of a manufacturer</u>

In the OPEN category 5 different classes are defined

- Class C0 : MTOM <250g
  In this class the UAS may fly over uninvolved people with a max speed of 19 m/s in level flight, limited to a max height of 120m above surface or take-off point. If equipped with a ‘follow me mode’ the UA will remain within 50m from the pilot, the pilot will have a regain control and emergency possibility. There are no remote pilot competency requirements.
- Class C1 : MTOM <900g or 80J
  In this class the UAS may fly over uninvolved people with a max speed of 19 m/s in level flight the UA has a max height of 120m or is equipped with a system that limits the height and gives clear information about the height to the pilot. If equipped with a ‘follow me mode’ the UA will remain within 50m from the pilot, the pilot will have a regain control and emergency possibility.
  The UAS operator is registered, the pilot has successfully finished an online training and online test.
- Class C2 : MTOM <4kg
- In this class the UAS may fly at a safe distanced from uninvolved people with a max height of 120m or is equipped with a system that limits the height and gives clear information about the height to the pilot. If the US is not a fixed wing it should be equipped with a low speed mode of max 3 m/s. If tethered the tether is less than 50m and has a defined strength. The UAS operator is registered, the pilot has successfully finished an online training and a theoretical test in a centre recognized by the aviation authority.

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- Class C3 : MTOM <25kg
- The UAS must fly far from people and urban areas. If tethered the tether is less than 50m and has a defined strength. The UAS operator is registered, the pilot has successfully finished an online training and online test.
- Class C4 : MTOM <25kg
  Same as class C3, but with an UAS without automatic control modes

A more detailed overview of the OPEN category aspects and requirements is depicted in the overview hereunder.

operation	sub category	A1 Fly over people			A2 Fly **close** to people	A3 Fly **far** from people		
operation	area of operation (far from aerodromes, max height 120 m)	You can fly over **uninvolved people** (at height >3m but not over crowds)			You can fly at a safe distance from **uninvolved** people	You should: • fly in an area where it is **reasonably expected** that **no uninvolved** people will be **endangered** • keep a **safety distance** from **urban areas**		
UAS	Class	privately built	C0	C1	C2	C3	C4	privately built
UAS	MTOM or Joule	<250g		<80J or <900g	< 4 kg	< 25 kg		
UAS operator registration				Yes	Yes	Yes		
remote pilot competency	Online training			Yes	Yes	Yes		
remote pilot competency	Online test			Yes	Yes	Yes		
remote pilot competency	theoretical test in centre recogn by the aviation auth				Yes			

EASA info limits&obligations			Yes	Yes	Yes	Yes	Yes	
manual	ops restrictions and warnings		Yes	Yes	Yes	Yes	Yes	
manual	UA characteristics, trouble shooting procs			Yes	Yes	Yes	Yes	
manual	freq electr ident emmission			Yes	Yes	Yes		
requirement for UA	designed + manufactured for fly safely, CE marking		Yes	Yes	Yes	Yes	Yes	
requirement for UA	max speed		19 m/s	19 m/s	no FW select <3m/s			
requirement for UA	equipped with max alt		120m	120m or selectable heigth + pilot info				
requirement for UA	follow me: <50m from pilot + regain control + emerg		Yes	Yes				
requirement for UA	thetered drone <50m + defined strength tether				Yes	Yes		
requirement for UA	safely controllable following manufact instruct		remote pilot	pilot	pilot	pilot	no autom modes	
requirement for UA	unique serial nr		Yes	Yes	Yes	Yes	Yes	
requirement for UA	broadcast e-identification		Yes	Yes	Yes	Yes	Yes	
requirement for UA	req mechanical strength			Yes	Yes			
requirement for UA	design construction minise injury		Yes	Yes	Yes			
requirement for UA	max electricity		24V DC, AC	24V DC, AC	48V DC, AC	48V DC, AC		
requirement for UA	geo awareness system			Yes	Yes	Yes		
requirement for UA	geo fencing			Yes	Yes	Yes		
requirement for UA	battery low			Yes	Yes	Yes		
requirement for UA	data link protected				Yes unless tethered			
requirement for UA	after LoL reduce effect third party: method to recover or terminate			Yes	Yes unless tethered	Yes unless tethered		
requirement for UA	nav lights for controllabitiy			Yes	Yes + for vis ablility	Yes + for vis ablility		
requirement for UA	sound pressure <60 dB(A) at 3m			Yes	Yes			

7.2.2 Specific category

If the operation cannot be performed within the limitation of the OPEN category a risk assessment (SORA) is an excepted way to find out if the operation is possible within the limitations of the SPECIFIC category. Alternatively this assessment may already been performed by another operator (with the subsequent issuance of a standard scenario) or the operator holds a Light Unmanned aircraft operator Certificate with approved procedures to assess the operation himself. If the SPECIFIC limitations are not met, the operation falls in the CERTIFIED category.

