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NLR-TR-2021-278 | August 2021

Safety Targets for UAM Vehicles

From a Third Party Risk perspective

CUSTOMER: Royal Netherlands Aerospace Centre NLR

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EXECUTIVE SUMMARY

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REPORT NUMBER
NLR-TR-2021-278

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REPORT CLASSIFICATION
UNCLASSIFIED

DATE
August 2021

KNOWLEDGE AREA(S)
Safety
Third Party Risk and Policy Support

DESCRIPTOR(S)
UAM
Third Party Risk
Individual Risk
Societal Risk
Public Acceptance

Problem area

There are numerous initiatives and on-going developments to enhance the mobility in large and densely-populated cities by means of Urban Air Mobility (UAM). These initiatives intend to provide a frequent service to transport persons over short distance at low altitude into the congested area of a large city.
The UAM vehicles are characterised by distributed, electrically driven, propulsion and corresponding advanced flight control systems.
Because these vehicles do not fit well in the descriptions of existing aerial vehicles (like regular aircraft or helicopters), EASA has published a Special Condition to specify the certification requirements for these new UAM vehicles: the SC-VTOL. The SC-VTOL indicates that the current CS-23 (small aircraft) acceptable means of compliance are no longer considered appropriate for determining the aircraft and system safety objectives, and that instead the system safety objectives for CS-25/CS-29 (large aircraft/helicopters) aircraft should be maintained as a minimum for UAM using VTOL aircraft to address the risks to persons on board and on the ground. The question is however, whether this certification standard is sufficient to enable a sizeable volume of UAM traffic over a congested area of a city taking into

account the third party safety objectives. This question is addressed in this document.

Description of work

The analysis has been based on a typical, challenging but not unrealistic, scenario where the UAM vehicle provides transport of passengers from the airport of Schiphol directly into the centre of the City of Amsterdam, to a vertiport located at the Amsterdam Central Railway station. This scenario is considered representative for the service that the Urban Air Mobility concept intends to provide.
The third party risk metrics (Individual Risk and Societal Risk) and computational model have been based on specifications in the Dutch regulations for civil airports and modified to the specifics of the UAM concept. The UAM vehicle is assumed to be type certified against the recently published Special Condition for small VTOL aircraft and meets the corresponding (internal) safety level, which is assumed to be equivalent to the safety level of a current multi-engine turbine helicopter.

Results and conclusions

Based on the specified third party risk metrics (in particular the Individual Risk) the analysis indicates that on average only one flight per day could be accommodated to a vertiport located at the Amsterdam Central Railway Station, with acceptable third party risk. It is shown that an increase of the traffic could be possible by one of (or combination of) the following measures:

- Relax the third party requirement for acceptable risk;
- Reduce the accident probability;
- Reduce the crash area (accident consequence).

It is argued that from a realistic point of view, and based on expert judgment, the first two measures will be very difficult to realise. Only the third measure could provide some improvement, by installing for instance an emergency parachute system that could reduce the crash area and lethality. It is estimated that this may support an increase in traffic volume to five flights per day.

Applicability

The results of this study may be used by any entrepreneur that would envision to initiate an UAM service into a major city in a way that he or she is aware of the associated challenges and the traffic volume that realistically can be achieved, taking into account the third party risk involved in the operation. Furthermore, the results of this study may also help the regulator to evaluate the public acceptance of UAM operations in an urban area.

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OWNER	**Royal Netherlands Aerospace Centre NLR**
DIVISION NLR	**Aerospace Operations**
DISTRIBUTION	**Unlimited**
CLASSIFICATION OF TITLE	**UNCLASSIFIED**

APPROVED BY:		**Date**
AUTHOR	P.J. van der Geest Y.S. Cheung T.M. van Birgelen	14-07-2021 14-07-2021 04-08-2021
REVIEWER	G.W.H. van Es	06-08-2021
MANAGING DEPARTMENT	A.D.J. Rutten	11-08-2021

Contents

Abbreviations

ACRONYM	DESCRIPTION
AGL	Above Ground Level
CA	Crash Area
CS	Certification Specification
EASA	European Aviation Safety Agency
eVTOL	Electrically powered VTOL
F	Frequency of occurrence
FH	Flight Hour
GA	General Aviation
ICAO	International Civil Aviation Organisation
IR	Individual Risk
N	Number of fatalities
NLR	Royal NLR - Netherlands Aerospace Centre
OWI	Orientation Value for Establishments (in Dutch: OrientatieWaarde Inrichtingen)
PDF	Probability Density (or Distribution) Function
SC	Special Condition
SERA	Standardised European Rules of the Air
SR	Societal Risk
TPR	Third Party Risk
UAM	Urban Air Mobility
VTOL	Vertical Take-Off and Landing

1 Introduction

There are numerous initiatives and on-going developments to enhance the mobility in large and densely-populated cities by means of Urban Air Mobility (UAM). The aerial vehicle used in the UAM are known for diversity in configurations and technological innovations applied[1]. The vehicle include types like multi-copter, vectored thrust and lift+cruise concepts, mostly electrically driven. In general there are a wide variety of configurations with limited common characteristics except for VTOL capability and distributed propulsion. These vehicles do not fit well in the description of small helicopters or normal category of aircraft, which are certified based on the corresponding EASA certification specifications (CS-27 and CS-23 respectively). Therefore EASA developed a Special Condition for small-category VTOL aircraft (SC-VTOL [1]) extensively based on CS-23 Amendment 5 integrating elements of CS-27 and new elements where deemed appropriate.

The special condition has been established to prescribe the technical specifications for the type certification of a person-carrying vertical take-off and landing (VTOL) heavier-than-air aircraft in the small category, with lift/thrust units used to generate powered lift and control. In order to be proportionate to the nature and risk of the particular activity to be conducted by VTOL aircraft, two certification categories are introduced in this special condition, namely Basic and Enhanced, linked to the intended type of operations. Introducing this link allows proportionality in safety objectives and enables to apply the highest safety levels of Category Enhanced to protection of third-parties when flying over congested areas and when conducting commercial air transport of passengers.
Based on this distinction it is clear that air vehicles designed to provide Urban Air Mobility will have to be certified in the Enhanced Category.

The SC-VTOL is unique in the sense that it mentions a link between third party risk and the safety objectives of the certification specification. No other EASA type certification specification specifically mentions this link. In general it is assumed that the internal safety of certified aircraft is sufficient to ensure that the risk for third parties is acceptable, or even is not considered at all.
In case third party risk would become a dominant risk, due to a specific operation, it is furthermore assumed that this is solved by specific measures, as will be further explained in Section 3.
It is argued that in general the specific measures (such as specifying public safety zones, with limited access for third parties and with the intention to protect them from aviation accidents) are difficult to realise, or are even completely infeasible, in the very densely populated area of a major city.
This means that acceptable third party risk should be an inherent element of the safety objectives of the SC-VTOL certification specifications.

This raises an essential question:

Are the current safety objectives of the SC-VTOL (for the Enhanced Category) sufficient to achieve acceptable third party risk for a sizeable volume of UAM operations, without specific operational measures?

This report addresses the above-mentioned question.

[1] In the present study these vehicles will be referred to as a UAM-vehicles.

An analysis of third party risk due to high frequent operations with UAM vehicles over a densely-populated area in a hypothetical scenario is performed, in order to illustrate the relation between the vehicle (internal) safety target and the resulting third party risk for typical UAM operations.

The third party risks are assessed in agreement with the Dutch regulatory framework, which specifies the acceptable external safety[2] level and the associated computational method. The third party risks are expressed in terms of Individual Risk (IR) and Societal Risk (SR), as explained in Section 2 of this document. In the analysis, the NLR risk calculation method for third party risk, as developed for airports, is adjusted to incorporate the risk due to flight above a city area. Appendix B gives a short description of the risk calculation method.

The main objective of the report is to provide a method and the criteria to assess UAM operations over a densely populated area, and to illustrate the correlation between internal and external safety objectives. Also it provides insight in the traffic volume that could be accommodated over urban area with acceptable third party risk, based on a realistic, but challenging, scenario for an UAM route from Schiphol airport to the inner city of Amsterdam, with a vertiport located at the Central Station.

After this introduction, this report is further organised as follows:

- Section 2 provides a short introduction to applicable third party risk metrics.
- Section 3 describes how the vehicle safety objectives are related to third party risk criteria, with focus on the UAM operations.
- Section 4 covers a hypothetical scenario for risk calculation and the assumptions made.
- Section 5 presents the results of risk calculations.
- Section 6 discusses the outcomes and conclusions.

In addition:

- Appendix A describes the model of individual risk and societal risk in a generic form;
- Appendix B addresses the modelling choices and adjustments made in the NLR risk calculation model for the purpose of analysing third party risk of UAM operations over an urban area.

[2] In this context: external safety and third party risk are equivalent and thus interchangeable in interpretation.

2 Third Party Risk Metrics

Third party risk concerns those people that are at risk while they are not involved in the activity that induces this risk. Typically, regarding aviation, the third party concerns people living and working on the ground. While not involved in any aircraft flying overhead, they may certainly be exposed to risk due to an aircraft crash. The fatality risk of people on board the aircraft, crew and passengers, is not taken into account, because these people are involved in the risk inducing activity and therefore they are not regarded as third party.

Air transport is considered an extremely safe mode of transportation. However airports generate a concentration of air traffic over the area around the airport. Furthermore, historically aircraft accident data shows that the majority (about 60%) of the accidents occur during the initial and final phases of the flight (Figure 2-1). As a result, the risk to people nearby an airport will be significantly above average. Therefore, the third party risk analysis is concentrated on the people residing in the vicinity of the airport and on the risk caused by aircraft departing from or arriving at the airport.

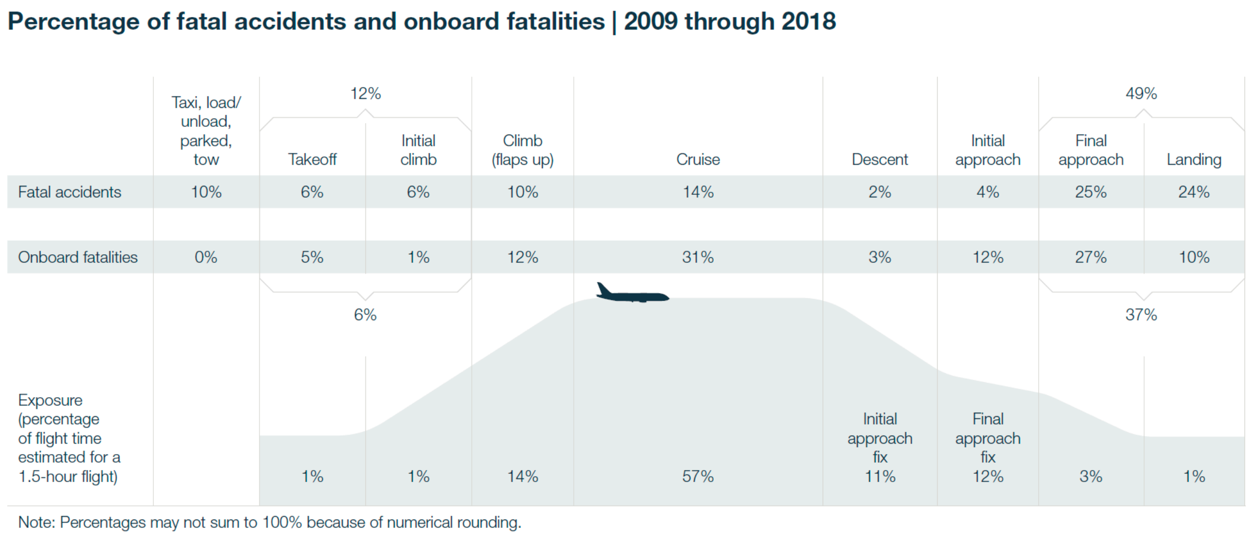

Figure 2-1: Percentage of accidents in different phases of an aircraft flight cycle (source: Boeing Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations 1959-2018, September 2019) [2].

