A conceptual third party risk model for personal and unmanned aerial vehicles

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EXECUTIVE SUMMARY

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Problem area

The impact of aircraft on the environment has always played an important role in the acceptance of new airports, air routes, and aircraft types. With the current development of personal aerial vehicles (PAVs) and unmanned aerial vehicles (UAVs), new aerial transportation concepts will arise that will only succeed to be implemented if the environmental impact is accepted by the public. Third party risk (TPR) concerns the safety (risk) for the people on the ground, who are involuntarily exposed to an aircraft accident.

The TPR is important in the (densely populated) Netherlands and, therefore, the NLR has been doing research on TPR around airports and developed a TPR model for conventional aircraft. This model is neither suited for PAV and UAV aircraft, nor for the associated operating modes for these aircraft.

Description of work

A conceptual third party risk model is developed, implemented, and tested to demonstrate the capability of determining the risk to the population in a metropolitan city exposed to personal aerial vehicles and unmanned aerial vehicles traffic operations. The conceptual model that is primarily based on the methodology and experience of risk modelling for conventional aircraft is modified and the parameters are adjusted suitable for a determination of risk in the arrival, departure and cruise phase of flight for those new aircraft types.

Results and conclusions

For a demonstration of the conceptual risk model, simulation tracks from the Metropolis project (Sunil, Hoekstra, Ellerbroek, Bussink, Vidosavljevic, & Kern, 2015) are used as inputs. In this 7th framework project of the European Union, four different concepts for airspace organization are evaluated for PAV and UAV traffic. The experiment area is a metropolitan city of the size of Paris in the year 2050. For the purpose of comparison of different future operation concepts and different scenarios in a metropolitan area the model suffices the need. Two examples of operation concepts and traffic scenarios for PAV and UAV aircraft movements, respectively, are demonstrated.

However, validation of the conceptual model, without the availability of the empirical accident data of UAVs and PAVs, is not possible. To further improve the model, more research can be performed in collecting relevant accident data of UAVs and PAVs. Another approach to improve the model is to make use of simulation platforms to simulate failures of these vehicles and their impact on populated area.

Applicability

This conceptual TPR model suffices the need of comparison of different future operation concepts and different scenarios in a metropolitan area. Another opportunity that this research has shown is the systematic approach to analyze TPR for PAVs and UAVs. It helps with identifying the areas of existing research that can be applied for these calculations, but equally important, it shows the areas that still requires additional research. To further improve the model, more research can be performed in collecting relevant accident data of UAVs and PAVs.

A conceptual third party risk model for personal and unmanned aerial vehicles

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Summary

A conceptual third party risk (TPR) model is developed, implemented, and tested to demonstrate the capability of determining the risk to the population in a metropolitan city exposed to personal aerial vehicles (PAVs) and unmanned aerial vehicles (UAVs) traffic operations. The conceptual model that is primarily based on the methodology and experience of risk modelling for conventional aircraft is modified and the parameters are adjusted suitable for a determination of risk in the arrival, departure and cruise phase of flight for those new aircraft types. Without the availability of the empirical accident data of these aircraft, however, a validation of the conceptual model is not possible. For the purpose of comparison of different future operation concepts and different scenarios in a metropolitan area the model suffices the need. Two examples of operation concepts and traffic scenarios for PAV and UAV aircraft movements, respectively, are demonstrated.

Content

1 Introduction

The impact of aircraft on the environment has always played an important role in the acceptance of new airports, air routes, and aircraft types. With the current development of personal aerial vehicles (PAVs) and unmanned aerial vehicles (UAVs), new aerial transportation concepts will arise that will only succeed to be implemented if the environmental impact is accepted by the public. Considering the rapid developments of both unmanned and personal aerial transportation, research for this future operation may help address the environmental concerns that would become more topical.

When new aerospace concepts are developed, including those for these new classes of PAV and UAV aircraft, their environmental impact should be assessed as well. For important economic areas, such as a densely populated area of the Netherlands, this impact cannot be neglected. In Figure 1, an overview is given of some of the most important concerns with respect to PAV and UAV operations within a city. These impacts can be split into two categories. The first category includes the main environmental concerns that are known for conventional aircraft, such as emissions/pollution, noise pollution, and third party risk (TPR). Emissions may be of less concern as the vehicles are smaller than conventional aircraft, and the progress in sustainable energy sources may resolve emission issues in the future. The topic of noise pollution has been addressed at NLR (Arntzen & Aalmoes, 2015). Third party risk concerns the safety (risk) for the people on the ground, who are involuntarily exposed to an aircraft accident. By definition, people who are on board of an aircraft (air crew and passengers) and people who work within an airfield are considered as first party and second party, respectively.

Figure 1: Environmental concerns related to personal and unmanned aerial vehicles

The second category relates to concerns that may gradually become important such as shadow flickering (similar to wind turbines) or light pollution in case of night operations, privacy,

distraction, and effects on the biotope. It is noteworthy that the impact on the society is still not clear and requires further analysis to study the real impact. For these reasons, the focus here is on the third party risk.

The TPR is important in the (densely populated) Netherlands and, therefore, the NLR has been doing research on TPR around airports (Ale & Piers, 2000) (Weijts, Vercammen, Vijver, & Smeltink, 2004) and developed a TPR model for conventional aircraft. As one of the few countries in the world, it is now part of Dutch law to determine safety zones around airports in the Netherlands (Weijts, Vercammen, Vijver, & Smeltink, 2004). This model is neither suited for PAV and UAV aircraft, nor for the associated operating modes for these aircraft. A good analysis of the safety risk of UAVs is done by Lum and Waggoner (Weibel & Hansman, 2005). Important work has also been done by Dalamagkidis et al. (Dalamagkidis, Valavanis, & Piegl, 2008), who predicts ground risk for aircraft types in relation to population density, but this work does not take (simulated) traffic tracks into account, which is needed for the comparison of different concepts. Other relevant work is done by Clothier et al (Clothier R. , Walker, Fulton, & Campbell, 2007) (Clothier & Walker, 2006), and also Lum et al. (Lum, Gauksheim, Kosel, & McGeer, 2011) who examine the risk during cruise phase of a UAV and do take traffic tracks into account. Moreover, the increased risk of both take-off and landing phases is not part of these studies.