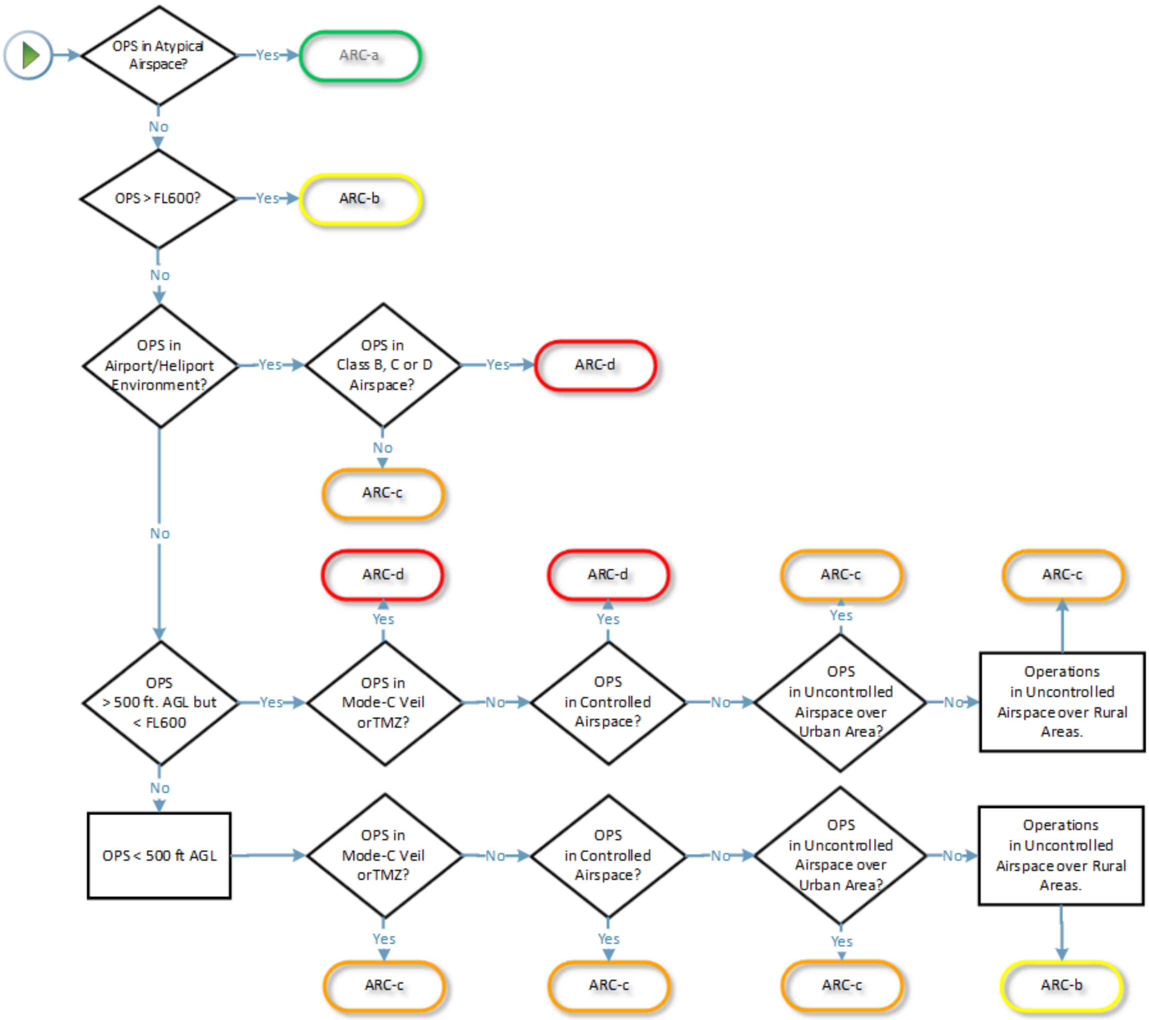
The requirements for UA in the SPECIFIC category will depend on the risk, but are not defined as detailed as in the OPEN category. This risk based approach makes it difficult to categorize UA.

In the SORA the ground risk and air risk is assessed. The ground risk class (GRC) depend on weight (dimension) and kind of operation. A BVLOS flight in populated area with a UA heavier than 25kg is not forbidden but increases the GRC and can result in CERTIFIED category operation.
To lower the Ground Risk, SORA proposes ad hoc mitigations (named harm barriers) which could take the form of a parachute or means to ensure the technical containment of the aircraft (e.g. the use of a tether).
To lower the Air Risk, some Strategic Mitigations are potentially available, in order to demonstrate in a Strategic phase that the risk of collision in certain airspace is lower than predicted by SORA.
The combination of ground and air risk will result in a level of integrity and level of assurance for Operation Safety Objectives (OSO). If sufficient mitigation of the ground risk is not possible or it's the intention to have persons on board, the drone and its operation falls in the CERTIFIED category. For this category certification specifications and other regulations in analogy with manned aviation will be defined.
Within the SORA process a CONOPS needs to be established as a basis for the assessment. That CONOPS forms the basis for determining the associated ground and air risk.