In an analysis of third party risk, two metrics, Individual Risk (IR) and Societal Risk (SR), are used. Both risk metrics have their own characteristics in expressing risk. They are complementary to each other and are commonly used as basic information for third party risk studies and risk communications.

2.1 Individual Risk

Individual Risk (IR) is defined as: "the local probability per year that a person, who is permanently residing at this particular location, suffers fatal injury as a direct consequence of an aircraft accident on or near his position."

Two important characteristics of the Individual Risk are:

- Individual Risk represents a point-location risk; it is calculated separately for every location around the airport and differs from location to location.
- Individual Risk is independent of the actual population around the airport; it is calculated for a fictive person who is presumed to stay permanently in one single location.

In general, the Individual Risk decreases with increasing distance to the runway and flight routes. Individual Risk is commonly visualised by iso-risk contours, plotted on a topographical map. This way of presentation is comparable to visualizing a mountainous landscape, where the altitude of the mountain represents the level of Individual Risk. According to the Civil Airport Regulation (Regeling Burgerluchthavens[3] in Dutch) in The Netherlands it is required to determine the 10^{-5} and 10^{-6} Individual Risk contours. These contours are subsequently input to a public safety zoning process. The general practice is that within the 10^{-5} contour no houses (for permanent living) are allowed and existing houses are demolished. Only existing objects for non-permanent usage are allowed in this area. Within the 10^{-6} contours existing houses are allowed, but no new housing developments are allowed. Basically, 10^{-6} is considered the boundary of acceptable third party risk. A slightly higher risk (in the area between the 10^{-5} and 10^{-6} contours) is only considered tolerable in case of existing houses in that area.
Therefore, from a third party risk perspective, the following criterion applies:

- $IR \leq 10^{-6}$: acceptable risk
- $10^{-6} < IR \leq 10^{-5}$: tolerable risk
- $IR > 10^{-5}$: unacceptable risk

For the purpose of the present study, third party risk resulting from UAM operations is therefore considered acceptable when the resulting Individual Risk is $< 10^{-6}$. This appears slightly more strict than the current practice in The Netherlands, where for existing airport operations and existing houses tolerable risk is also accepted. But for this new type of operations (UAM operations in congested areas of the city) it appears prudent to safeguard existing houses from third party risk based on an acceptable risk level.
In other words the UAM operation should be designed to avoid exposing any existing houses and its inhabitants to an individual risk $>10^{-6}$.

2.2 Societal Risk

Societal Risk (SR) is defined as “the probability per year that a group larger than a given number of persons (third parties) is killed due to a single aircraft accident”.

Societal Risk is presented as an FN-curve, where F (frequency)[4] stands for the probability per year and N stands for the group size. Due to the wide range of values of probability and group sizes, the FN-curve is practically plotted on a double-logarithmic scale. In practice, only a selected number of group sizes is calculated, for example, $N \in \{2, 3, 5, 10, 20, 40, 100, 200, 400, 1000\}$; other selection of group sizes is possible.

[3] https://wetten.overheid.nl/BWBR0026564/2019-11-07
[4] In terms of statistics this quantity is a frequency that depends on the distribution of group sizes in the population sample.

Two important characteristics of the Societal Risk are:

- Societal Risk represents the risk over the total study area around the airport.
- Societal Risk depends on the actual population distribution around the airport; in a hypothetical situation where no population is present anywhere around an airport, the Societal Risk for this airport would be null (zero).

The essential difference between Individual Risk and Societal Risk is shown in Figure 2-2. Depicted in the figure are two situations, A and B, with an identical risk source. Although both situations have the same individual risk as a consequence of the risk source, due to the different population distributions in the surrounding of the risk source, situation B has larger societal risk than situation A. It may be clear that the use of both main risk metrics can be important in expressing third party risk.

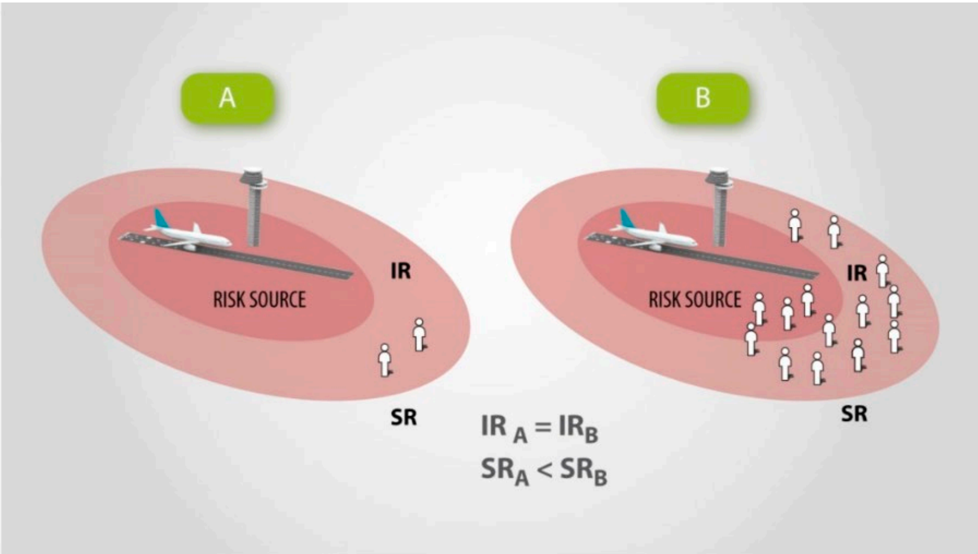

Figure 2-2: Difference between Individual Risk (IR) and Societal Risk (SR). The Individual Risk levels are for situation A and B the same. However, due to the different distribution of population, Societal Risk for situation B is higher than that for A. Figure is adapted from reference Jonkman et al, reference [3].

The Societal Risk is used in The Netherlands to support public safety zoning decisions. However, there are no strict criteria that define an acceptable level of Societal Risk due to aviation operations. Societal risk is not a standard, but there is an accountability obligation. As part of this obligation Societal Risk is compared with a so-called Orientation Value for Establishments (in Dutch "Orientatiewaarde voor Inrichtingen", abbreviated as OWI). The OWI is used as a guideline or reference of societal risk to which the competent authority must adhere to as much as possible.

The OWI is defined as $10^{-3}/N^2$, where N is the group size.
Applying this definition of acceptable Societal Risk, it can be established that the risk for a group of two or more persons due to the UAM operations should not be higher than 2.5×10^{-4}.

3 Vehicle Safety Targets in relation to Third Party Risk

Current type certification specifications do not contain any specific requirement to ensure acceptable risk for third parties. This means that it is basically assumed that the internal safety[5] of a type certified aerial vehicle is sufficient to prevent unacceptable risk exposure to third parties.
In general this may be considered as an acceptable assumption, because in the rare case of an aircraft accident usually no third parties are involved. A large share of aircraft accidents occurs in non or scarcely populated areas (e.g. in sea, mountainous terrain or sparsely populated areas near airports). Nevertheless, based on information from NLR's Aviation Safety Database, in the last 10 years around 150 worldwide fatal accidents with commercial aircraft occurred, of which in 14 cases third parties were affected, leading to 185 ground fatalities and 70 injuries.
It shows that third party risk should not be considered as negligible, in particular in congested areas close to airports where air traffic streams concentrate. Therefore, it may be questioned whether the hypothesis that the internal safety of a type certified aircraft indeed ensures an acceptable level of external safety is actually true.

A well-known example of an accident, resulting in multiple fatalities on the ground, is the crash of an El-Al Boeing 747 in an apartment building in Amsterdam in 1992[6]. In the Netherlands this has led to a reconsideration of the mentioned hypothesis, in particular when operations to or from an airport occur frequently over the congested area of a nearby city. This raised the question, what level of safety (i.e. absence of fatal risk due to aviation operations) would be acceptable for third parties which are involuntarily exposed to aviation risks. In the Netherlands it was established (see Section 2) that an individual, continuously present at a certain location near an airport, should be safeguarded from fatal consequences of an aircraft crash with a probability of less than once per million years.

Let's do a simple calculation to see whether this external safety target can be achieved with the internal safety level of a type certified commercial aircraft. The safety objectives of an aircraft is usually expressed in an accident probability per flight hour. For instance the required minimum safety level of a CS-25 certified commercial aircraft is an accident probability of 10^{-6}/flight hour. However, we are here mainly interested in the take-off and landing operations at an airport near a large city. Let's assume that we limit the analysis to a distance of around 6NM from the airport, in order to cover the final approach and the initial climb. This would mean that the exposure time for a landing or departure would be around 3 minutes. If the accident probability would be equal for all flight phases the accident probability would then be equal to $5x10^{-8}$ per movement. However, it is well known that the approach/landing and take-off/climb phases are the most risky parts of the flight. Research by Boeing (see Figure 2-1) shows that around 12% of the accidents occur during the take-off and climb and 49% of the accident during the final approach and landing. Based on an average 1.5-hour flight duration it is shown that during the take-off and climb the accident probability is 4 times higher than the average accident probability per flight hour. For the approach and landing phase it is even a factor of 18.
So, on average the probability of a fatal accident near an airport is roughly 10 times as high as the average probability. This means that the average accident probability per movement near the airport would be around $5x10^{-7}$.
Let's now assume that we have a busy airport that accommodates 100,000 movements per year on a single runway. In that case the probability of an accident near that particular runway is then $5x10^{-2}$ per year, or once per 20 years.

[5] In this report the term internal safety refers to the safety of crew and passengers on board of the aircraft. The term external safety refers to the safety of persons outside the aircraft and not involved in any way in the aircraft operation. These persons are often referred to as the third party (not being the flight crew -the first party- or the passenger -the second party).
[6] Aircraft Accident Report 92-11, El Al Flight 1862, Boeing 747-258F 4x-AXG, Bijlmermeer, Amsterdam, October 4, 1992, Netherlands Aviation Safety Board

So, if this area would be fully populated this would also be the external safety level expressed in individual risk. Clearly, this is far from the acceptable level of once per million years. Obviously, this is a crude estimate, not taking into account that the actually achieved safety level is currently higher than the minimum certification standard. Also an external safety analysis takes other details into account, such as accident location and aircraft weight, as explained in Appendix A. Nevertheless, it may be assumed that these details will not overcome a safety deficit of a factor 50,000 to achieve the acceptable third party risk level.

This leads to the simple conclusion that the internal safety level of a type certified commercial aircraft is not sufficient to ensure an acceptable external safety level, in particular when it is involved in high volume operations near an airport in a densely populated area surrounding a city.
So, what is the solution to this problem and to let aviation and the populated areas around airports safely co-exist? In fact there are two possibilities:

1. Define an operational scenario for which the type certificate is valid. This scenario would define the maximum number of operations over densely populated areas that is intended to be conducted by the aircraft to be type certified. In that case we could match the required internal safety level of the aircraft with the required external safety level, corresponding to the selected scenario.
2. Accept the current internal safety level of type certified aircraft and ensure by public safety zoning measures that exposure to aircraft accidents of persons living around airports is sufficiently reduced in the high risk areas, by simply avoiding the presence of people in those areas.