2 A conceptual third party risk model

A conceptual TPR model can be developed and used to evaluate and compare concepts or scenarios, but it is not meant for finding absolute risk values. As the development of PAVs and UAVs is still in early stages, there are not enough operational information and accident data of these vehicles available to develop a risk model with absolute values. By making assumptions based on existing model knowledge of TPR, a comparison can be made between concepts or scenarios with the model. It is expected when empirical data becomes more available with the introduction and use of this new class of aircraft, this conceptual model can be refined for actual TPR calculations.

3   Third party risk for PAVs and UAVs

The introduction of PAVs and UAVs may lead to a different use case compared with conventional aircraft: instead of concentrations of aircraft around airports and air routes, these smaller sized aerial vehicles, with their capabilities to operate within confined air space, will operate in or in the close proximity of built-up areas. It is also envisioned that the amount of traffic can be significant. In order to understand the magnitude of risk that people on the ground are exposed to, there is a need to quantify the third party risk due to the traffic of those aerial vehicles.

The framework of the NLR TPR model is applied here in the development of a conceptual model for UAVs and PAVs. However, the specific procedures of this future concept must be considered, and in particular the cruise phase of flight: for a TPR model around an airport, this phase is exempted from consideration. PAV and UAV operations are expected above a (densely) populated area. Therefore, this risk cannot be ignored and should be taken into account as well.

3.1   Assumptions and considerations for TPR model

Risk factor related to (human introduced) hazards depends on the compensating benefit (Starr, Rudman, & Whipple, 1976): the higher the societal benefit, the higher the risk that is accepted for a lethal accident. At this moment the benefit of using drones or personal air vehicles is low and not considered beneficial, so the safety criteria for these vehicles will be high. Perception of safety plays an important role for UAV operations (Clothier & Walker, 2013). It could be expected that when the benefits of improved delivery times or reduced travel times become more obvious, the safety criteria may be re-evaluated.

Future aircraft types that are foreseen will also differ from the current fixed-wing and rotorcraft aircraft types. Tilt-rotorcraft can operate both as rotorcraft (for take-off and landing) and as fixed-wing (during cruise phase), thereby benefiting from both the advantages of rotorcraft (capable of performing vertical take-offs and landings) and fixed-wing aircraft (more efficient and faster cruise phase). Furthermore, the smaller unmanned aircraft can have a quad-copter (four engine) to octa-copter (eight engine) configuration suitable for services like package delivery or surveillance missions. These aircraft will operate with similar characteristics as rotorcraft.

The following factors have influence on the TPR model:
- Probability of an accident during landing or take-off. This probability is expressed per flight stage.
- Probability of an accident during cruise. This probability is expressed per flight hour.

- Location of the crash area after malfunction (it depends on whether the aircraft is fixed wing or not). There should be some estimation of the location of the crash area. Also the chance that an aircraft crashes into a building and leads to casualties in the building or on the ground underneath should be taken into account.

Secondary effects caused by accidents such as an aircraft crashing into a gas station causing huge fire or explosion shall not be taken into account in this model. Only the risk of direct causalities on ground caused by aircraft crashes is considered relevant.

For risk in cruise phase, the following kind of hazards can be discerned (Clothier R. , Walker, Fulton, & Campbell, 2007):

- Mid-air collision with other aircraft;
- Other hazards, such as system failure, weather, bird strike, terrorism, and human error.

To calculate the probability of mid-air collision for a new airspace concept, a detailed analysis for this concept should be performed. This requires an extensive research of the possible failures in systems that are used in these concepts (both ground and airborne systems), and the consequences for the total risk of mid-air collisions. A systematic approach can be taken based upon the type of concept that is being used. For instance, for a free flight airspace (Hoekstra, Ruigrok, & Gent, 2000), the concept is based upon a Sense & Avoid system. The failure of this S&A system leads to the probability of a mid-air collision. For other concepts, such as a *layered concept*, collisions are reduced by separating aircraft vertically, based upon the direction they fly to. The mechanism that is used to make sure the aircraft fly within the designated layer should be used as estimation of a possible mid-air collision. This estimation should be made with engineering judgment if empirical data are not available. If the probability can be determined that an UAV avoids another UAV or another aircraft, the total mid-air collision probability can be determined, as explained in (Lum & Waggoner, 2010). For the conceptual TPR model, an estimate shall be used for the average mid-air collision risk, which is based upon flight hours per aircraft.

The routes that the aircraft take are influenced by:

- The airspace concept used and associated routing scheme.
- The take-off and landing zones.
- The scenario in which traffic demand appears.

For the impact of the crash, the following factors play a role:

- Consequence area in terms of aircraft size expressed in maximum take-off weight. This is the area in which the people on ground could receive fatal injury should an aircraft accident occur.
- Density of the population.
- Shielding of population by buildings (Melnyk, Schrage, Volovoi, & Jimenez, 2014).
- Commuters/traffic on the street.
- The time of day in relation of the number of people in the area.

The model should include the lethality of a crash, which is determined as the ratio of the number of people affected in the crash area and the number of people present in that area. A separate method can be used to determine the number of people in the crash area at a certain time of day.

A summation of all traffic shall be provided, but it is expected that in scenarios where both small and large aircraft operate together, the TPR of the smallest aircraft type (an unmanned quad-copter) will have a negligent impact on the resulting, total TPR, because of relative small impact of a crash caused by a small aircraft. However, for the calculation of mid-air collision, these aircraft may have an influence on the TPR risk for the larger aircraft.

Aircraft movements over the lower density areas of the evaluated area will also have a relative small contribution to the total risk.

3.2   Model restrictions

The third party risk model presumably can make use of values or model parameters that are derived from existing risk models and methodologies known to third party risk experts and literature study. This approach may not be entirely representative for operations of PAVs/UAVs in a dense city as there are no data available for accidents of this kind. Thus, the results should only be used in the comparison between the different scenarios.

The results of a TPR calculation are also deemed to be useful in the determination of the target level of safety for future PAV/UAV operations.

The TPR model implementation can be computational intensive due to the number of tracks that are being processed, the length of the simulation, and/or the chosen model parameters. For this reason, further simplifications to the calculation may need to be chosen, so a representative value for the TPR can still be calculated. Examples of simplification can be:

- Reduction of interpolation of the tracks or grid size or density or size of the simulation area.
- Reduction of number of tracks or simulation time.
- Reduction of the number of aircraft types, so only those aircraft types that have a significant influence on the TPR are taken into account.

