READ 2024
RESEARCH & EDUCATION IN AIRCRAFT DESIGN
WARSAW, POLAND | 6-8 NOVEMBER 2024

SIMULATION OF URBAN AIR MOBILITY TRAFFIC

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Abstract

The concept of Urban Air Mobility (UAM) assumes that a significant part of road traffic and services will be moved to the airspace. The appearance of thousands of vertical take-off and landing (VTOL) aircraft over urban agglomerations must be preceded by a transitional period during which solutions regarding air traffic management and safety will be developed. In order to support this process, a tool for aircraft traffic analysis in urban agglomerations, called Urban Air Mobility Traffic Analysis Tool (UAM TAT), has been developed.
The main challenge in transferring so many services up to the air is that not all solutions derived from general aviation could necessarily be applied in the UAM environment. The main idea behind the tool for traffic analysis is to develop a reliable environment in which different scenarios and methods for air traffic management could be tested. Second advantage of the developed tool is its capability to test capacity of any given airspace with its own restricted areas and no-fly zones. One of the most important features of the tool is its open architecture that allows to implement and test various flying regulations and VTOLs' behaviour.
In the article, the software tool is presented, where all crucial aspects, features and configuration possibilities are shown. Final part of the paper contains a description of the nominal configuration used to conduct test simulations, along with a justification of the choice of individual parameters and their sources. The results of the test simulations and their analysis are described.

Keywords: Urban Air Mobility, unmanned aerial vehicles, air traffic analysis, simulation

1. Introduction

The growing complexity of advanced aviation systems brings new threats to safety and security and poses several regulatory and technical challenges. As VTOL traffic increases, it is important to ensure the safe integration of VTOL into an air traffic management system initially designed to support manned aircraft [1]. The expanding use of VTOLs in urban environment will increase the risks of potential collisions, various incidents and accidents that can result in serious losses or injury. Since the use and applications of VTOLs are increasing and diversifying, it is necessary to develop effective risk management practices, methodologies, and processes in order to ensure the safety of operations. Identifying and understanding risk factors [2, 3] is a key step in developing risk mitigation and response measures for VTOL operating in urban environments.
To verify various approaches, methods and air traffic rules to the UAM, a dedicated simulation tool was developed. A virtual environment in which different scenarios could be tested may be used to identify and mitigate some risks in the UAM. The goal of the UAM TAT is to identify potential hazards and then determine which safety regulations and procedures applied are most reliable and safe.
From among the research [4, 5] it seems that centralised method for controlling VTOLs may not be efficient and it is needed to apply a decentralised approach. Conducting the various case studies it is possible that not all methods and regulations are scalable from general aviation. The UAM TAT allows to simulate various platforms with different range of autonomy, dynamic properties (e.g. velocity, turn radius, weight, onboard sensors, ability to S&A). Consequently, the software and hardware onboard the VTOLs needs to be unified and integrated, which is a significant challenge to overcome in the future. Conducting simulations by varying those parameters could result in defining the regulations

for national aviation authorities regarding the minimum requirements for VTOLs to be approved in the current U-Space. The developed tool is also capable of defining various methods of air traffic rules such as queuing, prioritization and emergency situations. This feature could result in determining effective and safe methods of controlling the U-space. In the following paper, the tool for traffic analysis and its features is presented, followed by some case studies.

2. Input data, modelling and simulation

Urban Air Mobility Traffic Analysis Tool is comprised of several modules which allow to run the full simulation and obtain the desired output:

- input data generation script;
- input data preprocessing module;
- simulation module;
- plot and output files generation module.

2.1 Input data generation

The goal of the input data generation script is to create an input file containing data about each simulated VTOL based on parameters provided by the user which were presented in Tab. 1 and 2. These parameters are stored as JSON-formatted text in population declaration files.

Table 1 – Description of parameters used for invariant input data generation

Parameter name	Description
familyName	VTOL family name, it has no influence on their behavior during the simulation.
numberOfDrones	Number of VTOLs of this family present in the simulation.
failureRate	Failure rate parameter, it influences the frequency of malfunctions occurring in the simulation.

