Urban Air Mobility Traffic Analysis Tool for Airspace Involving Vertiport Hub Operations to Examine Simulated Conflicts

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***Abstract*—Presented herein are details of the development of an Urban Air Mobility Traffic Analysis Tool (UAM TAT), designed to analyze the traffic of Vertical Take-off and Landing (VTOL) aircraft in urban agglomerations to enable the Urban Air Mobility (UAM) operations. The tool aims to address challenges of UAM operations in a simulated airspace by testing different scenarios and methods for air traffic management. It emphasizes the need for effective risk management practices and methodologies to ensure the safety of operations, given the increasing use of highly automated aircraft (i.e., Advanced Air Mobility (AAM)) in urban environments. The tool is modular and allows for the simulation of various families of VTOLs and different air traffic rules, making it suitable for defining and estimating airspace and vertiports capacity, determining VTOL requirements, and testing and comparing air traffic management methods. The results of five different simulations are presented that show the capabilities and functionalities of the tool. The simulations present the impact of vertiport hub operations and various ATM approach on the VTOLs' conflicts.**

***Index Terms*—Key Words: Urban Air Mobility, Unmanned Aircraft Systems, Air Traffic Management, Simulation**

I. Introduction

The Urban Air Mobility (UAM) concept, one example of Advanced Air Mobility (AAM), creates new challenges in managing airspace shared by commercial aviation operators, general aviation operators, and Unmanned Aircraft Systems (UASs). Several issues need to be solved which are caused by multiple manned and unmanned systems with various dynamics characteristics operating together in defined airspace [1], [2]. The growing number of flying vehicles and rapidly increasing number of operations generate unknown risks and threats that are difficult to prevent at the moment [3]. Aviation authorities are not allowed to implement any solutions into the airspace management schemes before safety tests are performed. Some risk analysis may be conducted based on experience gained from commercial and general aviation. However, general aviation and UAM challenges are not necessarily comparable nor scalable [4], [5]. To develop safe solutions, understand risks, and prevent dangerous events, it is necessary to simulate the large-scale scenarios where various methods could be tested. To ensure that simulations are accurately modelled, all components of the system must be defined and implemented with proper details (UASs, environment, autonomy parameters, etc.) and define criteria so the scenario can be assessed and compared [6], [7].

An Urban Air Mobility Traffic Analysis Tool (UAM TAT) simulation has been developed for use as a test bed of various aspects of UAM operations. UAM TAT permits implementing different scenarios and defining the constrains along with the user requirements. It may be used to simulate the airspace capacity, airspace corridors parameters or vertiport efficiency. The simulation tool may be used to test algorithms needed to define UAS routes. Thus, it may be used as a supporting tool for Air Traffic Management (ATM) rules and procedures development. Results from the UAM TAT presented herein simulates airspace in Warsaw, Poland specified in documents published by the Polish Air Navigation Services Agency [8]. The area covers 30x30 kilometers.

II. Modelling and simulation

UAM TAT has several components which allow the user to prepare, perform, and analyse a full simulation.

A. Input data generation

The first step requires the user to prepare a definition file containing information about UAS VTOL families to operate in the simulation. Several different methods of generating waypoints were implemented, such as: "point-to-point" for simulating taxi operations, "hub-to-point" for simulating parcel deliveries, "loitering" for simulating recreational VTOLs, etc. Most parameters of the VTOLs are randomly drawn based on the probability distributions specified by the user in the definition file. The result of the input data generation is a simulation input file containing information (such as waypoints, size, velocity, altitude, etc.) about each VTOL which is going to appear in the simulation.

B. Input data preprocessing

The input file contains only the waypoints necessary to perform the VTOL missions. Thus, it is necessary to plan

the aircrafts' routes considering no fly and limited-fly zones. These are zones that no VTOL can enter and ones that a VTOL can enter only when one of its waypoints is located in such a zone.

C. Simulation module

Once the routes are planned, the program begins performing its main task which is to simulate the VTOL motion. They are modelled as point particles with 3 degrees of freedom. Their positions in consecutive time steps are calculated based on a simple equation of motion:

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

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

One of the most important functionalities of the tool is conflict detection. Its goal is to provide a metric for comparing different air traffic management solutions. For this purpose, the VTOLs are modelled as spheres (radii = 1 meter) and the program checks whether the distance between their centers is smaller than the sum of their radii. Based on the VTOL autonomy levels, they can perform conflict resolution and collision avoidance maneuvers which are another metric that is stored and presented to the user at the end of the simulation.

The tool is also able to simulate VTOL malfunctions of which three types were implemented: free fall, autonomy level drop, and loitering. Each VTOL has a failure rate assigned in the input file and each type of malfunction has a probability level assigned in the simulation settings.