4 Conceptual TPR model design

The schematic to calculate the TPR is presented in figure 2. The model shall make use of aircraft tracks and iterate over the given tracks. For each of the aircraft tracks, the risk is calculated by the combination of:

A. The probability of an accident of the aircraft.
B. The potential impact area (the location of the crash area, in case of an accident).
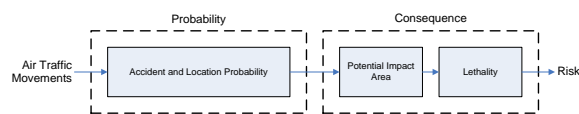C. The lethality probability.

Figure 2: Schematic of the Third party Risk model

4.1 Probability of an accident

To calculate the probability of an accident of one flight, each flight will be split up into a take-off phase, a cruise phase, and a landing phase. For each of these phases, accident probabilities of previous research exist. The values are based on accident data and statistics. With this, a model can be developed that is able to calculate the risk on the ground for the take-off, cruise, and landing phases. After that, these risks can be summed up for the whole flight.

4.1.1 Take-off and landing phases

For the take-off and landing phases, the probability of an accident is ideally calculated based upon prior research of similar aircraft types. An extensive data set should be available that includes both the aircraft utilization in terms of number of movements, and the number of accidents during take-off or landing phase of flight. However, such approach in data research is not feasible for the given aircraft types and operating procedures for the given concept for PAVs and UAVs, as it is impossible to obtain reliable historic data at this moment. Therefore, current aircraft types must be used, such as other rotor-based aircraft, which are deemed comparable to the PAVs and UAVs considered here. The probability that a landing or a take-off results in an accident is a parameter in the model.

For describing the aircraft accident locations, a Weibull distribution (Runger, 1994) as used in the NLR TPR model (Weijts, Vercammen, Vijver, & Smeltink, 2004) is chosen here to determine where the accident likely occurs. The specific parameters of the Weibull distribution are based on data research.

Specific take-off and landing failure rates for rotor-craft aircraft can be found in (Cheung, Haij, Smeltink, & Stevens, 2007), but they explicitly exclude data from tilt-rotor aircraft. However, a Congressional study indicates that a typical tilt-rotor aircraft such as the V-22 Osprey has similar failure rates (Bolkcom, 2004). In (Cheung, Haij, Smeltink, & Stevens, 2007), a distinction is made between single (or piston) and twin turbine engines, where the failure rate of twin turbine engines is lower due to the redundancy of the propulsion. Therefore, in this TPR model, the failure rate depends on the aircraft type and the number of engines. For a tilt-rotor aircraft, the twin turbine engine failure rate is taken. For a quad-copter aircraft type, where it is assumed that it cannot perform a safe landing if one of the four engine fails, the worst-case value (single turbine) is taken. It is noteworthy that accident rate (failure rate) applied here is higher than that presented by (Dalamagkidis, Valavanis, & Piegl, 2008), in which the accident rate of 10^{-7} per year is proposed. Therefore, the conceptual TPR model presented here could be considered conservative.

To determine the probability of accident location during take-off or landing, the flight track needs to be available from take-off to a certain distance where the Weibull distribution can be considered 1 (one). For landing, the track should be reversed from touch-down back to the point where the Weibull distribution is valid for this phase of flight. For these calculations, iteration along the route should take place based on fixed distance steps.

Two other modifications are proposed compared to the NLR TPR model. First, in the NLR TPR model for helicopters, an aircraft is considered to be in cruise over 500 feet (Cheung, Haij, Smeltink, & Stevens, 2007). For a scenario in a metropolitan area, it can be expected that some aircraft, in particular UAVs, will have a more vertical than horizontal flight path. For this reason, instead of using the height of 500 feet as cut-off, the total flown distance of 1000 metres of the flight path is taken as limit for which part is considered as take-off or landing. Second, the Weibull curve that is used for start-and landing risk will reach a probability value close to 1, but not exactly 1 after a distance of 1000 metres. Therefore, the residual risk that is normally neglected for an airport-based TPR model, shall be distributed over the trajectory in which the aircraft is within this distance of 1000 metres.

4.1.2 Cruise phase

For the cruise-phase, the probability of an accident is based on number of accidents per flight-hour. In (Clothier & Walker, 2006), an accident rate of 5.6×10^{-5} per flight hour is given. This is derived from empirical data from the National Transportation Safety Board (NTSB), which leads to an accident resulting in a fatality on the ground to 1.48×10^{-7}. For PAVs and UAVs, no

comparable empirical data are available. Therefore, similar accident rates are assumed. Also it is assumed that the risks in the different flight phases (starting, cruising, and landing) are similar for PAVs and UAVs as for conventional aircraft.

As the accident probability for cruise is based upon flight-hours, the *speed* of the aircraft shall be taken into account. To determine the risk for the cruise-phase, the model needs to iterate through the given route, and calculate the risk for each iteration step. The time step (in seconds) of this *iteration speed* will be a parameter in the model.

If the aircraft route is given as a list of waypoints, an approximation must be made for the iteration step between the waypoints. It is expected that subsequent waypoints are not too far away and the iteration can be considered to be a straight line. Alternative methods are the use of interpolation techniques like splines (Schoenberg, 1988), but these methods are more computational intensive and are not needed for a simple model set-up described in this context. It is also assumed that the aircraft speed is known for each of the given waypoints, and therefore, the average speed between the previous and next waypoint is used to calculate the aircraft speed during the interpolation.

4.1.3 Mid-air collision risk

The risk of mid-air collisions for a specific number of aircraft movements within a volume of airspace can be translated into certain chance on a mid-air collision per flight hour (Weibel & Hansman, 2005). For this reason, an additional factor can be added to the risk that is found in cruise-phase.

4.2 Potential impact area

A grid will be defined that will contain the operating area of the aircraft. Each grid cell will receive a risk value based upon the offered number of tracks and the model that calculates the risk of this cell. For the sake of simplicity and consistency, the shape of the grid cells is considered to be square. The number of grid cells and the size of a grid cell will be a parameter in the model. The smaller the grid size, the more precise the Third Party risk can be calculated, but then the more complex the calculation that must be done. The same holds for the previously mentioned *iteration speed*.