For determination of the Ground Risk Class, the SORA applies the following operational categorisation:

- VLOS/BVLOS over controlled ground area
- VLOS in sparsely populated environment
- BVLOS in sparsely populated environment
- VLOS in populated environment
- BVLOS in populated environment
- VLOS over gathering of people
- BVLOS over gathering of people

The SORA uses the operational airspace defined in the ConOps as the baseline to evaluate the intrinsic risk of mid-air collision and by determining the air risk category (ARC). The ARC is



defined as "a qualitative classification of the rate at which a UAS would encounter a manned aircraft in typical generalized civil airspace"

To determine the ARC the below decision tree should be applied.

ARC-a is generally defined as airspace where the risk of collision between a UAS and manned aircraft is acceptable without the addition of any tactical mitigation. (f) ARC-b, ARC-c, ARC-d are generally defining airspace with increasing risk of collision between a UAS and manned aircraft.

7.2.3 Certified category

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The requirements for UA in the CERTIFIED category are not defined yet, but expected to be similar to manned aviation. EASA is expected to publish a NPA on the certified category by the end of 2019. Although specific requirements are not defined yet, for sure both the aircraft and the operator shall be object of certification processes and a remote pilot license is required as well. Based on the assumption that for the CERTIFIED category existing manned regulations are adapted to accommodate unmanned aspects their operational classification is considered to be similar as to manned aviation. This is substantiated by the publication of a SPECIAL CONDITION for Vertical Take-Off and Landing (VTOL) Aircraft (EASA, Proposed Special Condition for small-category VTOL aircraft, Doc. No: SC-VTOL-01 Issue: 1 (proposed), 2018) Which is explicitly applicable to aircraft with pilot on-board, remotely piloted or with various degrees of autonomy.

7.3 UAS ATM Airspace Assessment Guidelines

The UAS ATM Airspace Assessment guideline (Eurocontrol, 2018) provides a basis for discussion on airspace assessment for integrating UAS into air-traffic management (ATM). In that report an airspace assessment is considered to involve critical look at a certain airspace volume to identify the types of operation that will be conducted in that airspace, and examining the associated air and ground risks. These guidelines identify several types of environment to be taken into account when performing an airspace assessment, being:

For GROUND RISK

PEOPLE

Population-related

- Permanently or cyclic populated areas (cycle < 1 day)
- Dense areas (city centre streets, etc.)
- Sensitive areas (schools, hospitals, etc.)
- Occasional or seasonal events (concerts, stadiums, beaches, etc.)

Security-related

- Military barracks
- Summits
- VIP protection

INFRASTRUCTURE

Industry-related

- Permanent and non-permanent industrial sites
- Chemical and Nuclear sites
- Laboratories
- Windfarms, power stations
- Cranes

Transport-related

- Airports, aerodromes and identified take-off and landing sites, model-flying sites
- Roads and highways
- Harbours

• Rail

Security-related
• Military areas

ENVIRONMENT-RELATED
• Animal Reservations

For AIR RISK
• High probability of traffic (hospitals, etc.)
• Seasonal or permanent recreational activities (base jump, flying suits, kite surf, etc.)
• Localised events (hotels water jets, geysers, etc.)
• Airports, aerodromes and identified take-off and landing sites, model-flying sites

THREAT-RELATED
• Electro-magnetic wave-emitting sites (radars, high-voltage lines, solar farms, etc.)
• GNSS-outage forecast areas

The role of an airspace assessment is to determine which areas of airspace are to be assigned to which classes of airspace. However, whereas traditional airspace classes are categorised based on the services provided to pilots in those airspaces, in the case of UAS the categorisation will also be a function of where those UAS are allowed to fly, what equipage they need to fly there, etc.
These guidelines must define the new classes of airspace and provide an indication of how an airspace assessor should allocate areas to these classes.

7.4 U-Space services

In accordance with (SESAR Joint Undertaking, U-Space Blueprint, 2017) U-space is capable of ensuring the smooth operation of drones in all operating environments, and in all types of airspace (in particular but not limited to very low level airspace). It addresses the needs to support all types of missions and may concern all drone users and categories of drones. In this sense 'all operating environments' are considered to include urban, suburban, rural, regardless the density of population. All types of missions are considered to include visual line of sight (VLOS) and beyond visual line of sight (BVLOS) operations and all drone users encompass commercial and leisure users as well as State (including military) and public entities. The categories of drone to be considered in this sense are the open, specific and certified categories (as described above). From this description it's clear that U-Space has the ambition to encompass all type of drone operations and does not entail an operational distinction.