D. Output data generation

The program generates several types of output files: animation, heat maps, plots and simulation report.

The animation (see Fig. 1) serves as a way of visualizing air traffic situation as a function of time. The heat maps present the density of traffic and conflicts resulting in a collision over the simulated region. The generated plots present the number of airborne VTOLs as a function of time, and histograms of conflicts and collision avoidance maneuvers as a function of time. The simulation report contains the most important metrics about the performed simulation, including but not limited to: simulation start time, simulation time duration, and total number of VTOLs in the simulation. Additionally, the report includes the number of VTOLs present in the simulation divided based on their autonomy levels, total number of VTOL collisions, and collision avoidance maneuvers.

III. Simulated cases

The presented case studies show some capabilities of the UAM TAT as currently developed. The first simulation (Cases 1 and 2) shows the importance of modelling elements of the environment and infrastructure with caution and precision. It is important to note that an incorrectly modelled element of the system can change the results significantly. Subsequent

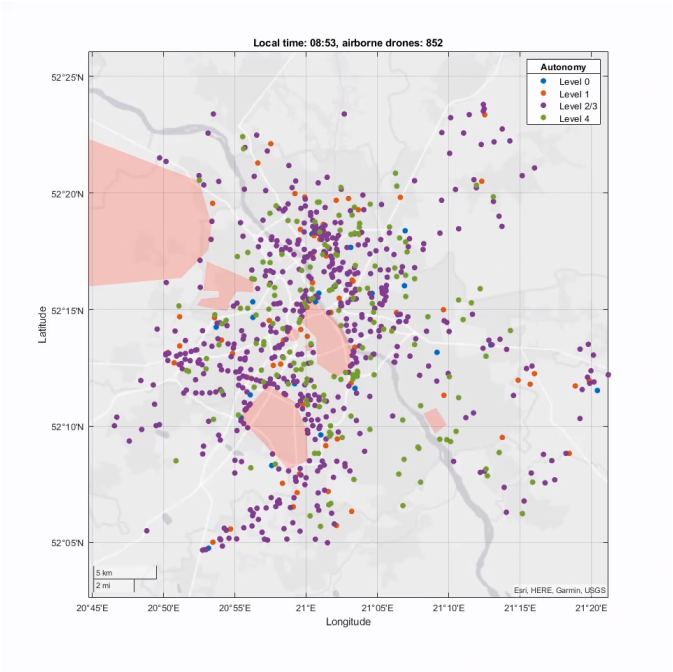


Fig. 1. Frame from simulation.

scenarios (Cases 3 to 5) were implemented to test some of the challenges regarding Air Traffic Management. Assuming conflicts and/or collisions are high risk events in UAM and UAS operation, it is possible to assess which traffic management approach is safer.

The following examples simulate UAM traffic in the airspace over Warsaw (Poland) with 73167 VTOLs of various autonomy levels and different route types (point-to-point taxis, multi-point parcel deliveries, recreational loitering, etc.). The number of the VTOLs in the simulation was based on the statistical data given by [9], [10], [11], and the statistical analysis of deliveries numbers for 2023. The size of the VTOLs was enlarged to make the conflicts more visible. The selected cases are as follows:

1) Hubs defined as points, random VTOLs altitude distribution;
2) Hubs extended, random VTOLs altitude distribution
3) Hubs extended, dedicated altitude bands for each VTOL family, random altitude distribution
4) Hubs extended, dedicated attitude bands for each VTOL family, controlled altitude distribution
5) Hubs extended, VTOL's altitude associated with its course

Fig. 2 and Fig. 3 show the air traffic density in the Warsaw airspace. In Fig. 2 the traffic distribution is presented as a heat map. The more intense color indicates more VTOLs take the same path within the time interval. The red areas are the no-fly zones defined by [12], and the yellow/light green areas are limited-fly zones. VTOL can only fly through the area if it has takeoff or destination points are within the zone. The flight must be performed along the shortest

possible path to minimize the time spent within the zone. Those limited-fly zones were added to the simulation to reduce VTOL traffic over certain areas of the city so that VTOLs do not fly indiscriminately over Warsaw. Therefore, no-fly zones were purposefully organized to avoid densely populated locations (i.e., buildings or public spaces) to reduce risk. It was assumed that for safety reasons (e.g., uncontrolled loss of altitude resulting in VTOL collision with obstacle or ground), it is preferred to organize the traffic above the streets. Thus, the implemented zones result in specific VTOL trajectories so that the VTOLs avoid dense population areas as depicted in Fig. 2. In Fig. 4 one can notice the exact locations of VTOL hubs that were placed in these spots based on real logistic centers that already exist in the Warsaw metropolitan area [13].