In case of an accident, a potential impact area on the ground (footprint) can be calculated based upon aircraft type, aircraft weight, speed, direction, etc. This footprint, as displayed in yellow in Figure 3, will cover one or more grid cells on the ground. For each of the grid cells, the probability

is calculated for the aircraft impact in this cell. In this figure, a hypothetical ellipse is used as potential impact area.
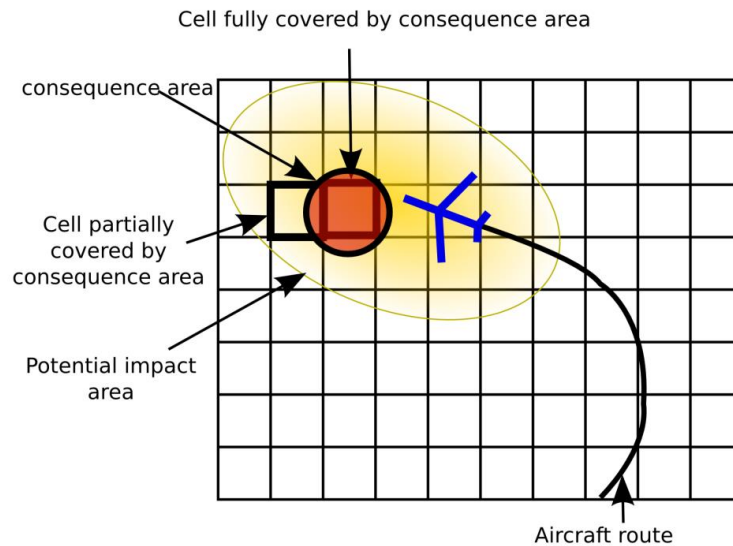

Figure 3: Accident location probability and impact area of a single aircraft track

An estimate must be made about which grid cells will be taken into account and what kind of probability distribution is used for the potential impact area. For instance, cells on the outside the potential impact area could have a considerably smaller probability of impact than the cells lying more towards the centre of the impact area.

The size of the potential impact area in this TPR model depends on the flight and accident characteristics of the aircraft. The glide angle of the aircraft involved is a parameter to determine the outer limits of this area. For two new types of aircraft that are later used in this article, NLR experts have estimated their glide angles, see Table I.

Table I: Glide angles and consequence area (CA) of some PAV and UAV airacraft types

Aircraft type	MTOW [kg]	Start/landing configuration	Cruise configuration	CA [m^2]
Medium-sized tilt-rotor (PAV)	7620	1:5	1:10	797
Quad-copter (UAV)	15	1:2	1:2	42

4.2.1 Bivariate normal distributed potential impact area

According to (Clothier R. , Walker, Fulton, & Campbell, 2007), a bivariate (2D) normal distribution is proposed for the potential impact area, where 99% of the impacts will occur within the maximum glide distance. The variance orthogonal to the track heading is considered half that of

the variance in the heading of the track. An exception is made for aircraft similar to quad-copters that do not have a dedicated flying direction, so the variance of the width is considered the same as the length.

Discrimination between mid-air collision risk and system failure risk is not made for the potential impact area in this model, as it is assumed that this distribution functions applies for both types of accidents.

4.2.2   Consequence area

The consequence area is the size of the affected area if a crash happens at that location. Within this area a third party could be fatally injured due to this crash. The consequence area can either be:

1.   smaller than (or equal to?) the cell size, and thus only affect this cell; or
2.   larger than this cell, and that other adjacent cells are affected as well.

For simplicity of the model, the distribution of the accident consequence due to aircraft crash is considered uniform within the consequence area. If part of a cell (or part of a neighboring cell) is affected, the percentage of overlap is used to determine the lethality of the cell. This will be discussed further in the next paragraphs.

If the consequence area for all the different aircraft types and routes is smaller than the cell size, then the model can be made simpler: the consequence of an impact on neighboring cells can be considered zero and the consequence area need not be distributed to neighboring cells, as is done in the original NLR TPR model (Weijts, Vercammen, Vijver, & Smeltink, 2004). This simplification requires that the grid size is not chosen too small, and at least larger than size of the impact area of the aircraft with largest impact area size.

4.2.2.1   Consequence area for aircraft ≥ 500kg

According to NLR's research on helicopter crashes and third party risk for inland heliports (Cheung, Haij, Smeltink, & Stevens, 2007), the consequence area can be determined by the following empirical relation:

$$CA(x) = 230 \ln(x) + 330 \tag{1}$$

Equation (1) gives the size of the consequence area of a helicopter crash, where x represents the helicopter MTOW given in metric tons (1000kg) and CA the consequence area given in square metres. This relation is valid for a range from 500 to 12,000 kg.

4.2.2.2   Consequence area for aircraft < 500 kg

The quad-copter UAV cannot use this formula as its mass is well below the minimum of 500kg required by (1).

$$A_{LHp} = (\omega_{ua} + 2R_p)(L_{ua} + H_p/(\tan \gamma) + 2R_p) \tag{2}$$

As an alternative, Equation (2) in (Lum & Waggoner, 2010) represents the worst-case consequence area of an aircraft in horizontal glide. Equation (2) gives the size of the consequence area based upon an aircraft gliding horizontally. It will be applied with the following values:

- Height of the person (H_p) of 2.0 metres and radius (R_p) of 0.5 metres
- Dimensions of a quad-copter aircraft of length (L_{ua}) = 2 metres and width (ωua) of 2 metres
- Glide angle according to 1:2 glide ratio (Table I)

This leads to a consequence area of 21 m^2 for vehicle with the diameter of the quad-copter. But this vehicle has moving rotor blades and it may cause harm beyond the projected diameter/area. For this reason, a more conservative consequence area is suggested for this type of vehicle. Therefore, the calculated consequence area is doubled and a value of 42 m^2 is used in the model.

According to Table I, a grid size of at least 30 by 30 metres (equals 900 m2) will fit the consequence area for these aircraft types.

Another simplification made in the model is by not rotating the grid cells for which the impact probability is calculated, see Figure 4. By not rotating the cell, the calculation of the impact probability for that cell can be calculated easier, and thus reducing processing time. Analysis for this approach has shown that the deviation from the actual value is small, as the area surface for the impact is still the same.
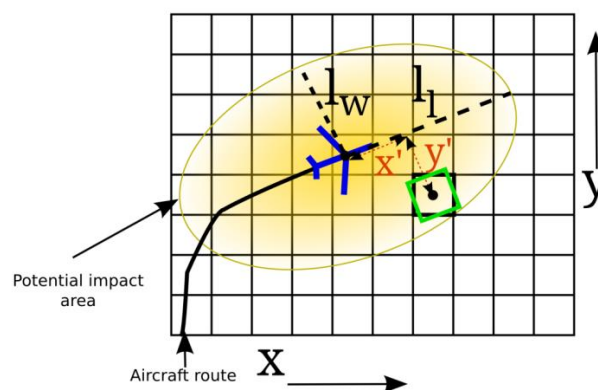

Figure 4: The green box demonstrates the simplification in the model by not rotating the affected grid cell

4.3 Lethality

In the determination of the lethal effects within an impact area, the probability of not surviving an aircraft crash must be known. This chance is called lethality. The lethality could be influenced by, amongst others, the energy of aircraft impact, the density of the population in the area and the shielding of building, vehicles, etc. in that area.