VTOLs' waypoints are generated by using population density data in the simulated region. The data for Warsaw used in the simulation was published by Statistics Poland as one-kilometer grids [6]. The no-fly zones for presented airspace are published by Polish Air Navigation Services Agency [7, 8]. To allow for testing new Urban Air Mobility traffic solutions, it is possible to add user-defined zones to the simulation.

The first step of preparing simulation is generating parameters for particular families of VTOLs. The parameters shown in Tab. 1 such as `familyName` and `failureRate` are directly assigned to each VTOL from the family, whereas `numberOfDrones` is the number of VTOLs that should have their data generated. Parameters shown in Tab. 2 are randomly generated for each VTOL. For parameters containing a probability density function described by user-provided weights the program uses this data to randomly draw their values. Four types of routes were implemented in the program. The generated waypoints are ensured not to lie inside a no-fly zone.

Point-to-point Based on the population density, the program generates take off and landing waypoints. It is the simplest type of route, comprising of two waypoints only. This type represents e.g. taxi routes.

Hub-to-point VTOL takes off and lands in one of the hubs and flies via waypoints. This implementation simulates courier deliveries – the parcels are picked up from large hubs and then delivered to customers. Deliveries statistics were estimated, based on a parcel locker used by a leading Polish parcel delivery company – InPost. It was estimated that:

- 32% of VTOLs would fly to between 1 and 2 waypoints,
- 44% of VTOLs would fly to between 3 and 4 waypoints,
- 23% of VTOLs would fly to between 5 and 8 waypoints,

Table 2 – Description of parameters used for randomized input data generation

Parameter name	Description
autonomyLevel	Two-row matrix containing VTOL autonomy levels and corresponding weights. The autonomy level of a particular VTOL is drawn according to this probability density function.
size	Vector containing lower and upper bounds of VTOL size. The size of a particular VTOL is drawn using a uniform distribution with these parameters applied.
safetyZone	Vector containing lower and upper bounds of VTOL safety zone size. The size of a particular safety zone is drawn using a uniform distribution with these parameters applied.
velocity	Vector containing lower and upper bounds of VTOL cruise speed. The speed of a particular VTOL is drawn using a uniform distribution with these parameters applied.
range	Vector containing lower and upper bounds of VTOL range. The range of a particular VTOL is drawn using a uniform distribution with these parameters applied.
altitude	Vector containing lower and upper bounds of VTOL cruise altitude. The cruise altitude of a particular VTOL is drawn using a uniform distribution with these parameters applied.
departureTimes Distribution	Two-row matrix containing departure hours and corresponding weights. The departure time of a particular VTOL is drawn according to this probability density function.
routeType	VTOL route type: "point-to-point", "hub-to-point", "hub-to-point-to-point-to-hub" or "loitering".
hubsList	Matrix containing geographic coordinates of VTOL hubs and weights corresponding to them.

The number of waypoints is drawn from a Weibull distribution whose probability density function is described as follows:

$$f(x;\lambda,k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} \mathrm{e}^{-(x/\lambda)^k}. \tag{1}$$

The Weibull distribution parameters allowing for satisfying the estimated number of deliveries were calculated to be: $\lambda = 3.31506$ and $k = 1.88177$. The mean number of delivered parcels per VTOL for these parameters is 3.41.

After summing up the total number of waypoints for a given VTOL family, the program draws the waypoints' locations based on the population density distribution. Then, one of the waypoints is chosen as the first point of the route. The next step is to pick the following waypoints as the ones closest to the first point. Moreover, the closest hub is selected as the takeoff location. It ensures optimal distribution of the "parcels" in the hubs. The last step is to apply a travelling salesman algorithm to the waypoints in order to determine their optimal order.

Hub-to-point-to-point-to-hub In this type of route the VTOL takes off in one of the predetermined hubs, flies to two points and ends its flight in one of the hubs (possibly the first one). This type of route simulates food deliveries from restaurants to clients.

Loitering This type of route simulates the flight of VTOLs which are used to fly in specific areas (e.g. for recreational or inspection purposes). They move chaotically over a limited area, take off and ending their flight in the same spot. The waypoints are drawn taking into account the VTOL's range.

2.2 Input data preprocessing

Since the input data contains only the main waypoints, it is necessary to determine a path which the VTOL should follow in order to avoid entering the no-fly zones and take into account the limited-fly zones.