In case option 1 would be chosen it would lead to different certification standards depending on the particular use scenario. It could lead to similar aircraft types with different internal safety levels commensurate with the intended use of the aircraft. It is clear that this would be a total deviation from the current practice and would complicate aircraft design and certification enormously. Therefore, this solution is not endorsed by any of the certification authorities world-wide. In practice, aircraft design standards and external safety standards are completely decoupled. This leaves option 2 as the only feasible solution. And, indeed in several countries external safety requirements are used for public safety zoning in order to reduce risk exposure of people around airports. For instance, such public safety zoning regulations exist in the UK, Germany and Italy. Also In US, more and more airports are subjected to Land Use planning requirements. A well-known example is the state California.
Probably the most advanced regulations in this context can be found in the Netherlands and were developed after the El-Al crash in Amsterdam[7]. These regulations require the application of a specific third party risk calculation method, which has been developed by NLR (see Appendix A) and embedded in the national aviation law.

It might be argued that UAM operations cannot be compared with commercial operations on large airports, but rather with general aviation (GA) operations. There are sources [4] that state for instance that third party risk for general aviation is not statistically significant. It is true that the aircraft weight of GA aircraft is significantly less than commercial aircraft and therefore the potential lethality is significantly less. Also it can be assumed that GA aircraft in general try to avoid flying over congested areas of cities, towns or settlements or over an open-air assembly of persons. And if they do so, they are required to take into account additional safety margins, as required by the rules of the air (see SERA.5005 (f)). Nevertheless, it still occurs that people on the ground are killed by GA aircraft. And therefore it depends again on what is meant with statistically significant and what is considered acceptable. In any case, in the Netherlands it is recognised that also GA may present a certain third party risk, and therefore, the public safety zoning requirements do not only apply to the larger commercial airports, but also to the smaller GA airfields and heliports.

[7] See https://wetten.overheid.nl/BWBR0026564/2019-11-07

So, now we are returning to the core subject of this report. Can we envision that the UAM vehicles, certified according to the EASA SC-VTOL specification, are sufficiently safe to ensure that the required external safety levels are met? Here it is relevant to assess what the EASA SC-VTOL mentions in this context.
It states "*In order to be proportionate to the nature and risk of particular activity to be conducted by VTOL aircraft, two certification categories are introduced in this special condition, namely Basic and Enhanced, linked to the intended type of operations. Introducing this additional link allows proportionality in safety objectives and enables to apply the highest safety levels of Category Enhanced to protection of third-parties when flying over congested areas and when conducting commercial air transport of passengers. The operational rules can then be built on demonstrated aircraft safety levels and adapted as necessary to local particularities.*"

So, what is actually stated here?

- The certification category is linked to the intended type of operations;
- The highest safety level is required for the Category Enhanced to protect third parties;
- Operational rules can be based on the demonstrated safety level and adapted to local particularities.

Apparently the SC-VTOL covers two different safety standards, based on a specific use case; the lower for the Category Basic and the higher for the Category Enhanced. The actual difference in safety objective for both categories is not mentioned, but the difference is specified as a different response to a failure. The Category Enhanced is required to be capable of continued safe flight and landing after a failure, whereas the Category Basic needs only to be capable of a controlled emergency landing. This is more or less similar to the discrimination of Performance Classes (1,2 and 3) for regular helicopters.

The second bullet indicates that the higher standard is required to protect third parties. It is however not mentioned what safety standard is required to sufficiently protect third parties. It only seems to relate to the capability of continued safe flight or a controlled emergency landing after a failure. Nothing is stated concerning the acceptable probability of loss of control, or other accident types, for both categories, while for instance loss of control is one of the major causes for fatal accidents and thus also for third party risk.

The third bullet appears to indicate that the demonstrated safety level may not be sufficient to achieve the required third party risk level and that this may be solved by operational rules adapted to the local particularities. This suggests that some (operational) mitigating measures may be required to achieve the required third party risk level.
What these mitigating measures could be, in terms of operational rules, is not addressed in the SC-VTOL.

For normal airport operations, public safety zoning is a logical solution to deal with third party risks. However, for UAM applications in the congested area of major cities it will be hard to realize suitable public safety zones that are not available for housing or gathering of people. It is the essence of Urban Air Mobility to deliver passengers in the centre of congested cities in which it will be not practical to specify such zones as a condition for the UAM operations. Therefore, other measures have to be found or it has to be demonstrated that, with the demonstrated safety level of the UAM vehicle, it is possible to conduct the UAM operations with an acceptable risk for the exposed third parties.

The question is then of course what the demonstrated safety level is, or should be.

In this context SC-VTOL provides some interesting statements:

- *EASA concluded that the levels of system complexity that is introduced by the distributed propulsion and corresponding advanced flight controls is deemed sufficiently unusual and novel that the* ***current CS-23***

acceptable means of compliance are no longer considered appropriate for determining the aircraft and system safety objectives.

- *the current system safety objectives for CS-25 and CS-27/29 aircraft should be maintained as a minimum for the commercial air transport operations of passengers* ***as well as for urban air mobility using VTOL aircraft*** *to address* ***the risks to persons on board and on the ground****.*
- *The corresponding safety objectives* ***have been increased by one level compared to CS-23****, due to the higher dependency on systems that are associated with distributed propulsion, VTOL and the possible invalidation of other CS-23 assumptions*

The bold-faced quotes are of particular interest. In simple terms it is stated the CS-23 safety objectives are not appropriate, the safety objectives of CS-25/27/29 should apply to UAM vehicles and the safety objectives should be raised with one level relative to CS-23.
In fact this means that UAM vehicles are to be certified with the same safety objectives as for large aircraft or helicopters. Basically, this means that the fatal accident probability should be at least $<10^{-6}$ per flight hour.

As already explained this target level of safety is insufficient to ensure external safety, in the congested area around an airport, when applied to large aircraft. The question is whether it is sufficient to ensure an acceptable level of external safety for UAM operations with specific UAM vehicles, certified in agreement with the EASA SC-VTOL.
This question is further addressed in the next sections.

4 Hypothetical scenario and assumptions

The mathematical model, which is applied for the third party risk calculation is presented in the appendices of this report.
Appendix A describes the general form of the mathematical model, as currently used in The Netherlands for third party risk assessments for airports and heliports and as required by the Dutch aviation law.
Appendix B describes the specific modifications to the model for application to UAM operations. Particular attention is given to the third party risk in the en-route phase. The general model is only applicable for the approach/landing and take-off climb phases, because these phases present the dominant risk. For UAM operations, where the en-route phases frequently occur at relatively low altitude over congested areas of the city, this risk contribution cannot be neglected and therefore is also considered in the risk modelling specifically for the hypothetical scenario here.

As a starting point of third party risk calculation for a typical UAM operation, a calculation scenario must be first devised. The calculation scenario concerns a hypothetical situation in which the UAM vehicle is allowed to operate above the city or urban area and transport passengers from some location outside the city to the congested centre area of the city. The hypothetical scenario selected here is an eVTOL used as an air taxi (2 to 4 seater) operating between Amsterdam Schiphol Airport and Amsterdam Central Station. Figure 4-1 depicts the route between the two locations. This route is conjectured to be a lucrative and most-demanding trip for rapidly and efficiently bringing business travellers from the airport to city centre and vice versa. The (fictive) vertiport is located at the Amsterdam Central Station; it is constructed on top of the terminal building as shown in Figure 4-2. A typical UAM vehicle that could perform the operation is also shown in Figure 4-1.

Due to prevailing wind conditions in the Netherlands, four flight routes in total are defined for departure from and arrival to the vertiport (Figure 4-2). Departure can be made in south west direction, or first in north east direction followed by a turn towards city centre and continued flight to south west direction. Arrival can be made in north east direction, or first in north east direction followed by a turn away from city centre over the water (IJ River) and approach flight in the south west in the direction.

The UAM vehicle assumed to be used is a multi-copter, as shown in Figure 4-1, which makes it possible to operate from a vertiport construction located on top of the building of railway station terminal. The vehicle is assumed to be certified in agreement with EASA SC-VTOL and controlled by a single, certified pilot. In the future this type of operation might possibly be performed autonomously, without a pilot on-board. This type of operation is however not covered by the SC-VTOL, which assumes that the vehicle is controlled by a pilot. It should be noted that in terms of target level of safety both kind of operations, should be equivalent. However, in terms of failure conditions and scenarios both type of operations could be significantly different. For instance an autonomous operation will be inherently free of pilot-error and pilot induced loss of control. However, at the same time the type certification cannot rely on pilot intervention credit in case of a system failure. This will require an analysis of all possible system failures, including the failure consequences, in case no pilot is on board to correct them. This might lead to potential failure scenarios, such as fly-away events in case of a navigation failure, which may be unique to autonomous operations and which may affect the resulting third party risk. Although the focus of the study is on piloted operations, it also takes into account a typical autonomous failure scenario. Therefore, for the en-route risk from Schiphol Airport to the vertiport and vice versa, both types of failures during this phase of flight are combined in a single scenario, addressing both the fly-away and loss-of-control events.

For the take-off and landing risk it is assumed that the risk characteristics of an eVTOL operating at the fictive vertiport are not different from those of a multi-engine helicopter (performance class 1 or 2) operating at a heliport.

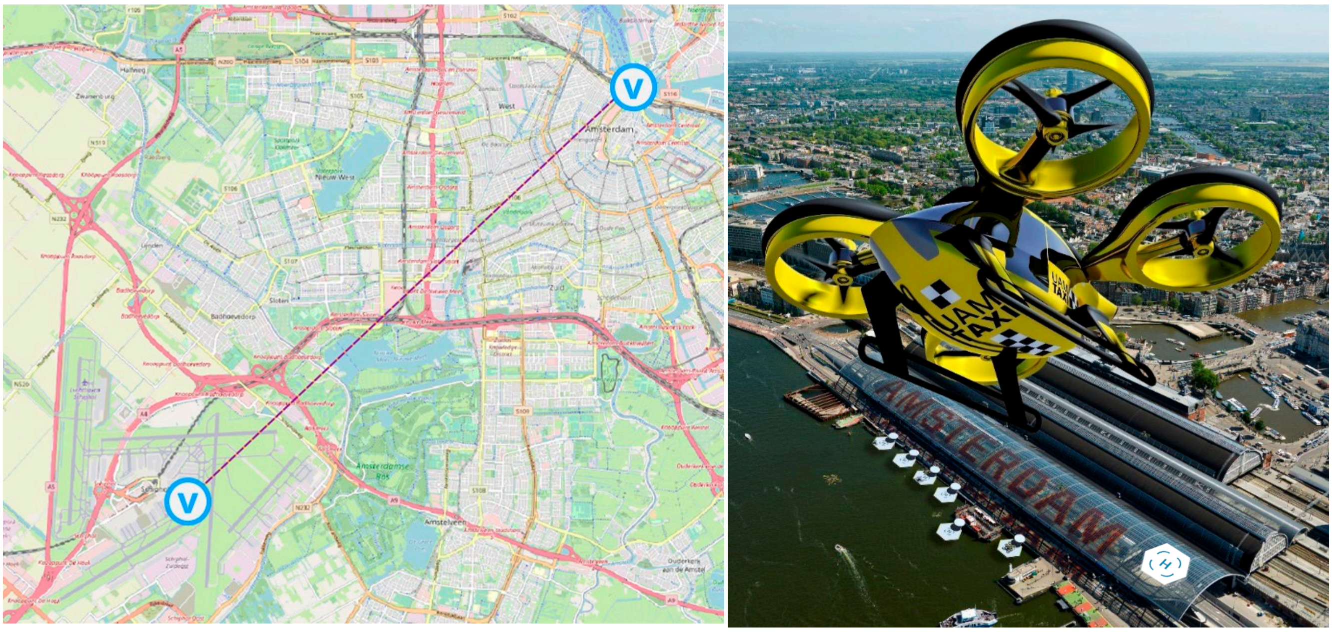

Figure 4-1: The hypothetical eVTOL flight route between Amsterdam Schiphol Airport and Amsterdam Central Station (left). Artist impression of the operation (right).