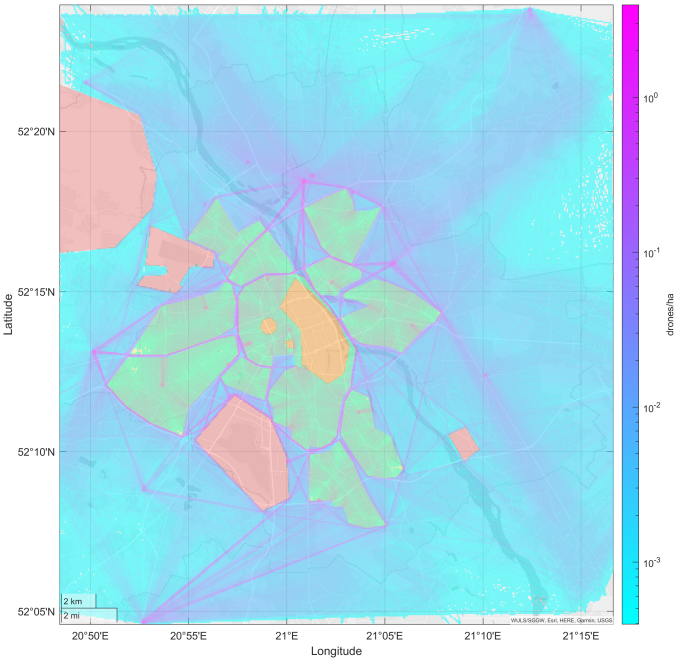


Fig. 2. Airborne VTOLs heatmap.

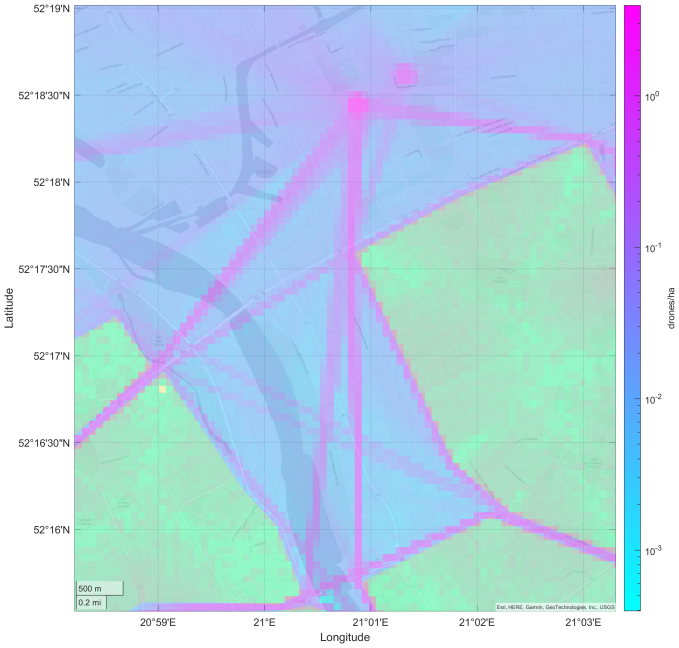


Fig. 3. Airborne VTOLs heatmap - close-up.

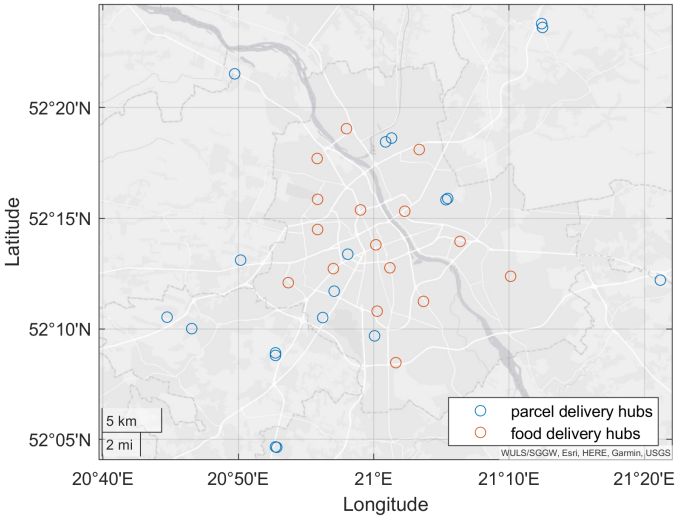


Fig. 4. Distribution of VTOL hubs. Parcel delivery hubs associated with major logistics centres, food delivery hubs associated with major shopping centres.