No-fly zones If a route leg crosses a no-fly zone, the program determines intermediate waypoints in such a way that allows to avoid flying through this zone. For this purpose, the A* algorithm [9] is used.

Limited-fly zones The limited-fly zone, as opposed to the no-fly zone, is not entirely inaccessible for the VTOLs. The VTOL can fly in the zone if its departure or destination point is located there. The intermediate waypoints are determined in such a way that minimizes the time of the VTOL's presence in the zone.

2.3 Simulation module

The VTOL is modelled as a point particle with 3 degrees of freedom. In order to determine its position and velocity in consecutive steps of the simulation the following equation of motion is used:

$$\vec{r}^{\,k}_{i+1} = \vec{r}^{\,k}_{i} + \vec{v}^{\,k}\Delta t, \tag{2}$$

where:
$\vec{r}$ – VTOL's position vector,
$\vec{v}$ – VTOL's velocity vector,
k – VTOL's number,
i – time step number,
Δt – time step.

A constant time step is used in the simulation (usually set as $\Delta t = 1\,\mathrm{s}$). Components of the velocity vector are determined based on the direction from the VTOL's position in the current time step to the next waypoint's position and the cruise speed of the VTOL:

$$\vec{v}^{\,k} = \frac{\vec{w}^{\,k} - \vec{r}^{\,k}_{i}}{\left\| \vec{w}^{\,k} - \vec{r}^{\,k}_{i} \right\|} V^{k}, \tag{3}$$

where:
$\vec{w}^{\,k}$ – next waypoint's position,
V^{k} – cruise speed.

One of the most crucial functionality is the detection of collisions between the VTOLs and violations of safety zones. The safety zones were implemented to help analyze cases in which it might be desirable to ensure a specific separation distance between the VTOLs. In the case of VTOLs' collision, which are modelled as spheres in this part of the program, it is checked whether the distance between the centers of the spheres is smaller than the sum of their radii (which is a half of their size). Safety zone violation is checked in the same way, however the safety zones are generally larger.
The program simulates drone malfunctions based on a preassigned failure rate. Three types of malfunctions were implemented:

- free fall,
- autonomy level drop,
- loitering.

As part of the program settings, the user has the ability to input probability levels for the occurrence of each type of malfunction. It is important to note that a VTOL with the "0" level of autonomy cannot experience a malfunction causing it to drop its autonomy level or start loitering.

Free fall If the drone experiences the free fall, its horizontal velocity is zeroed. Its vertical velocity is calculated based on a predefined ratio of free-fall to cruising velocity.

Autonomy level drop After detecting an autonomy level drop, it is reduced by 1, and if it falls to 0, the VTOL take off loitering.

Loitering In case of the loitering malfunction, the program determines the loitering route waypoints based on the current VTOL position, its range and the distance that it flew up to this moment.

2.4 Output data generation

The program is able to generate several types of output files which help in analyzing the simulation results.

Animation The first type of output file is an animation which visually presents the air traffic over the simulated region (see Fig. 1). The generated map presents the VTOLs that were airborne at the particular point in time. Different colors allow to distinguish VTOLs with different autonomy levels. The no-fly and limited-fly zones are marked with red and yellow polygons, respectively. Moreover, the animation shows the current local simulation time and the number of airborne VTOLs.

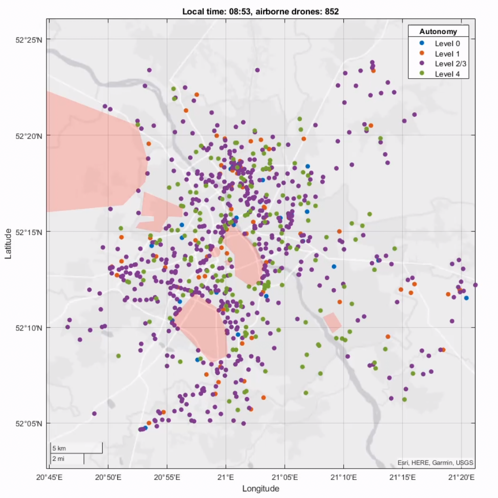

Figure 1 – Animation screenshot.