As an alternative for using the energy level to calculate the lethality, in (Cheung, Haij, Smeltink, & Stevens, 2007) an estimate is made. The estimated value is 17% chance that a third party could be lethally affected in a helicopter crash within the consequence area, as defined by (1). It should be noted that this value was based on the empirical data available for helicopter crashes investigated. So it is conjectured that the use of this value for lethality is appropriate for the aircraft types used for other rotorcraft aircraft like tilt-rotorcraft. For much smaller aircraft like quad-copter, there are again not enough empirical data on lethality available for an expected lower value. For this reason, the 'worst-case' value of 17% is applied here as well. This value is provided to the model as parameter and can be adjusted if new research proves otherwise.

By combining the model components, accident probability, accident location and accident consequences with the traffic operations (aircraft movements), the Individual Risk be determined. The individual risk (IR) due to all aircraft movements in point (x,y) is determined by (3) and is simplified from the risk calculation formulae as derived in (Weijts, Vercammen, Vijver, & Smeltink, 2004).

$$IR(x,y) = N_{mov}*AR*P(x,y)*CA*Let \qquad (3)$$

N_{mov} represents the number of take-offs and landings (movements) per aircraft type regarded per year, AR the accident rates (probabilities) per aircraft type differentiated in take-off and landing, $P(x,y)$ the probability of accident at location (x,y), CA the extent of consequence area and Let the lethality.

5 Model implementation

The conceptual model has been implemented using the python programming language, and it runs on different operating systems (MS-Windows, Linux). The python language allows for quick prototyping, but provides enough structure in the language for a structured, object-oriented architecture. By making use of specific libraries, such as scientific and plotting libraries, the model could be implemented in a short time and results can be produced that can demonstrate the results in a graphical way.

The implementation has been focused on developing the functionality of the described TPR model, and is therefore not optimized for the calculation performance. If more aircraft movements and/or a larger experiment area are required for TPR calculations, a higher performance may be required. In (Aalmoes, Erkamp, Cheung, & Nieuwport, 2013), it has been demonstrated that for a similar a high-performance implementation for TPR calculation is possible.

6   Results

For a demonstration of the conceptual risk model, simulation tracks from the Metropolis project (Sunil, Hoekstra, Ellerbroek, Bussink, Vidosavljevic, & Kern, 2015) are used as inputs. In this 7th framework project of the European Union, four different concepts for airspace organization are evaluated for PAV and UAV traffic. The experiment area is a metropolitan city of the size of Paris in the year 2050. Because of uncertainty in the growth of the city, use is made of four different city growth scenarios. Traffic is simulated for the whole city, but data logging has been done in a smaller, trapezoidal shaped area. Population density varied depending on the distance from the city center (origin) (Sunil, Hoekstra, Ellerbroek, Bussink, Vidosavljevic, & Kern, 2015).

A description and explanation of the four different concepts (*Full Mix, Layers, Zones*, and *Tubes*) is described in detail in (Sunil, Hoekstra, Ellerbroek, Bussink, Vidosavljevic, & Kern, 2015). For the evaluation described in this document it should be known that the traffic demand for each of the concepts is the same, but the actual aircraft movement will be different based on the rules within the concept that is used. In this article, only gathered data from the Full Mix and Zones concepts are presented.

To examine the results of the TPR model, two traffic scenarios are defined. Both of the simulations, multiple aircraft movements are accumulated to create a –so called–multi-event calculation. The scenarios are:
   A.   A total of 50 movements of a heavy (bus-like) tilt-rotor PAVs, to act as a flying alternative to a bus.
   B.   A total of 40 movements of a small-sized quad-copter UAVs, for surveillance or package delivery purposes.

These aircraft movements are selected from one of the scenarios in Metropolis. These movements are not representative for a scenario in the Metropolis project, but are just selected to demonstrate the capabilities of the TPR model. However, the TPR model is equipped to do calculations of multi-event traffic from multiple aircraft types.

6.1   PAV third party risk example

In figures 5 and 6, the PAV tracks created by the Full Mix concept are displayed, whereas in figures 7 and 8, the tracks of the Zones concept are shown. As can be observed, even though the same traffic demand is handled, the tracks are different. The other two concepts (not displayed) also show a different pattern of flight tracks. The displayed tracks do not immediately indicate that there is a difference in TPR.
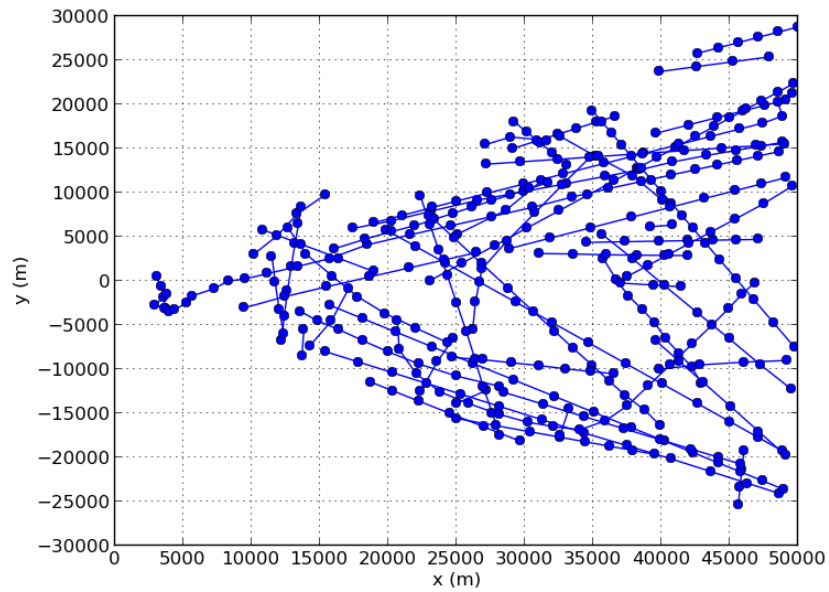
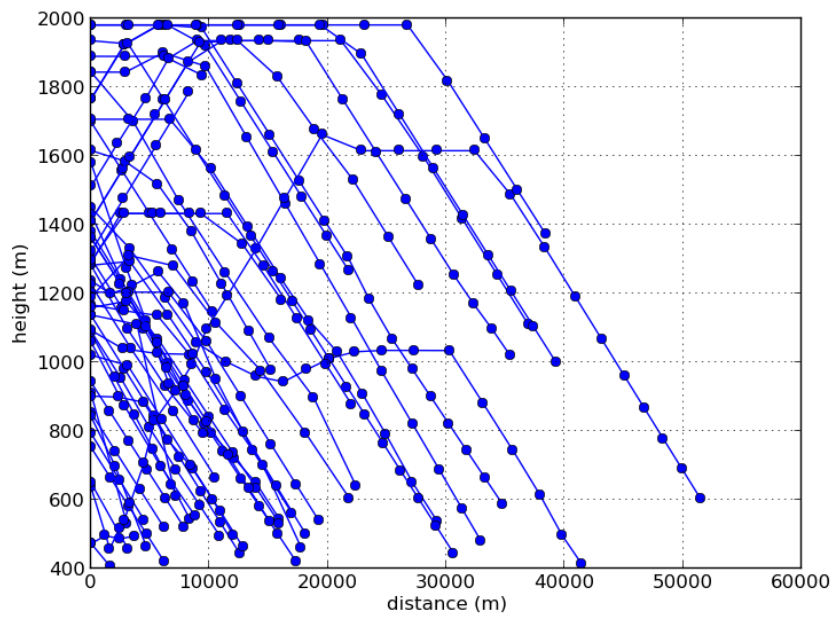*Figure 5: PAV movements in the Full Mix concept (lateral view)*