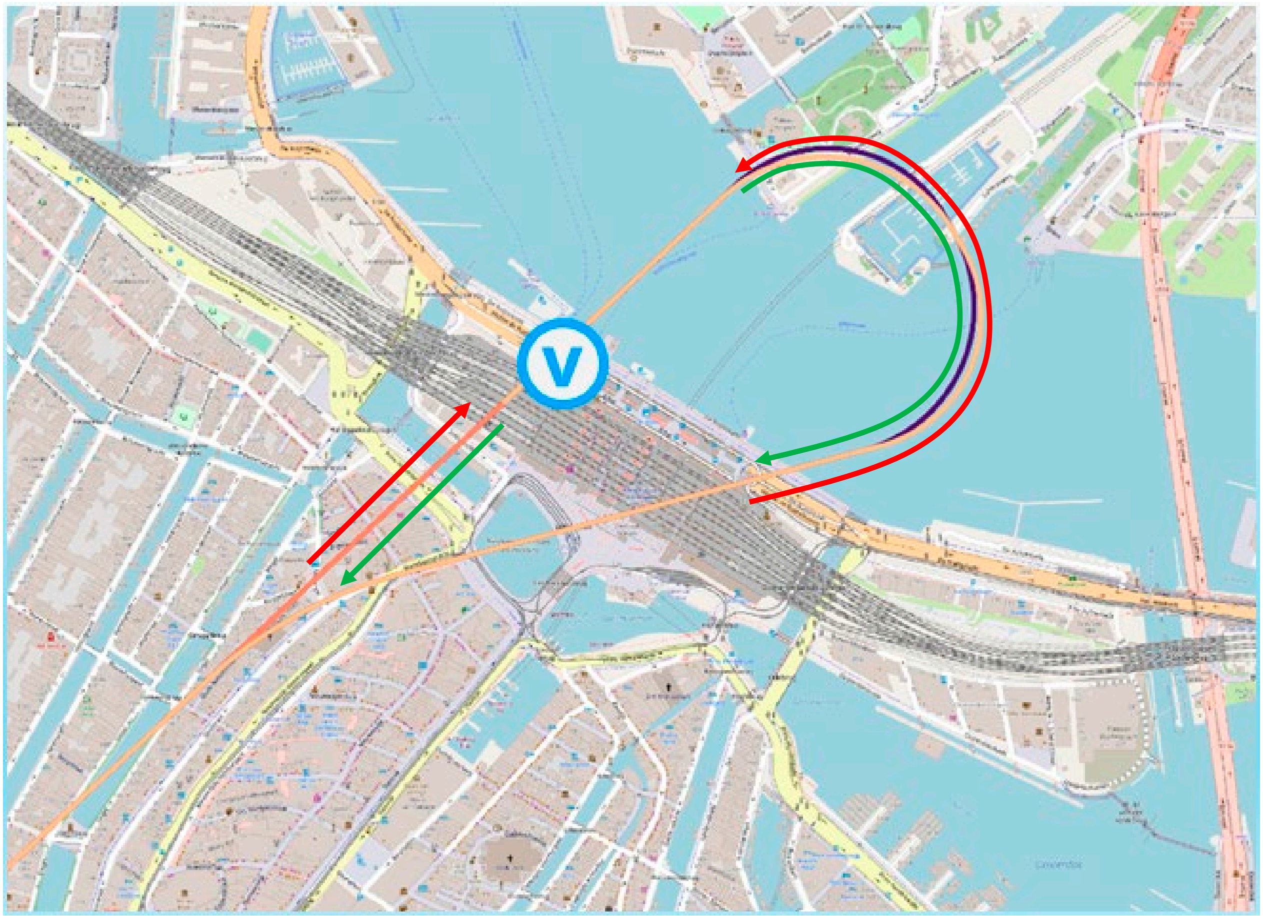

Figure 4-2: Departure routes (green) and arrival routes (red) for the vertiport located at Amsterdam Central Station.

5 Results of Third Party Risk calculations

This section describes the third party risk calculations for the eVTOL operations in urban area and presents the results in terms of individual risk and societal risk.

The results of individual risk calculations are compiled from results of a number of separate calculations for en-route risk and of take-off and landing risk. A starting number of movements is chosen for the “basis-calculation” for the scenario. This number is initially set to 10,000 movements per year for reference (i.e. roughly 30 per day). When the result is combined from different en-route and take-off and landing risk results, the result of the basis-calculation is then scaled up or down in order to find the number of movements that can be accommodated with acceptable third party risk. The maximum traffic volume is found when no houses or other critical objects are covered within 10^{-6} (per year) individual risk contours, or when the probability for a group of two or more persons be killed in an accident by eVTOL is smaller than societal risk guideline (see Section 2.2).

The result represents a scenario with the maximum number of UAM operations that would be allowable from a third party risk perspective, given the safety level that is ensured by the type certification safety objectives.

The results of individual risk calculations are presented as contours (iso-probability lines) on a topographical background. The results of societal risk calculations are presented as a plot on a double-logarithmic scale presenting the probability against the group of fatalities.

5.1 Individual risk

For the calculation of individual risk a study area of 15 by 15 kilometres is chosen. The study area covers the entire flight routes from Schiphol airport to the fictive vertiport located at the Amsterdam railway station. The calculation grid cell size is 25 by 25 metres. The individual risk is calculated for the centre of each grid cell. For the chosen study area, it means that individual risk values for 360,000 (=600x600) grid cells must be evaluated.

Figure 5-1 presents the combined results of en-route and take-off and landing risks for 10,000 movements a year. In the figure a number of risk contours are depicted. According to the criteria used in the third party risk around airports in the Netherlands, only the 10^{-5} and 10^{-6} risk contours are actually of interest. However, sometimes the 10^{-7} and even 10^{-8} risk contours are requested in an environmental impact assessment. For demonstration purpose the contours of the aforementioned values together with 10^{-9} risk contours are presented here.

It can be seen that that the risk contours of 10^{-6} or lower values north of the vertiport curve with the flight route over the water and turn back towards southwest direction.

In Section 2.1 it has been derived that for the purpose of the study it is assumed that no houses (with permanent residents) are allowed within the 10^{-6} IR contour. As can be seen from Figure 5-1 it is clear that part of residential area in the inner city of Amsterdam is located within this contour, and even on the other side of the River IJ some houses are within the contour. Figure 5-2 zooms in on the location of 10^{-6} IR contour in order to better show the affected area.

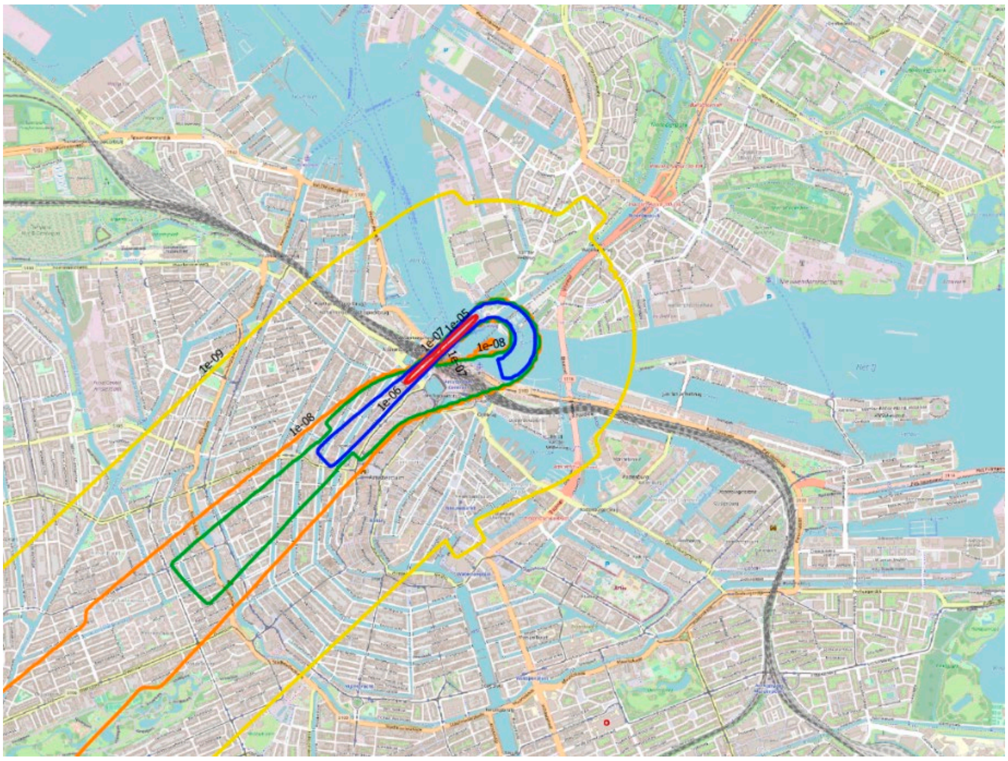

Figure 5-1: Individual risk contours around the vertiport and over the city area, for 10,000 UAM operations per year. The contours shown are 10^{-5} (red), 10^{-6} (blue), 10^{-7} (green), 10^{-8} (orange) and 10^{-9} (yellow) per year.

Figure 5-2: Individual risk contours (10^{-6} per year) for a situation with 10,000 eVTOL movements a year.

It is evident that this volume of operations to and from the vertiport is not acceptable from a third party risk perspective. To avoid that existing houses are located within the 10^{-6} IR contour the number of yearly movements has to be scaled down to around 700, as shown in Figure 5-3. This amounts to around one flight (one arrival and one departure) per day on average. It is very likely that this volume will not be sufficient to sustain the given UAM operation and certainly would have no impact on relieving other traffic streams (train, bus and car) to satisfy the traffic demand between Schiphol and the inner city of Amsterdam.

Figure 5-3: Individual risk contours (10^{-6} per year) for a situation with 700 eVTOL movements a year.

So, the next question is: which measures can be envisioned to achieve an increase in the traffic volume?
In practice there are three possible ways, viz.:

1. Relax the third party requirement for acceptable risk;
2. Reduce the accident probability;
3. Reduce the crash area.

It should be noted that all three methods have a direct and linear relationship with the traffic volume. So, accepting a 10 times higher risk and reducing the accident probability and crash area each with factor of 10 at the same time, will result in a 1000-fold increase of the acceptable traffic volume, and would thus boost the acceptable traffic volume from 1 to 1000 flights per day.
The questions is: how realistic is it that such improvements can be realised?

Relaxing the TPR safety criterion

In case the TPR safety criterion would be relaxed with a factor 10 the determining IR contour would be at the 10^{-5} level. This would be at the current boundary between tolerable and unacceptable risk (see Section 2). Presently, in The Netherlands this is considered acceptable for existing airport operations and existing houses. It is however, questionable whether this would be acceptable for an entirely new operation (from a new vertiport) in a congested area of a city. It would expose residents to a risk that is not clearly acceptable and that is considered only tolerable. Inhabitants in that particular risk area will perceive this as not being fully protected from a new risk to which they are involuntarily exposed without clear direct benefits to them (it may be assumed that the majority of the affected Amsterdam residents do not regularly use the UAM service). Therefore, it may be expected that any relaxation of the TPR criterion will meet fierce resistance from the local residents and will add to other arguments, such as noise hindrance, to avoid an increase of traffic volume. In this context it is not likely that any relaxation of the TPR criterion will be accepted in order to increase the traffic volume.

Reducing the accident probability

The accident probability that is used to calculate the IR-contours is based on the already strict certification requirements for UAM vehicles, as presented in the EASA SC-VTOL. As mentioned these requirements are already an order higher than for normal and utility aircraft as specified in CS-23 and are at the same level as large commercial aircraft (CS-25) and multi-engine large helicopters (CS-29).