Heat maps Another type of output files are heat maps. They present the traffic density over a particular region. Before starting the simulation, the whole region is divided into bins. During the simulation, the number of VTOLs present in the bins at the particular time steps is summed up. It allows to quickly evaluate where the most dense traffic occurs. Moreover, heat maps presenting the number of collisions generated, as well as the number of collision avoidance manoeuvres.

Number of airborne VTOLs In order to show the daily distribution of traffic, the program generates a plot of the number of airborne VTOLs as a function of time. The plot shows how the number of airborne VTOLs changes during a day, taking into account the division between the autonomy levels.

Collisions histogram The next type of plot is the collisions histogram. The plot presents the number of collisions as a function of time.

Simulation report The last type of output file is the simulation report which is the only output stored as a text file. It stores the most important metrics about the performed simulation. The file contains information such as: simulation start time, local simulation time at its beginning, simulation time duration, total number of VTOLs in the simulation, a table containing the number of VTOLs present in the simulation divided based on the autonomy level, total number of collided VTOLs, total number of collision avoidance manoeuvres.

3. Case study

This chapter covers several examples examined using UAM TAT. This case study investigates the influence of presence of no-fly zones and limited-fly zones over the area of Warsaw (Poland) on the traffic density and collision probability. The three presented cases use the same input data in terms of VTOL flight distribution and only differ in airspace configuration.

3.1 Input data

Four VTOL families were taken into account in the case study, i.e.: recreational drones, air taxis, parcel delivery and food delivery.
The recreational drone family consists of 100 VTOLs, all of which have the lowest autonomy level (0). Their route type is “loitering” with origins distributed according to the population density in Warsaw. The assumed departure times distribution is presented in Fig. 2.
The taxi family consists of 20000 VTOLs, all with the highest autonomy level (4). They fly “point-to-point” route type with departure and destination points distributed according to population density. Departure times are distributed according to daily road traffic distribution (see Fig. 3, source [10]).
The parcel delivery family consists of 45365 VTOLs with various autonomy levels (between 1 and 3). They fly “hub-to- point” route type with a 3.41 average number of stops distributed according to population density. Departure hubs were associated with the major parcel delivery hubs in the Warsaw area. The distribution of departures per delivery hub was determined based on the market share of the particular delivery company [11, 12]. Parcel delivery departure times were assumed to be uniformly distributed between 07:00 and 22:00.
The food delivery family consists of 7706 VTOLs with various autonomy levels (between 1 and 3). They fly “hub-to-point-to-point-to-hub” route type with two stops. The second stops (associated with the delivery point) were distributed according to population density, while the first ones (associated with pick-up points) were randomly selected in the vicinity of the delivery point. Departure hubs were associated with the major shopping centres in Warsaw (as a suitable area for housing large VTOL’s maintenance facilities). The nearest hub is selected for departure. The daily distribution of food deliveries was taken from [13]. The cruise altitude is randomly selected for each VTOL with the exception of recreational drones for which the altitude varies during the flight. All three simulations cover a period of 24 hours and the simulation time step was 1 second.

3.2 Results

Fig. 4 to 6 present the heat maps of airborne VTOLs for the three simulations (i.e. no airspace restrictions, no-fly zones, no-fly zones and limited-fly zones cases, respectively). The heat maps are expressed in drones per hectare which must be understood as the number of VTOLs visible over an area of one hectare for one day over a period of one day (i.e. 1 drone/ha means that over an area of one hectare there was one drone visible continuously for the duration of the entire day). VTOL hubs are clearly visible, as well as natural corridors of increased air traffic appearing after the introduction of airspace limitations.
Fig. 7 presents the heat map of VTOLs collision avoidance manoeuvres for the third case (with most airspace restrictions). It should be noted that although there is a visible increase in the number of events in the flight corridors, almost all events occur at the hubs where VTOLs take off and land.
Fig. 8 presents daily airborne VTOLs distribution for each autonomy level (only one graph, corresponding to case 3, is presented as the differences between cases were insignificant).
Fig. 9 presents the daily distribution of collisions and avoidance manoeuvres (only one graph, corresponding to case 3, is presented as the differences between cases were insignificant).
Tab. 3 summarises the results in terms of the number of collisions and avoidance manoeuvres. Counter-intuitively, it seems that the number of events does not increase with airspace restrictions but this effect is just dwarfed by the number of events in the vicinity of hubs.