Figure 6: The 50 PAV movements in the Full Mix concept (vertical View)
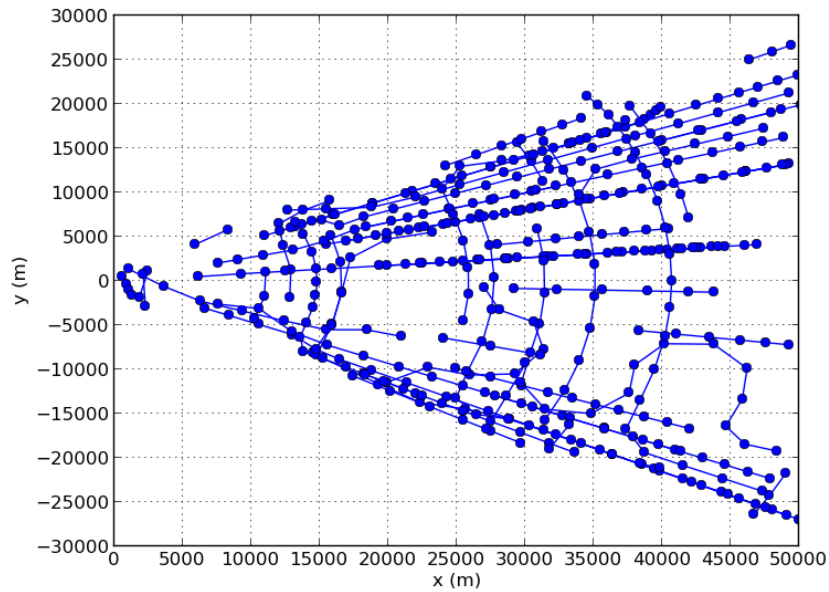
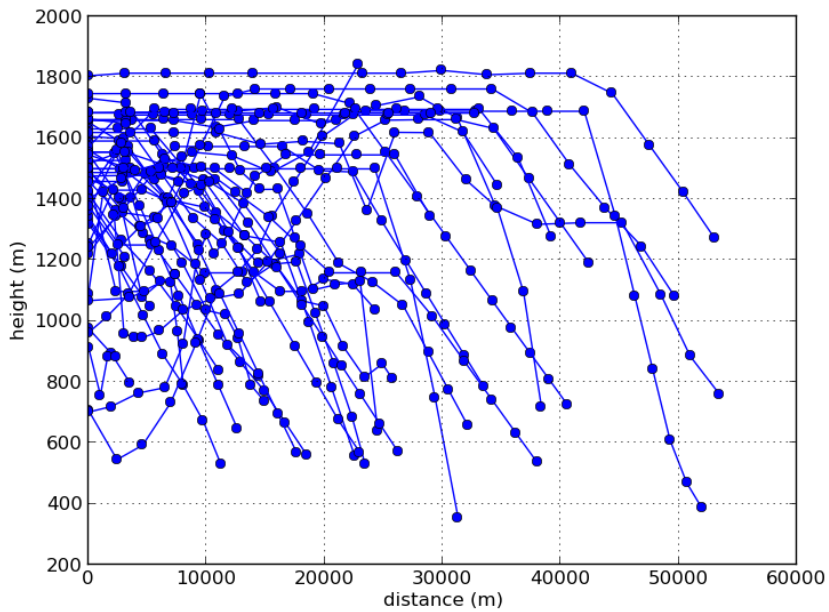*Figure 7: The 50 PAV movements in the Zones concept (lateral view)*

Figure 8: The 50 PAV movements in the Zones concept (vertical view)

A risk calculation with the conceptual TPR model is executed on the Full Mix and Zones concepts. To make a fair comparison, the absolute population risk is calculated for the Full Mix concept and the results are divided by this value. So a normalized result is obtained. This result represents the risk distribution in the event of one lethality. The value that is used to normalize the Full Mix concept is also used for the other concepts, so the probabilities of the concepts can be compared. The result for the Full Mix and Zones concept can be found in figure 9 and 10,