In order to reduce the accident probability the UAM vehicle would have to be certified against an even more strict standard than the current SC-VTOL and thus also more strict than CS-25/29. This would be a significant a challenge, in particular for these new type of aerial vehicles with a high level of system complexity due to the distributed propulsion and corresponding advanced flight controls. No commercial air vehicle has been ever designed to a more strict standard than CS-25/29. So, this would be uncharted territory in any case. It is even questionable if accepted design methods and means of compliance are available that would enable to certify an air vehicle against such stricter safety requirement. For instance the well-known CS25.1309 requirement, concerning System Design and Analysis, requires a minimum acceptable probability of 10^{-9}/FH for fatal failure conditions. For flight critical, fly-by-wire and software based, flight control systems it is already extremely challenging (and costly) to design such systems and prove that they meet the required safety level. If we would have to a certify the UAM vehicle to a 10-fold higher safety level then automatically the system safety requirement would have to increase to 10^{-10}/FH.

Certifying against such standard is clearly beyond the current practice and would significantly affect the system design. It would likely lead to even higher levels of complexity, such as for example a quad-redundant system architecture and application of dissimilar software for flight critical functions. Clearly this would significantly increase the cost of the UAM vehicle.

In addition, it should be noted that the accident probability is not fully determined by the type certification standard of the UAM vehicle. Part of the accident probability arises from operational issues, like environmental conditions and pilot error. As estimated in Appendix B, around two-third of the accident probability can be attributed to such causes. Therefore, certifying against a higher standard alone is not sufficient to achieve the targeted reduction of the accident probability. Therefore, the vehicle design would have to be much more resilient to pilot error and other external factors, in order to achieve in total the required 10-fold safety improvement.

It is evident, that it would be an extremely challenging task to reach this overall safety objective. Apart from the associated increase of design and certification cost, it may even be questionable whether current state-of-the-art technologies are capable of reaching the required safety level for UAM vehicles with such a high level of system complexity. At least, so far this has never been demonstrated. Therefore, it is concluded that it is not realistic to expect that UAM vehicles could or will be designed to a higher safety standard than currently is required, on the basis of the SC-VTOL.

Reducing the crash area.
The calculation of the IR contours is based on the standard model parameters for a light aircraft. This means a crash area of 145 square metres and an accident lethality of 0.13. These are typical values of a light aircraft, considering the weight, size and impact energy of these aircraft. It is assumed that these parameters are representative for eVTOL air taxis, because they will have similar size and weight. However, measures may be envisioned that could reduce the lethality and the corresponding crash area. For instance lethality could be reduced by equipping the vehicle with an emergency parachute system, which would be deployed when a crash is imminent. This will reduce impact energy and therefore may lead to a smaller crash area.
With an effective emergency parachute system it may possibly reduce the crash area to the area covered by the vehicle itself. Let's assume that the vehicle would have a dimension of 3x5 metres, then the crash area would reduce to around 15m^2, which is a factor 10 smaller than used in the third party risk calculation.
A recent study into the effectiveness of emergency parachute systems [5] indicates that these systems have around a 50% effectiveness during the terminal flight phase (approach/circuit)[8]. Historic data show that parachute systems are very effective, when deployed above 600ft. However, at lower altitude the effectiveness reduces. Around in one-third of the cases where the parachute was deployed below 600ft led to fatalities, indicating that the emergency parachute was not able to sufficiently arrest the impact. It is also shown that for a typical weight of a UAM vehicle the minimum safe recovery height is around 150ft. Therefore, it is unclear what the total effectiveness of an emergency parachute system could be during take-off and landing phases to reduce the lethality for persons on the ground.
Moreover, pilots might be reluctant to deploy the parachute in built-up areas, because the parachute might become entangled with high objects on the ground, or the vehicle could land uncontrolled at very dangerous places, such as on the high voltage power lines of the railway.
Finally, a parachute device will reduce the payload of the UAM Vehicle and add to the cost of the vehicle.
The typical weight of an emergency parachute for a UAM vehicle is around 12kg and will cost around €5000, without installation cost and weight to strengthen the airframe.
Therefore, it is concluded here that it appears possible to reduce the crash area, by means of a parachute system or other measures, but it will go at the expense of increased cost and reduced payload. It is difficult to estimate what the impact on the crash area could be, but likely It will not be a reduction of more than a factor 5, taking into account the system effectiveness at low altitude.

A realistic traffic volume.
Based on the considerations above it is concluded that it will be a challenge to increase the traffic volume for the vertiport above on average 1 flight per day. It is not likely that the TPR criteria for Individual Risk will be relaxed. The volume increase must therefore come from reduced accident probability and reduced crash area.
In order to reduce the accident probability the UAM vehicle must be designed to certification standard that exceeds the current SC-VTOL and should aim to have a higher safety standard than current large aircraft or helicopters. Based on expert judgment, it is considered unrealistic that this can be achieved without prohibitive costs and efforts.
The crash area might be reduced with a factor of five, with the aid of impact reducing devices, like an emergency parachute system.
Therefore, it might be envisioned that around 5 flights per day could possibly be accommodated with acceptable third party risk, in case all vehicles are equipped with systems like an emergency parachute system.
In conclusion, any business case should take this ultimate traffic volume into account to determine the return investments (which could be significant to overcome the described challenges).

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[8] This effectiveness relates to the internal safety. It is however assumed that in case that the remaining impact energy is such that it leads to fatal injuries to persons on board, that it also may cause fatalities on the ground.

5.2 Societal risk

In addition to Individual Risk, also Societal Risk can be computed. As mentioned in section 2.2, Societal Risk is used as a guideline based on an orientation value. In this context Societal Risk is not a hard criterion in the Netherlands, but may be used to support management decisions to allow installations or operations at a certain location, or not.

Stationary population densities

In order to calculate Societal Risk, the so-called population density data of the affected area are required. Upon the request of NLR the population data files in the desired detail and file format are provided by the "BAG[9] populatieservice" (https://populatieservice.demis.nl/#/).

The BAG-data files with information on the number of persons per object are processed into the population densities as calculation inputs. The underlying objects in the BAG-data files are stationary. These objects include houses and apartments; shops and department stores; offices and industrial buildings; hospitals, clinics and care-homes; schools and day-care centres; sport-centres and prisons; meeting rooms, theatres and cinemas.

Population densities are derived for every calculation grid cell within the whole study area. Figure 5-4 gives an example of converting the BAG-objects into the population densities per grid cell. For the study area, which covers a large part of Amsterdam city centre and area outside the city, there are about 1.4 million persons involved in the population density data.

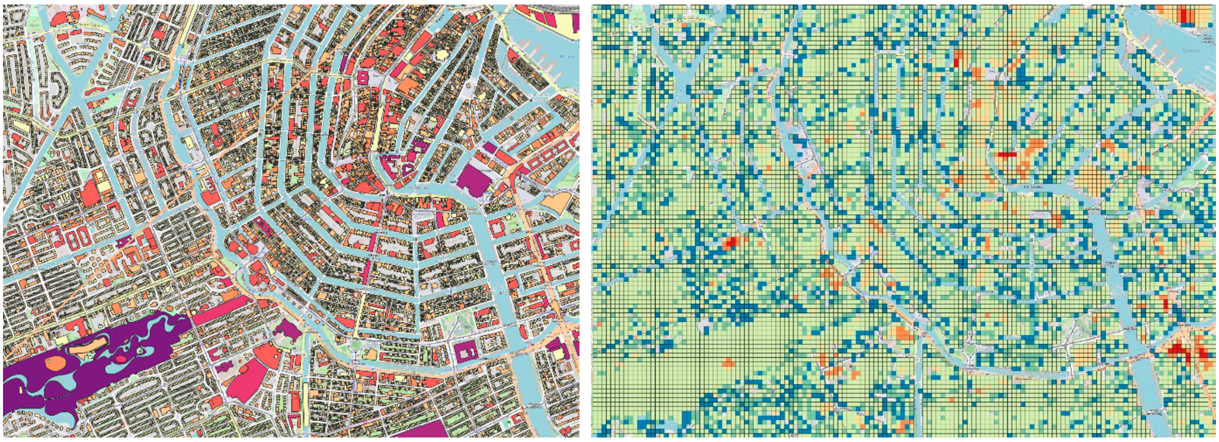

Figure 5-4: (Right) BAG objects (buildings) with population density. (Left) population densities for each calculation grid cell (25 by 25 metres).

Dynamic population densities

In theory it is sufficient to determine Societal Risk using the stationary population density derived with the use of the BAG-data. This means that the risk only takes into account persons for example living at their home address and employees at their company address, etc. However, the dynamic populations like visitors in Amsterdam, for instance near the Central Station, are not covered.

It may be expected that in general a substantial number of persons will be present in this area, which will be exposed to accident risk of an UAM vehicle operating to or from the vertiport at the Central Station.

[9] BAG stands for "Basisregistratie Adressen en Gebouwen".

To incorporate the dynamic populations in the Societal Risk calculation for the UAM operations, the visitors of Amsterdam Central Station are modelled as population densities data as calculation inputs, in addition to the stationary population densities derived from the BAG-data.
For the number of visitors of Amsterdam Central Station, the information of ProRail and Google Maps are consulted. According to the figures reported by ProRail there are 175,000 travellers at Amsterdam Central Station each day. The statistics recorded by Google Maps show that most of the travellers make use of the station during the hours from 6:00 AM (morning) to 12:00 AM (midnight), an 18-hour period. The statistics also show that the travel frequency has certain form of Gaussian distribution. For the risk calculation, it is assumed that 95% of the travellers make use of the station during the 18-hour period. This gives a total of 166,250 travellers. For the sake of simplicity, it is further assumed that the travellers are equally distributed over the hours and concentrated in areas in front of the entrances at the south side of the terminal building (facing towards the city centre) and in areas along the north side of the terminal building (facing towards the IJ).

Maximum traffic volume allowed

To determine the maximum traffic volume allowed, first the Societal Risk for the reference situation with 10,000 eVTOL movements per year is calculated. The result of Societal Risk is then scaled down in order to find a volume that would comply with the Orientation Values for Establishments ("Orientatiewaarde voor Inrichtingen", abbreviated as OWI, see Section 2.2).

In the Netherlands, the Societal Risk for groups of 10 persons or more is in general used to support management decisions. In the recent published Environmental Impact Assessment report conducted for Amsterdam Schiphol Airport, the groups for 10 fatalities or more are used in comparison with the OWI. The groups of 10 or more may be useful for large, critical infrastructure like airports or large, critical object like industrial facilities. However, for a small airport, heliport or vertiport in the present case, using only a group of 10 or more persons may limit the scope of assessing the Societal Risk for the surroundings, in particular for the urban areas.

For the purpose of present study, groups of 1 or more persons are evaluated. For comparison purpose, it is conjectured that the group of 2 persons or more is suitable for use.

Figure 5-5 presents a number of Societal Risk curves (*FN*-plots) for the reference situation based on 10,000 movements per year and the scaled-down situation with reduced number of movements. The guideline of OWI is also plotted for comparison. In the figure the x-axis presents the group of N or more fatalities whereas the y-axis gives the probabilities (F) for the groups N.

From the *FN*-plot it can be seen that the curve for the reference situation does not meet the guideline of OWI. Therefore a reduction should be applied in the number of traffic movements to lower the risk. If the reduction is done based on N>2 persons, the curve for the reduced number of movements would still lie above the OWI curve for certain group sizes N. It seems that the N>10 persons is the most critical in this case. Therefore the reduction factor is determined based on the risk valued found for N>10 persons.

Further it can be observed that the N_{max} is about 30. It is the maximum number of persons that could be killed in an accident with an UAM vehicle in the scenario considered. Although this number of fatalities is possible, the probability of occurrence is extremely small.