Table 3 – Number of collisions and collision avoidance manoeuvres for each simulation case.

Case	Number of collisions	Number of collision avoidance manoeuvres
No airspace restrictions	897	738825
No-fly zones	865	716675
No-fly zones and limited-fly zones	832	748061

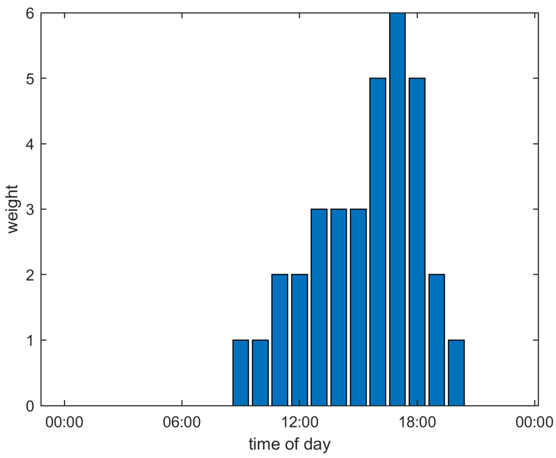

Figure 2 – Recreational VTOLs family departure times distribution.

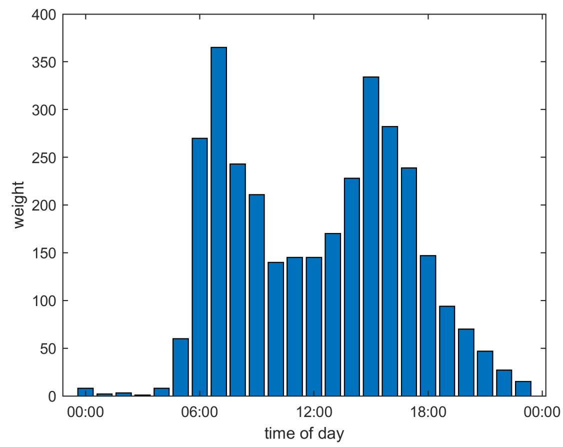

Figure 3 – Air taxi family departure times distribution.

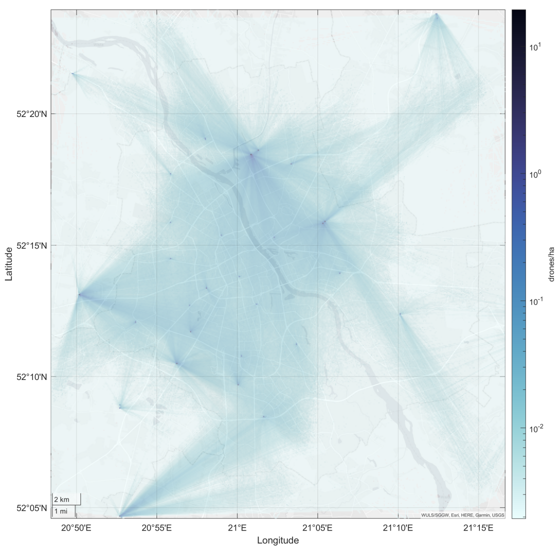

Figure 4 – Heat map of airborne VTOLs – case 1, no airspace restrictions.

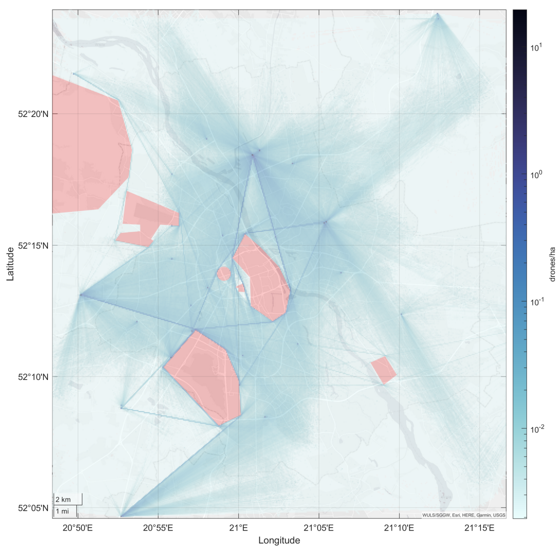

Figure 5 – Heat map of airborne VTOLs – case 2, no-fly zones (red).