respectively. The higher risk to the population for both concepts is clearly visible for the inner city (within 4 km from the origin), and to a lesser extent for the inner ring (within 12km from the origin).
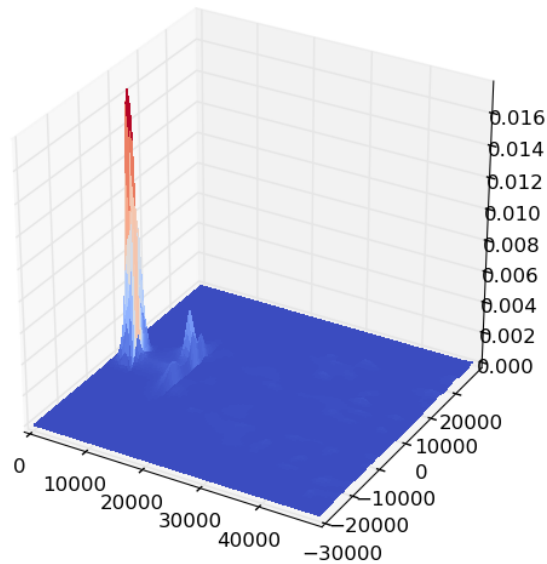
Figure 9: The Full Mix concept normalized population risk for the 50 PAV movements. This represents the risk distribution if there is a probability of one lethality within this traffic and concept
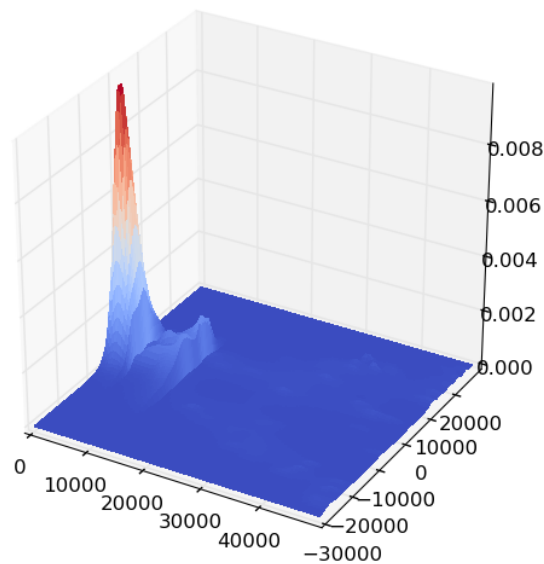

Figure 10: The Zones-concept population risk for the 50 PAV movements based upon the normalized risk of the Full Mix concept. It can therefore be compared with the values given in figure 9

A comparison between the Full Mix and Zones concept for these tracks results in a value of 56% higher risk in the Zones concept than in the Full Mix concept.

6.2 UAV third party risk example

For the UAV example, two scenarios are compared that differ in traffic density. In figures 11 and 12, the UAV tracks created by the high density traffic scenario are displayed. In figures 13 and 14, the UAV tracks of the low density traffic scenario are displayed. Compared to the PAV example, the UAV tracks are concentrated near the center of the city, so the evaluation area is reduced in size. A close examination of the vertical views (figures 12 and 14) shows that while the number of tracks is the same, the average distance of the UAV tracks in the low density traffic scenario is significantly shorter.
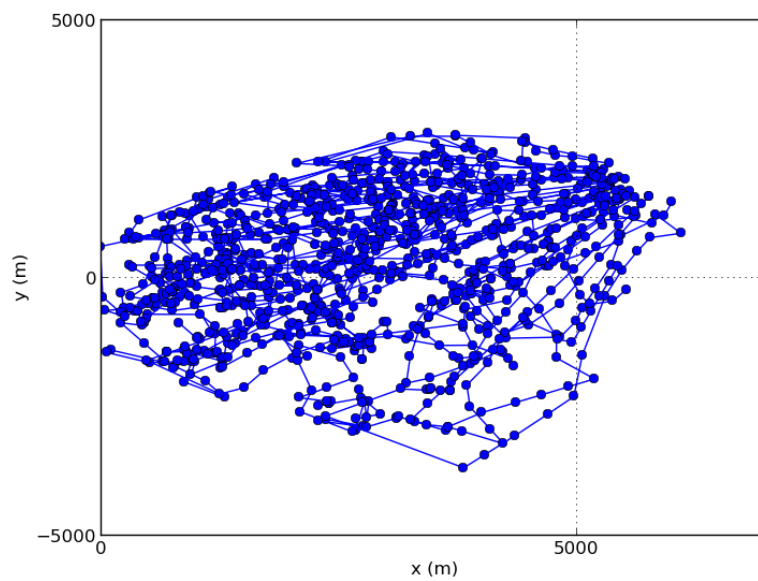
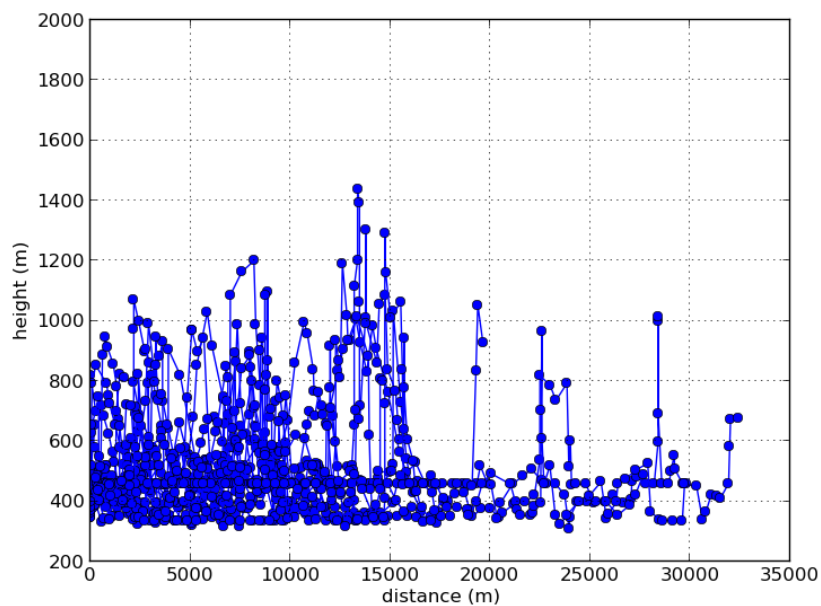*Figure 11: The 40 UAV movements with high density traffic (lateral view)*