In order to comply with the Societal Risk guideline, a reduction factor about 0.185 is determined and applied to the traffic volume. This gives a maximum traffic volume of 1850 movements a year, which equates to around 2.5 flights per day. The number of traffic movements determined with the Societal Risk criterion is somewhat larger than that determined with Individual Risk criterion. Nevertheless the movements number found for both criterion have roughly the comparable magnitude (700 versus 1850). Further, it has to be concluded that in this particular case the Individual Risk is more critical than the Societal Risk. And it should be noted that it is only valid for this particular case. For cases with another distribution of the population within the risk area and/or another population density the outcome could be different.

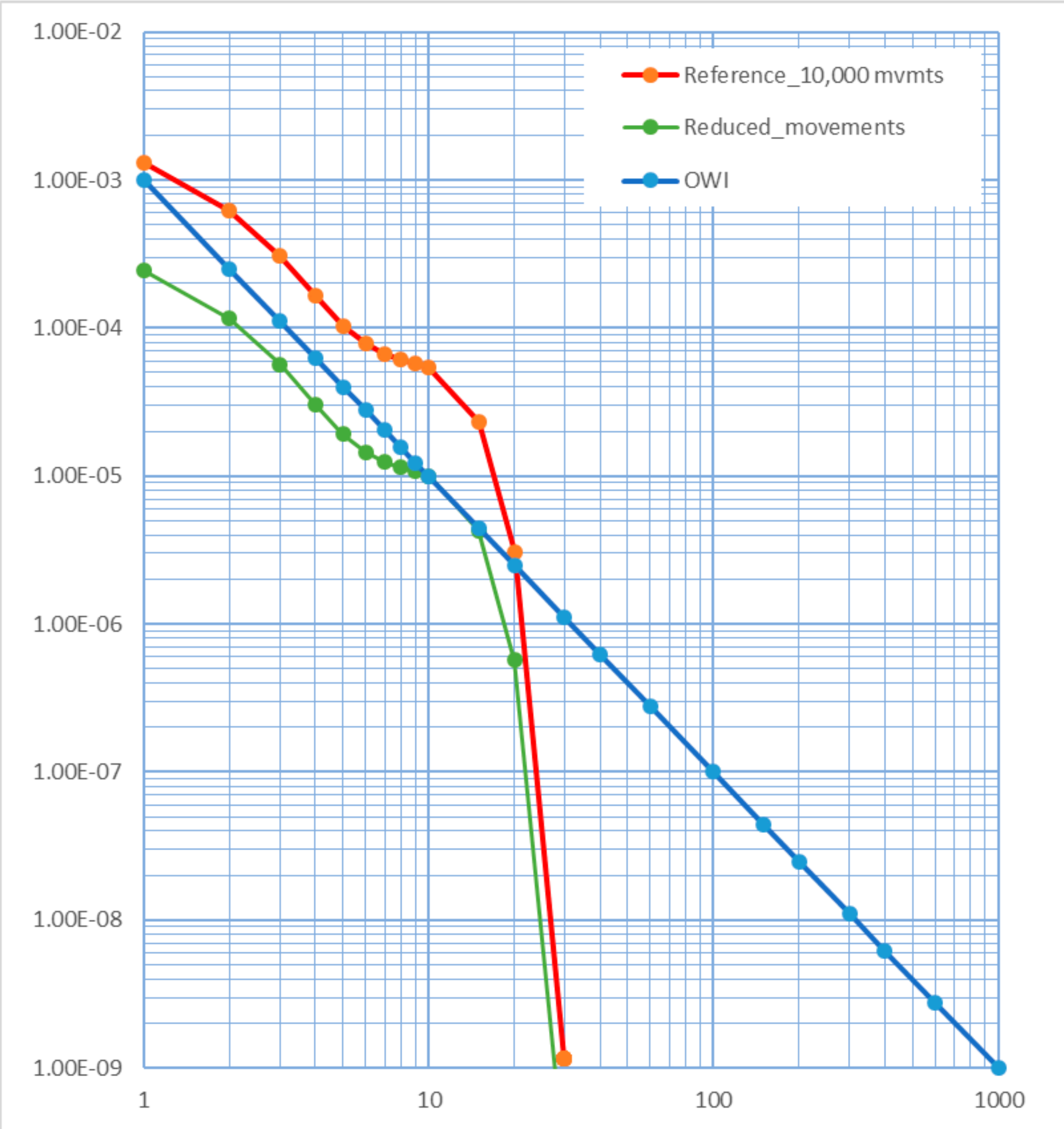

Figure 5-5: Societal risk curves, FN-plots, for the reference (in red) and scaled down (in green) scenarios. The x-axis denotes the number of fatalities (N). The y-axis presents the cumulative probabilities (F) for groups of fatalities. Also shown is the OWI reference line (in blue), which is the guideline of societal risk for establishments, industrial facilities and storage of dangerous goods.

6 Conclusions

In this report we have assessed the safety objectives of an UAM vehicle (eVTOL) from a third party risk perspective. The analysis has been based on a typical, challenging but not unrealistic, scenario where the UAM vehicle provides transport of passengers from the airport of Schiphol directly into the centre of the City of Amsterdam, to a vertiport located at the Amsterdam Central Railway station. This scenario is considered representative for the service that the Urban Air Mobility concept intends to provide.

The Third Party Risk metrics and computational model have been based on specifications in the Dutch regulations for civil airports and modified to the specifics of the UAM concept.
The UAM vehicle is assumed to be type certified against the recently published EASA Special Condition for small VTOL aircraft and meets the corresponding (internal) safety level.

The results of the Third Party Risk calculation show that with the given (internal) safety level of the UAM vehicle on average only **one flight per day** can be accommodated at the vertiport, without violating the present third party risk criteria.

An increase of the traffic volume at the given location can only be realised by relaxing the TPR criterion, increasing the (internal) vehicle safety, reducing the crash lethality (or crash area) or a combination of these measures.
Based on expert judgment it is concluded that a substantial increase of the traffic volume would be very difficult to realise.
It is argued that it is not likely that TPR risk criteria can be relaxed for this new type of operation in an environment (the congested area of a major city) that is not used to be exposed to risks of frequent, low flying, air traffic
The possibilities to increase the internal safety of the UAM vehicle are considered to be extremely challenging. It would require to design the UAM vehicle to a safety level in excess of current large commercial aircraft or helicopters. It is expected that this is currently not feasible without a prohibitive increase of costs and efforts.
A reduction of the crash area may be possible by installing for instance an emergency parachute system. It would have to be investigated how reliable and effective such system would be for operations close to the ground in an urban area with high objects. Based on expert judgment, it is perhaps feasible to reduce the crash area with a factor of five by such measures. This means that an increase of traffic from one flight to five flights per day is considered feasible with acceptable third party risk, in case all UAM vehicles are equipped with emergency parachute systems.

It is recommended that any entrepreneur that would envision to initiate an UAM service into a major city, as sketched in the scenario in this report, should be aware of the mentioned challenges and should base his/her business plan on a realistic traffic volume, taking into account the third party risk involved in the operation.

For third parties safety is the highest priority as shown in the first EU study on citizen's acceptance of Urban Air Mobility carried out by EASA [6]. It is therefore recommended to the (local) regulator to evaluate the public acceptance of (plans of) introducing UAM operations in an urban area, based on the actual risk exposure.

It should be noted that the scenario presented in this report is just an illustrative example. Other scenarios could lead to different results. However, any operation to a congested area of a large city will likely be faced by similar constraints, limiting the potential traffic volume.

7 References

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[7] ICAO Doc 9184, Airport Planning Manual, Part II – Land Use and Environment Management, Fourth Edition, 2018.

[8] Voorschrift en procedure voor de berekening van Externe Veiligheid rond luchthavens, NLR-CR-2004-083, februari 2004.

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Appendix A Models of Individual Risk and Societal Risk in generic form

To assess the third party risk around an airport, the NLR TPR calculation model is applied. This model is developed for the Dutch Ministry of Transport to analyse the third party risk around the airports in the Netherlands. The NLR model has a legal status in the Dutch Aviation Law, and is the only legitimate instrument to calculate third party risk for the airports including Amsterdam Schiphol Airport. The Dutch practice of Third Party Risk assessment and the NLR model have also been referred in the ICAO Airport Planning Manual (Doc. 9184, Part 2) [7] .

Most accidents in air transport occur in the vicinity of airports during take-off, initial climb, final approach or landing. The probability of an aircraft accident could be such that the risk to the population around the airport (third party risk) might be of relevance for airport operations and land-use planning. The NLR third party risk model has been developed to quantify this risk and to support the decision-making process.

The NLR third party risk analysis model comprises three components (sub-models)**:**

- **Accident Probability**
- **Accident Location** and
- **Accident Consequences**.

The three model components answer the following questions regarding the risk for which an inhabitant living in the vicinity of an airport is exposed to (thus, third party risk):

- What is the chance that an aircraft accident occurs in the vicinity of an airport? (**Accident probability**)
- What is the likelihood of an accident occurring at a given location around the airport, given that an aircraft accident occurred in the airport surrounding? (**Accident location probability**)
- What is the consequence of an aircraft accident, given that an aircraft accident occurred in the airport surrounding? (**Accident consequence**)

The model parameters of these three components were derived from an extensive set of data concerning historical aircraft accidents, operations and airports. These data are extracted from the NLR Air Safety Databases. Within the framework of third party risk model, the three components are brought together by means of statistical and mathematical formulations. A comprehensive description of the methodology adopted in the NLR third party risk model is given in references [8] and [9].

When the airport scenario input data, which comprise airport runway data, flight routes and traffic and fleet composition data, are fed into the model, third party risk can be calculated.
Third party risk is expressed with two indicators, viz. Individual Risk (IR) and Societal Risk (SR):

- Individual Risk is related to the probability that a person that stays continuously at a certain location is killed due to an aircraft accident.
- Societal Risk presents the probability that a group of persons (2 or more) living in the surrounding of an airport is killed due to an aircraft accident.

Figure A-1 gives a schematic depicting the relationship of different input data, risk model components and calculation results.

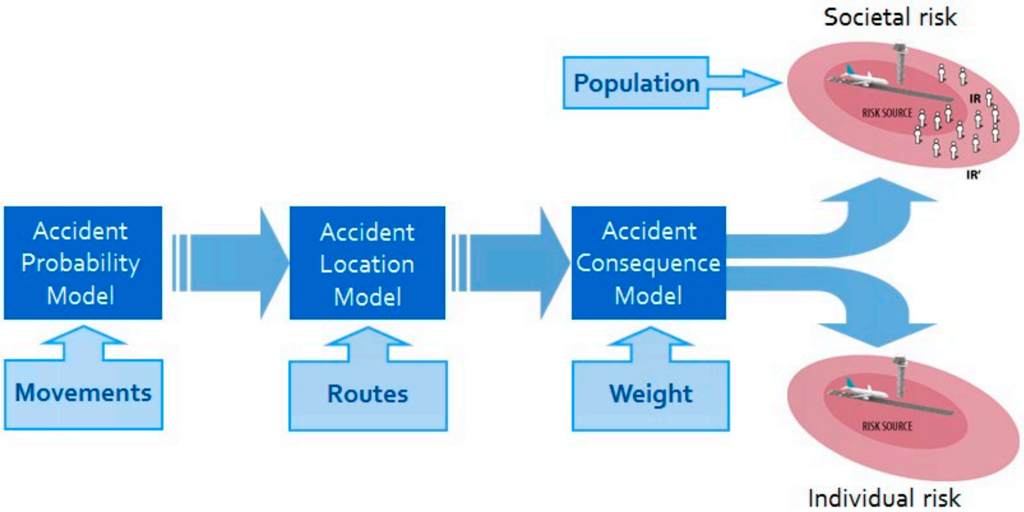

Figure A-1: A schematic representation of the third party risk model for calculation individual risk and societal risk. Required input data are traffic movements and aircraft types, flight routes, aircraft weights, population density data. The latter is meant for a calculation of societal risk.