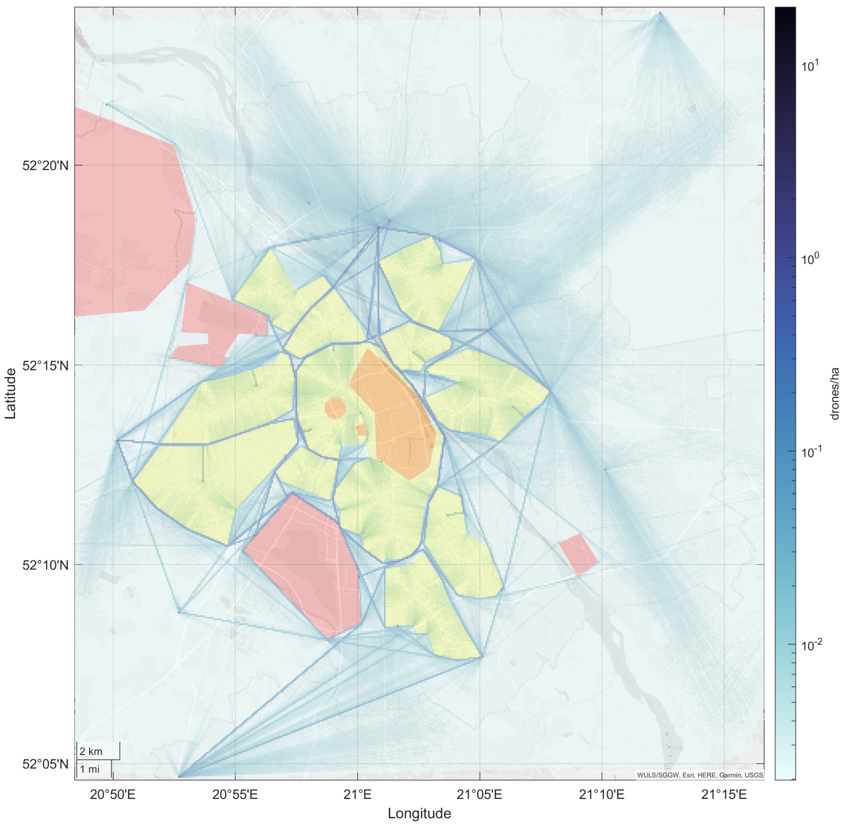

Figure 6 – Heat map of airborne VTOL – case 3, no-fly zones (red) and limited-fly zones (yellow).