Figure 12: The 40 UAV movements with high density traffic (vertical view)
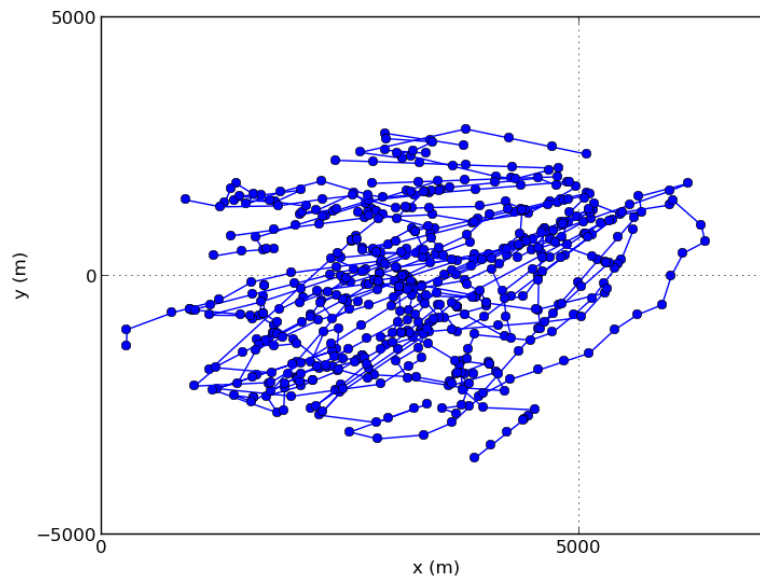
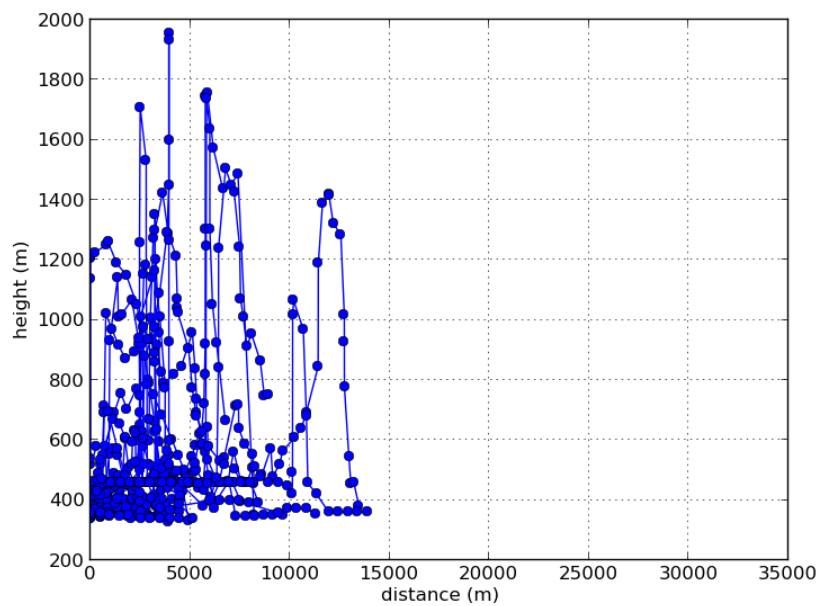*Figure 13: The 40 UAV movements with low density traffic (lateral view)*

Figure 14: The 40 UAV movements with low density traffic (vertical view)

The same normalization step is done for the UAV risk as was done for the PAV risk (the probability of one lethality), which results in figures 15 and 16. Also clearly visible here is the higher population in the inner city (4km around the origin). A comparison between the two scenarios results in a value of 32% lower risk in the low traffic scenario than in the high traffic concept.
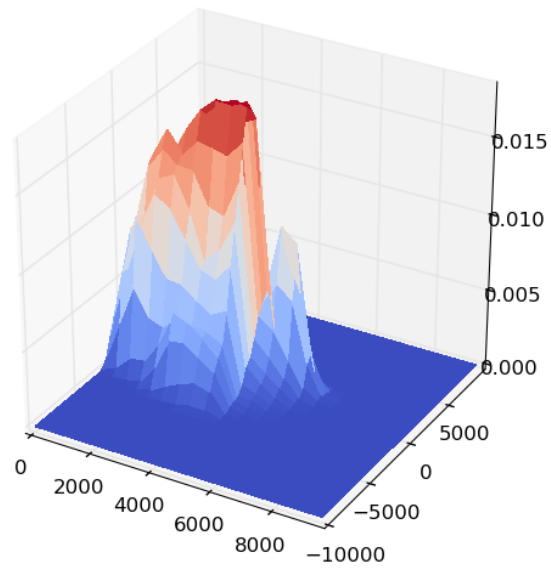
Figure 15: The high density traffic scenario normalized population risk for the 40 UAV movements. This represents the risk distribution if there is a probability of one lethality within this traffic scenario
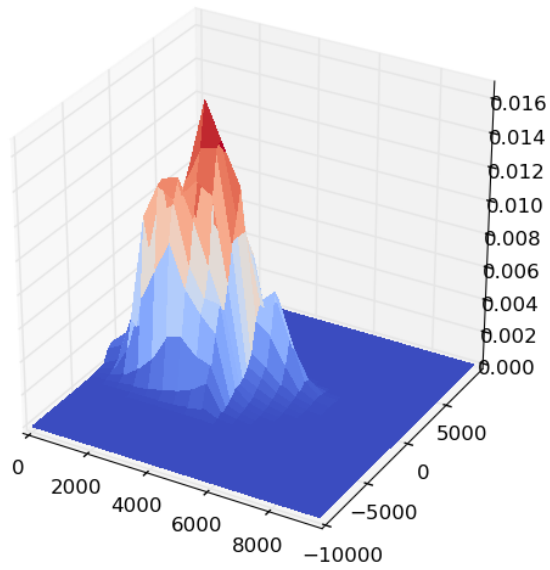

Figure 16: The low density traffic scenario population risk for the 40 UAV movements based upon the normalized risk of the high density traffic

7   Conclusions

A conceptual third party risk model is developed, implemented, and tested to demonstrate the capability in determining TPR that involves PAV and UAV operations. Without sufficient empirical data about accidents of these aircraft, this conceptual model can be used to compare different concepts. The relation between the arrival, departure, and cruise risk is based on the risk modelling experience of conventional aircraft. The model parameters are modified and based upon improved insight on TPR of these new types of aircraft and their expected operating procedures.

Another opportunity that this research has shown is the systematic approach to analyze TPR for PAVs and UAVs. It helps with identifying the areas of existing research that can be applied for these calculations, but equally important, it shows the areas that still requires additional research. To further improve the model, more research can be performed in collecting relevant accident data of UAVs and PAVs. Another approach to improve the model is to make use of simulation platforms to simulate failures of these vehicles and their impact on populated area. A topic that needs to be addressed by further research is the mid-air collision that can take place with new concepts. Finally, an important field of further research is to find target levels of safety for UAV and PAV operations: these targets can be compared with safety levels found in other forms of transportation. A conceptual model as presented here can help in this field of research.

Acknowledgement

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