IR is a point-estimate for a given location, independent of the actual population density in that area.
SR integrates the IR, taking into account the population density in a specific area.

The equations to determine the IR and SR are given below. The purpose of presenting the equations is to show how a change in one or more variables in the risk equation affects the outcome of the risk. This information is in particular useful in case of UAM operations, in order to establish which variable can be adjusted (or improved) in order to comply with a third party risk criterion.

Individual Risk (IR) calculation model is given by the following equation:

$$IR = n \times p \times KDH_{m^2} \times CA \times let \qquad \text{[Eq. 1]}$$

where

IR = individual risk for a point or location on ground (per year);
n = number of take-off and landing movements (per year);
p = accident probability (per take-off or landing movement);
KDH_{m^2} = accident location probability per square metre; KDH stands for probability density ("kansdichtheid" in Dutch);
CA = crash area (of eVTOL); and
let = lethality

Societal Risk (SR) calculation model is given by the following equation:

$$SR_k = n \times p \times KDH_{grid\_cell} \times \frac{N_{max}!}{k!(N_{max}-k)!} \times let^k \times (1 - let)^{(N_{max}-k)} \qquad \text{[Eq. 2]}$$

where

SR_k = societal risk for k number of persons (per year);
k = number of persons killed, group size with k = 1,2,3,… persons;
n = number of take-off and landing movements (per year)
p = accident probability (per take-off or landing movement);

KDH_{grid_cell} = accident location probability of a calculation grid cell, for example a cell of 25×25m of 100×100m;
N_{max} = maximum number of persons that can be killed within the crash area (CA); and
let = lethality.

The accident location probability of a calculation grid cell is given by:

$$KDH_{grid\_cell} = KDH_{m^2} \times r^2$$

where

KDH_{m^2} = accident location probability per square metre;
r = size of a square grid cell

The maximum number of persons that can be killed is determined by:

$$N_{max} = \frac{CA}{r^2} \times P_d$$

where

CA = crash area (of UAM vehicle)
r = size of a square grid cell, for example a cell of 25×25m, r=25; and
P_d = actual population density of the grid cell

From the presented equations (1 and 2) it can be easily seen how each variable influences the outcome of individual risk and societal risk value.

Suppose the accident location probability (KDH) is constant, the Individual Risk is proportional to number of movements, accident probability, crash area or lethality. Thus the change in risk is linear to these variables separately. For example, if the number of movements is doubled, the Individual Risk will be doubled as well. And if the accident probability is halved the IR is halved as well.

Societal Risk is proportional to number of movements or accident probability if the accident location probability (KDH) is assumed constant. Of course Societal Risk is also influenced by Crash Area or Lethality, however, their influences are not proportional (non-linear). This is due to the second part of Equation 2, which is a binomial distribution.

$$\frac{N_{max}!}{k!\,(N_{max} - k)!} \times let^k \times (1 - let)^{(N_{max} - k)}$$

In the risk model the Crash Area is determined the aircraft MTOW. The crash area in turn determines the maximum number of fatalities N_{max} that is possible within the area in the formula for societal risk. Further, the crash area is modelled as a circle. The population covered within the circle is the maximum number of persons that could be killed in an eVTOL accident. The probability that a group of *n* persons killed is not the same as the probability of the maximum number of fatalities. For example, the chance that only 1 person be killed or exactly the maximum number of persons be killed within the crash area is much smaller than a group size somewhere between. This situation is described with a “binomial probability distribution”. A well-known example is throwing two dice, the probability of getting an outcome of exactly 2 or 12 with two dice is smaller than getting an outcome of 7.

In Figure A-2, the blue curve depicts the binomial distribution for N_{max} =20 and the lethality (probability) = 0.5. The probability that exactly 1 person or exactly 20 persons be killed is much smaller than a group with 10 or 11 persons.

Figure A-2 also shows the effects of a reduction in Crash Area in terms of smaller N_{max} and a decrease in lethality. The red curve depicts the binomial distribution with 50% reduction in the maximum number of fatalities (N_{max} = 10) while the lethality remains 0.5. The green curve depicts the distribution with 50% decrease in the lethality (let = 0.25) while N_{max} = 20.

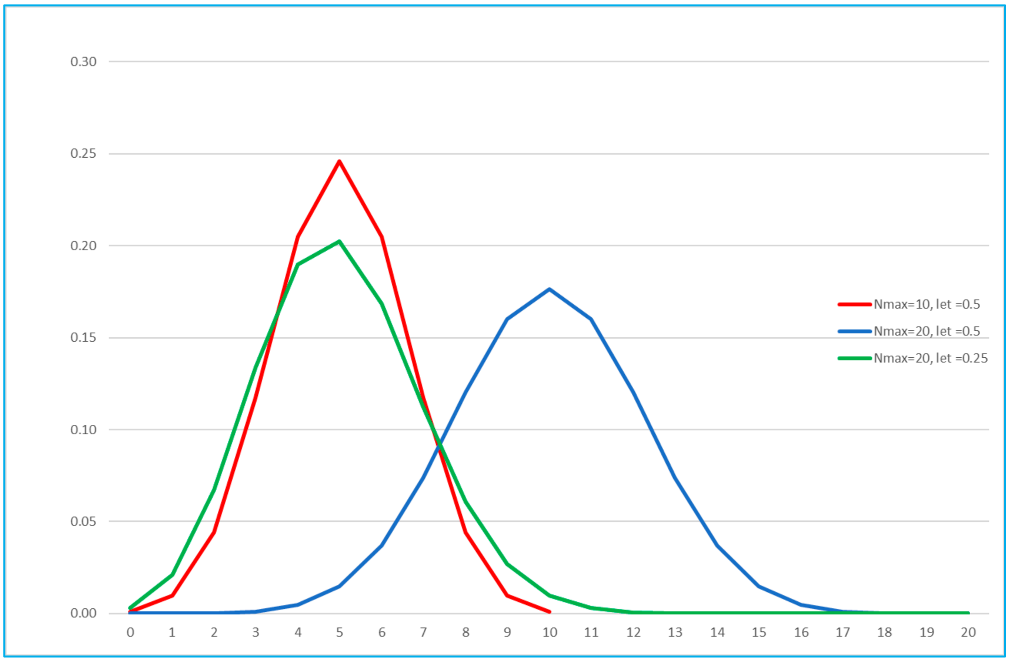

Figure A-2: Binomial probability distribution. Red curve denotes the case for N_{max} =10, let = 0.5; blue curve for N_{max} =20, let=0.5; and green curve for N_{max} = 20, let = 0.25. The x-axis denotes the number of fatalities. The y-axis presents the probabilities for groups of fatalities.

Appendix B Risk model application and model modifications for UAM operations

The general model for third party risk analysis is presented in Appendix A. In this section that the modifications of the model are presented for application to UAM operations.

Appendix B.1 Take-off and landing risk

As mentioned in Appendix A, the standard third party risk calculation model for heliport is used for calculating the take-off and landing risk around the UAM-vertiport. It is assumed that the UAM vehicle, from third party risk perspective, can be regarded as a Multi Engine Turbine helicopter type. The corresponding parameters for each model component have been specified in the Dutch regulatory specifications and are summarized below:

- **Accident probability**: The take-off and landing accident probability of a Multi Engine Turbine helicopter type is specified as 1.051 and 1.608 per million flights, respectively. On average, the accident probability is approximately 1.3 per million take-off or landing movements. This number is based on actual accident statistics. It is assumed that an eVTOL vehicle, certified according the SC-VTOL will achieve a similar accident probability.
- **Accident consequences**: the eVTOL has an assumed maximum take-off weight (MTOW) of 450 kg. According to the TPR risk model for helicopters, the crash area (CA) is 146 square metres. This is determined by the formula:
  CA = 230 *ln* (MTOW in 1000kg) + 330. The lethality within the crash area is a constant: 0.17.
- **Accident locations**: the departures and arrivals of the eVTOL take place in two sectors (‘cake wedges’) with the vertiport as centre: one sector in southwest and one sector in northeast direction. The sector has a top angle of 10 degrees. The probability distribution functions used in the accident location model are Weibull (in radial direction) and Uniform (in lateral direction) distribution functions.

It should be noted that the assumed accident probability is around 1.3×10^{-6} per take-off or landing movement. This is a probability based on the historic safety performance of this type of vehicles. It is not necessarily equivalent to the minimum safety objective associated with the type certification standard. The type certificate merely ensures the minimum safety of the vehicle itself. However, accidents do not occur only due to causes related to the vehicle, but also due to operational causes, such as for instance pilot error or meteorological conditions.
It has already been established (see Section 3) that the current certification standard provides a minimum safety level of around 0.5×10^{-6} per movement. Therefore roughly one third of the accident probability can be attributed to the safety of the vehicle itself and two thirds to operational issues.

Concerning the accident location it should be mentioned that the eVTOL can make use of two departure routes and two arrival routes for operations in the southwest and in the northeast directions. Normally due to prevailing wind conditions in the Netherlands, the preferred direction for flight operation is southwest, then a different distribution can be assumed for operation in SW-NE, e.g. 60-40% or 70-30%. In order to keep the test calculation simple, the distribution is set to 50-50%. That means the amount of traffic in southwest direction is the same as that in northeast direction.

Appendix B.2 En-route risk

The NLR TPR model in principle is developed for analysing risk due to aircraft take-off and landing movements at an airport. En-route risk is in general neglected, for two reasons. First of all, the en-route accident probability is small compared to the accident probability in other flight phases. Secondly, usually the en-route phase is executed at high altitude. This means that in case of an en-route accident the aircraft accident location may cover a very large area. Consequently the probability of an aircraft crashing at a particular location is extremely low. For this reason the third party risk, resulting from the en-route phase is in general considered negligible.
However, this might not be a valid consideration for UAM operations. By definition the UAM operations are mostly conducted over short distances at low altitude (< 1000ft AGL) and occur over densely populated areas. Therefore, third party risk, arising during the en-route phase cannot a-priori neglected for UAM operations.
To enable an analysis of risk due to en-route phase of flight, some underlying model components are needed to be adapted[10].

Accident locations
One model component that should be modified is the Accident Location Model. This model component incorporates certain statistical functions to give the spatial probability distribution of the accident locations around an airport.

The Accident Location Model for heavy aircraft discerns different probability distributions due to Take-off overshoot, Take-off overrun, Landing undershoot and Landing overrun accident types. For light aircraft, the Accident Location Model is simpler; it can only discern take-off and landing accident types. So in the present study, the model of light aircraft is chosen for modification.

In the Accident Location Model of light aircraft, two Probability Distribution Functions (PDFs) that can be adjusted to suit the purpose for calculating en-route risk: the Weibull function in the longitudinal direction and the Generalised Laplace function in the lateral direction.

Weibull function
The Weibull function is used to model the longitudinal distribution of locations. This function is defined for $x \geq 0$ and $\eta, \beta > 0$ as:

$$f_{Weibull}(\eta, \beta; x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} e^{-\left(x/\eta\right)^{\beta}} .$$

The parameter η is called the scale parameter. The parameter β is the shape parameter; for $\beta > 1$ the Weibull function is of an asymmetric clock shape and for $\beta \leq 1$ the function is exponential. The Weibull function is used in a wide range of applications to model the longitudinal distribution.

[10] The practice of modification of the TPR model for take-off and landing in order to calculate the en-route risk is based on NLR previous experiences with a comparable study for drone.