A. Case 1

Within the UAM TAT simulation presented here, the hubs were modelled as geographic points, with each associated VTOL taking off and landing at exactly the same spot. Fig. 4, depicts the locations of major VTOL hubs represented in the simulation. Fig. 5 and Fig. 6 present the heat map of conflicts per hour per hectare over a period of one day. In the Fig. 5 due to large scale of the figure, the collision spots are imperceptible at that map scale. Thus, in further examples only the selected hub will be shown. Comparing Fig. 4 to Fig. 6, makes obvious that the majority of conflicts occur at the hubs.

For the following scenario, the total number of conflicts resulting in a collision was 832. From safety point of view, this number of events is clearly unacceptable. However, this result was considered misleading as in the vicinity of the hubs, the VTOLs are under the direct supervision of their user and the U-space operator [14], so the operator is not expected to direct a VTOL to take off while the local airspace is occupied, thus avoiding conflicts.

B. Case 2

In Case 1, the definition of a hub was too specific (i.e., a single point) resulting in unrealistic operational constraints and excessive number of conflicts resulting in a collision. To more accurately represent the hubs in the simulation, in Case 2 the hubs were remodeled as circles of specific size at the hub geographic location. Furthermore, each VTOL departs or arrives at a point randomly selected from within the hub. Additionally, conflicts resulting in a collision directly within

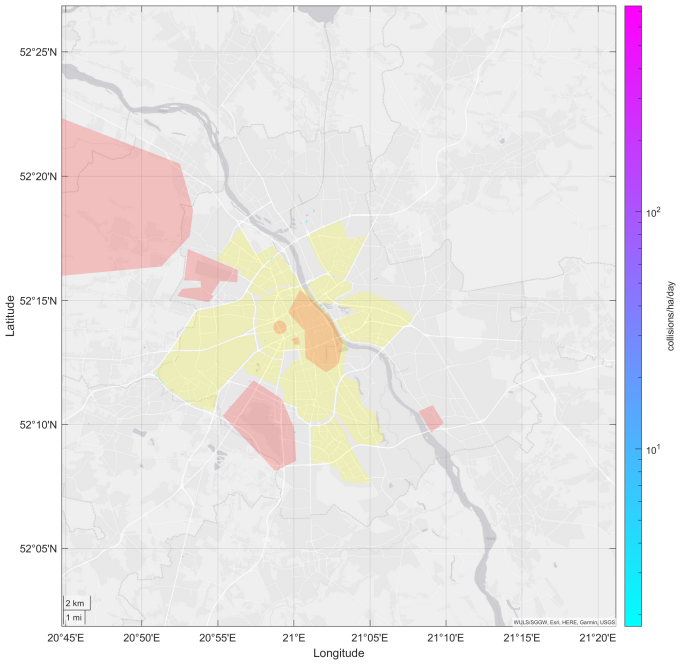


Fig. 5. Case 1 VTOL conflicts heatmap.

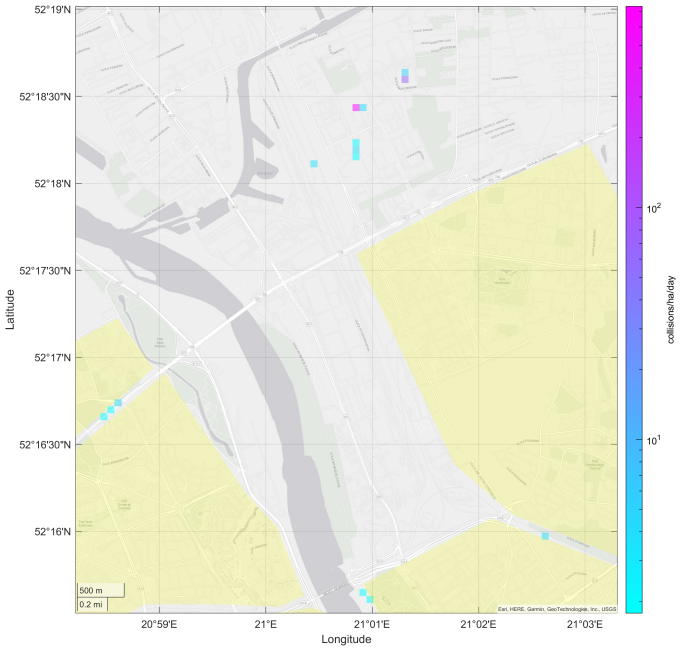


Fig. 6. Case 1 VTOL conflicts heatmap – close-up.

the hub are neglected. As a result, the total number of conflicts decreased to 52 (by an order of magnitude), and most conflicts were no longer clustered in the vicinity of hubs (see Fig. 7).