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7.5 Concluding remarks (synthesis)

In accordance with EASA UAS in Europe will be classified in 3 categories, the OPEN, SPECIFIC and CERTIFIED categories.

In the OPEN category the following types of operation are envisioned all ‘far’ from aerodromes and below 120 meters height:

- A1 Fly over uninvolved people at a height in excess of 3 meters, but not over crowds
- A2 Fly close (at a safe distance) from uninvolved people
- A3 Fly far from people in an area where it is reasonably expected that no uninvolved people will be endangered and keeping a safe distance from urban areas.

For the SPECIFIC category operations are characterised through the Ground risk they pose, combined with the type of airspace.
Ground risk based operational characterization of drone operations in the SORA guidelines are specified as

- VLOS/BVLOS over controlled ground area
- VLOS in sparsely populated environment
- BVLOS in sparsely populated environment
- VLOS in populated environment
- BVLOS in populated environment
- VLOS over gathering of people
- BVLOS over gathering of people

Air risk based operational characterization of drone operations in the SORA guidelines are specified as

- ARC-a: operations in Atypical airspace
- ARC-b: operations above FL600; or operations un Uncontrolled airspace over Rural Areas below 500ft
- ARC-c: Operations in an airport/heliport environment not being class B, C or D airspace; Operations between 500ft and FL600 in Uncontrolled airspace over Urban or Rural areas; Operations below 500ft in Mode-C Veil or TMZ or in uncontrolled airspace (over urban areas).
- ARC-d: Operations in an airport/heliport environment in class B, C or D airspace; Operations between 500ft and FL600 in Mode-C Veil or TMZ or in controlled airspace.

For assessing the associated risks, Eurocontrol (Eurocontrol, 2018) provided guidelines including several types of environment to be taken into account in the assessment. These focus for Ground risk matters on people (both population related as security related), infrastructure (industry related, transport related and security related) and environment related (focussing on animal reservations). For Air risks considerations should be given to High probability of traffic (hospitals, etc.), Seasonal or permanent recreational activities (base jump, flying suits, kite surf, etc.), Localised events (hotels water jets, geysers, etc.) and Airports, aerodromes and identified take-off and landing sites, model-flying sites. Furthermore, Electro-magnetic wave-emitting sites (radars, high-voltage lines, solar farms, etc.) and GNSS-outage forecast areas are included as threat related considerations.

Based on the assumption that for the CERTIFIED category existing manned regulations are adapted to accommodate unmanned aspects, their operational classification is considered to be similar as to manned aviation.

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8 Appendix D, Domains used in the Rolling Development Plan of EUSCG (EUSCG-054 Version 2.0)

In this section an overview is given of the domains used in the Rolling Development Plan of EUSCG (EUSCG, 2018).

The domains used are:

Identify correct drone system requirements for certain type of operation:
- Risk assessment
- Standard scenario's
- Definition and classification
- Noise and environment

Ensure meeting the requirements:
- Manufacturer organisation
- Development assurance (software)
- Maintenance
- Maintenance organisation
- Operator organisations
- Qualified entities

Liability:
- Marking and registration
- Electronic identification
- Local E-identification

Implementation of requirements (technical system/HMI, training, operations):
- Design and airworthiness
    - Ground control station
    - Human Machine Interface
    - C3 datalink and communication
    - Command, control and communication
    - RPAS automation
        - Automatic modes: take-off, landing, taxiing

        - Autonomous operations
    - Cyber security
    - UA design and airworthiness
        - Batteries / fuel cell generating system
        - Detect and avoid
        - Geo-awareness
        - Navigation
        - Emergency recovery / termination systems
- Flight Crew Licensing
    - Manuals
    - Remote pilot competence
- Operations
- ATM
    - UAS traffic management
    - UAS ATM
    - U-Space
    - Service provider
    - Definition of zones
- Airports
    - Take-off / landing zones

- General
- Environment

As can be identified, these domains closely resemble the regulatory domains used by manned aviation such as:

Risk assessment and development assurance:

- SAE ARP 4754A (SAE International , Guidelines for Development of Civil Aircraft and Systems, SAE ARP 4754A, 2010)
- SAE ARP 4761 (SAE International, Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment, SAE ARP4761, 1996)
- Do-178C (RTCA, 2012)

Design organisation

- EASA part 21 subpart J ()

Maintenance organisation

- EASA part 145

Operator organisation

- EASA Air Operations regulations

Airworthiness

- EASA CS-VLA, CS-LSA, CS-23, CS-25 etc.

Flight crew licensing

- EASA FCL

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Operations

- EASA Air Operations regulations

ATM

- EASA ATM/ANS

Airports

- EASA ADR