Generalised Laplace function
The lateral distribution of points is modelled using the generalised Laplace function. This function is defined for all *y* and for *a*, *b* > 0 as:

$$f_{gen\ \ Laplace}(b,a;y) = \frac{1}{2ab\Gamma(b)} e^{-\left|y/a\right|^{1/b}},$$

with *a* the scale parameter and *b* the shape parameter. When $a=\sqrt{2}\cdot\sigma$ and $b=½$, the generalised Laplace is equal to the well-known Gaussian Normal function. For larger values of *b* the tails of the generalised Laplace function are heavier than those of the Gaussian Normal function.

Since the TPR model works with departure and arrival phase of flight, in order to incorporate the en-route risk the PDFs used for the departure and arrival phase are adjusted such that the en-route risk can only be "simulated". The en-route risk is simulated by using the take-off and landing PDF with the same Weibull and Generalised Laplace functions and parameters assumed.

In the test calculation only '*fly-away event'* is concerned for the en-route risk. The en-route risk is assumed to be evenly distributed along the flight path. In the longitudinal direction, the probability distribution is assumed to be constant. In the lateral direction, the probability distribution is assumed to attain either the form of **a uniform distribution** or the form of **a Gaussian-Normal distribution**.

Approximation of a uniform distribution
The Weibull function as used in the longitudinal direction is not exactly flat. However, parameters can be chosen such that the function has a nearly flat slope: the function values decay gradually towards zero in the extreme far distance.

For the lateral direction it is chosen that Generalised Laplace function attains the shape of a hat. The choice for this is based on the assumption that in a fly-away event the eVTOL, when flying at an altitude of 300-500ft above ground level, can travel to approximately 1 km distance before hitting the ground. The parameters for the Generalised Laplace function are chosen such that the value between the distance between 0 and 1 km (approximately), left and right of the flight path, are the same. After a distance of about 1 km the values will decay abruptly towards zero.

Figure B-1 presents the Weibull and Generalised Laplace PDFs which can be used as the Accident Location Model for determining the en-route risk. It is noteworthy that, unlike the PDFs defined for airport which are basically based on the accident data and function fitting, the parameters for the PDFs defined here for the eVTOL are derived from a comparable study conducted earlier by NLR.

The parameters as used in approximating the uniform distribution are summarised as follows:
For Weibull: ***β*** = 1 and ***η*** = 1 000 000 (=10^6)
For Generalised Laplace: ***a*** = 1000 and ***b*** = 0.1

In summary, as observed from the figure, the Weibull function in the longitudinal direction decays towards zero but the distance could be much farther than 10 km. The Generalised Laplace function in the lateral direction decays towards zero at about -1 and +1 km.

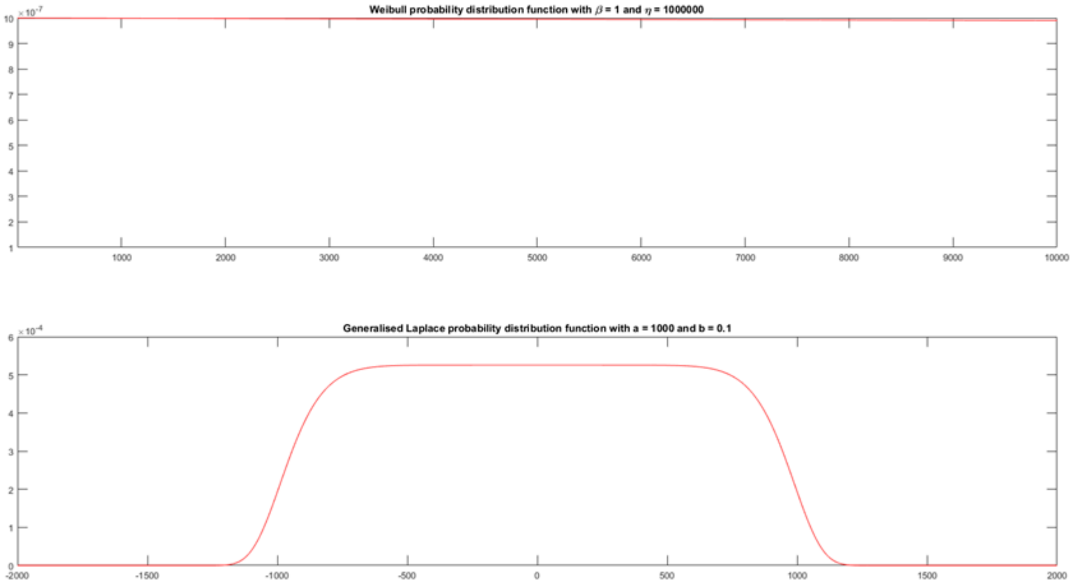

Figure B-1: Upper figure depicts the Weibull PDF with the chosen parameters beta and eta for the longitudinal distance up to 10 km. Lower figure depicts the Generalised Laplace PDF with parameters a and b for the lateral distance from -2 km to +2 km. Note the "hat" is found between the range approximately -1 to +1 km.

An impression of the Probability Density Function (PDF) by combining Weibull and Generalised Laplace distribution functions as generated by Matlab is given in Figure B-2.

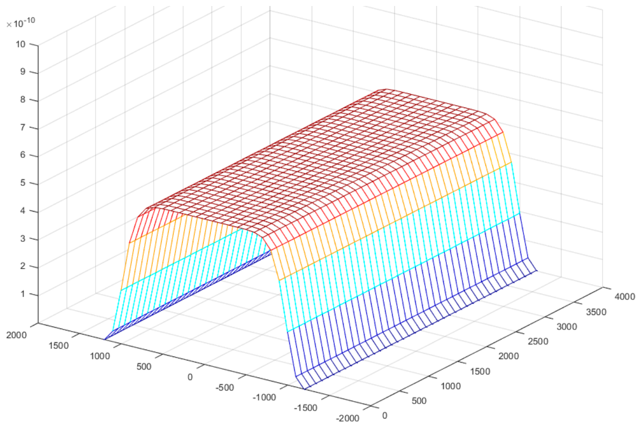

Figure B-2: The combination of Weibull and Generalised Laplace PDFs for the chosen parameters.

Determination of Gaussian-normal distribution

For the lateral direction it is chosen that Generalised Laplace function attains the shape of a bell. The Generalised Laplace function can become a Gaussian-normal distribution by choosing $a=\sqrt{2}\cdot\sigma$, $b=½$ and $y = (x - \mu)$. When $b=½$, the gamma function $\Gamma(b) = \sqrt{\pi}$. Assumed is the 2σ-region is 1000m. That means $a=\sqrt{2}\cdot\sigma = \sqrt{2}\cdot(1000/2) = 707.1$.

The parameters as used in gauss-normal distribution are summarised as follows:
For Weibull: $\boldsymbol{\beta}$ = 1 and $\boldsymbol{\eta}$ = 1 000 000 (=10^6)
For Generalised Laplace: $\boldsymbol{a}$ = 707.1068 and $\boldsymbol{b}$ = 0.5

The Weibull and Generalised Laplace Probability Density Functions, and an impression of the combination of both functions as generated by Matlab are given in Figure B-3 and Figure B-4, respectively.

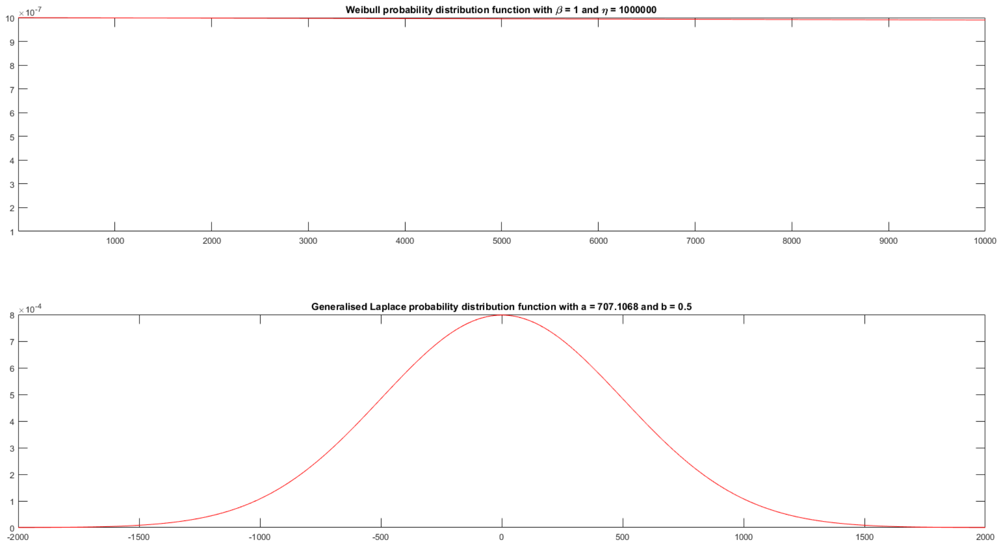

Figure B-3: Upper figure depicts the Weibull PDF with the chosen parameters beta and eta for the longitudinal distance up to 10 km. Lower figure depicts the Generalised Laplace PDF with parameters a and b for the lateral distance from -2 km to +2 km. Note the 95%-region of the "bell" is found between the range approximately -1 to +1 km.

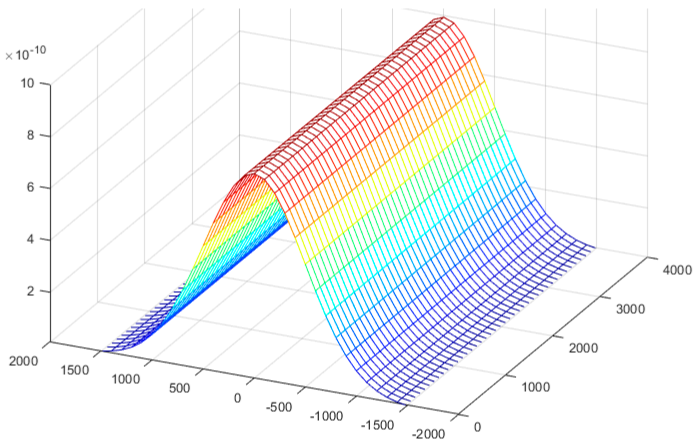

Figure B-4: The combination of Weibull and Generalised Laplace PDFs for the chosen parameters.

In the previous part of this section, much attention has been paid on the accident location model and adjustment of this model. Two remaining components that needed to be addressed are accident probability and accident consequences. These are discussed in the following.

Accident probability

The probability for a failure leading to fly-away is assumed to be 1 per million flight hours (10^{-6}). Since the TPR model uses only probability per movement, the probability per hour is needed to be converted into probability per movement.

As mentioned, there are two flight routes for travel a vertiport located on top of the railway station in Amsterdam city in the hypothetical scenario. The first route is directly from Schiphol airport to the vertiport and this route travels in north-east flight direction. The second route with its first part travelling in north-east direction curves over the railway station and across the water and approaches to the vertiport in south-east flight direction.

The total length of the first route is approximately 12 kilometres. With an eVTOL travelling at an air speed of 100km/h. The accident probability of this passage is only 0.12 per million movements.
The total length of the second route is approximately 13.5 kilometres. Also assuming that the eVTOL travels at 100km/h, the accident probability is then 0.135 per million movements.

Accident consequences
For the accident consequences the standard TPR model parameters for a light aircraft are assumed. The crash area is 145 square metres and the lethality is 0.13. These parameters are valid for every fixed wing aircraft with an MTOW up to 1.5 metric tonnes in the model. Further, it is noteworthy that the parameters used here for en-route risk do not deviate much from the TPR model for a heliport (see section 4.1) that is assumed for the take-off and landing risk (crash area is 146 square metres and lethality is 0.17).

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