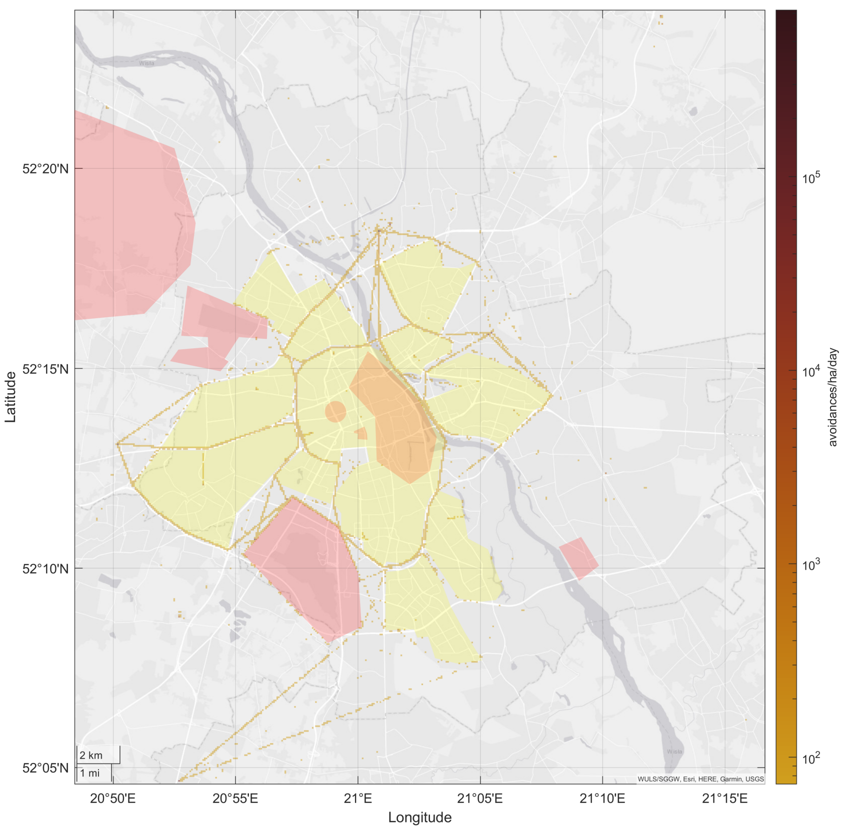

Figure 7 – Heat map of VTOL collision avoidance manoeuvres – case 3, no-fly zones (red) and limited-fly zones (yellow).

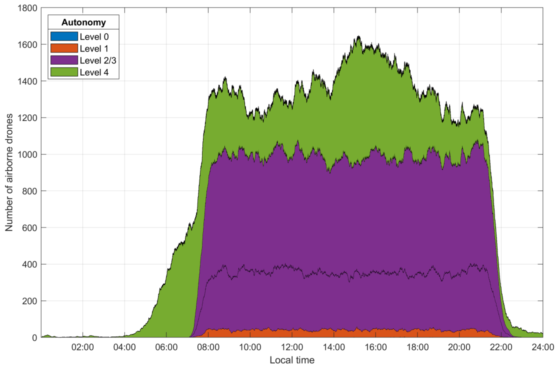

Figure 8 – Number of airborne VTOLs as a function of time – case 3, no-fly zones and limited-fly zones.

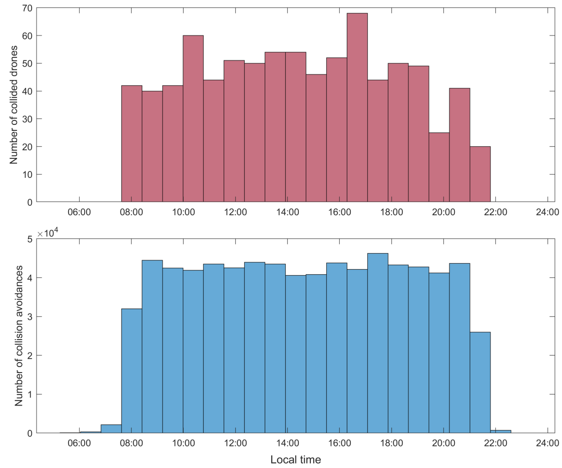

Figure 9 – Collision and collision avoidance manoeuvre histograms – case 3, no-fly zones and limited-fly zones.

4. Conclusion and further research

The following paper demonstrated a tool dedicated to Urban Air Mobility simulations. The tool allows to implement various families of VTOLs and different air traffic rules. Its modularity makes it easy to add new parameters or constraints. It is possible to extend and develop further the dynamics of the drones, their inertia and internal features that could impact how they interact, as well as to expand air traffic management such as to include optimisation of cruising altitude assignment.

The presented system's features provide a complete tool for simulation that could be used e.g. for national civil aviation authorities and U-Space users to define and estimate the capacity of the given airspace. Secondly, the tool could be used to define VTOLs' requirements that have to be met so that they are allowed into the air traffic. Finally, the various rules and methods for ATM could be tested and compared to provide the safest solution.

Plans for the nearest future are to incorporate probability-based approach into the conflict detection algorithm as opposed to a binary solution used currently. The algorithm would take into account inaccuracies of determining the VTOLs' positions and their on-board systems. The next important step is noise simulation which should prove useful when determining how the introduction of VTOLs into the urban environments will change the noise levels perceived by city dwellers. Noise pollution is a big problem in most-crowded parts of cities and it might become necessary to introduce flight rules which will limit the VTOL-generated noise in particular areas and/or times of day.

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6. Copyright Statement

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