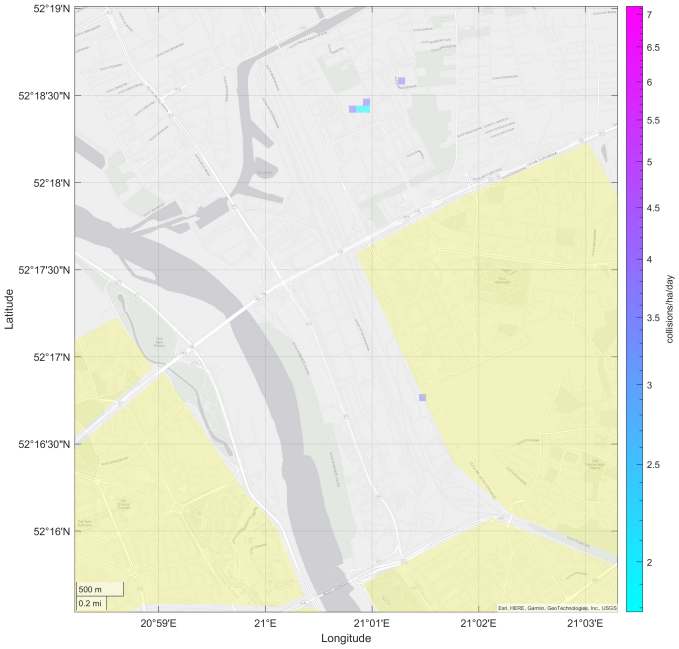


Fig. 7. Case 2 VTOL conflicts heatmap – close-up.

C. Case 3

This simulation investigated the impact of assigning each VTOL a flight altitude depending on its autonomy level. The segregation of VTOLs based on autonomy level was congruent with regulatory practices. Five different groups of VTOLs were operating at predefined altitudes. Each of VTOLs' groups had an altitude randomly selected from the altitude corridor with range of 90 meters. It means that the same number of VTOLs would fly in narrower airspace relative to Case 1 where the flight altitude for each VTOL was randomly selected from a single 800-meter band. As a result, the total number of conflicts resulting in a collision increased to 244, which is likely a result of vertical congestion of air traffic – now all VTOLs operate within airspace of a total height of 450 meters, and VTOLs with lower autonomy levels, which are much more likely to collide, fly closer to each other. In this case, the conflicts clearly appear along the main VTOL routes – see Fig. 8.

D. Case 4

In this scenario, the bands introduced in Case 3 were further divided into a finite number of vertical slots with a 5-meter separation. Each VTOL was assigned an altitude slot within the appropriate band based on the order of departure times. Therefore, theoretically, within a 90-meter band, 19 altitude slots were defined, and therefore, 19 VTOLs could populate a band without colliding. The slots were filled again if there were more than 19 VTOLs within a band. In this case, the total

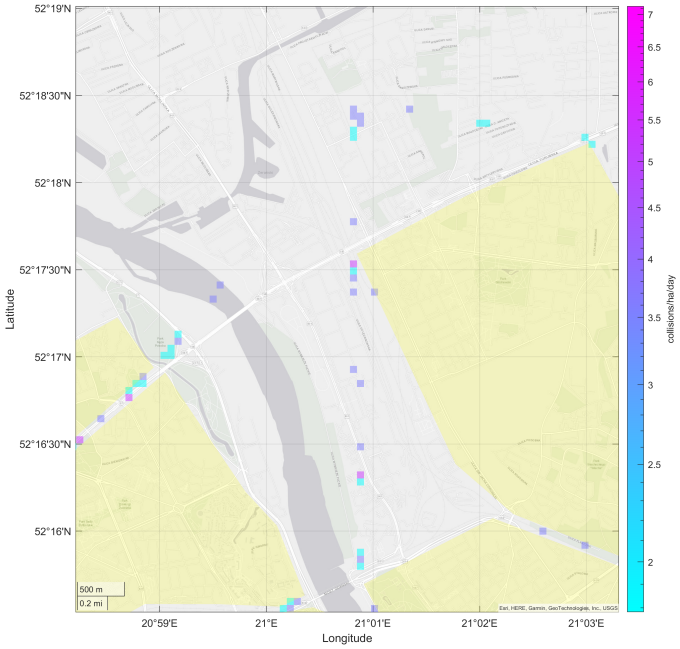


Fig. 8. Case 3 VTOL conflicts heatmap – close-up.

number of conflicts dropped slightly to 220, and the overall distribution of conflicts was similar to Case 3 (see Fig. 9).

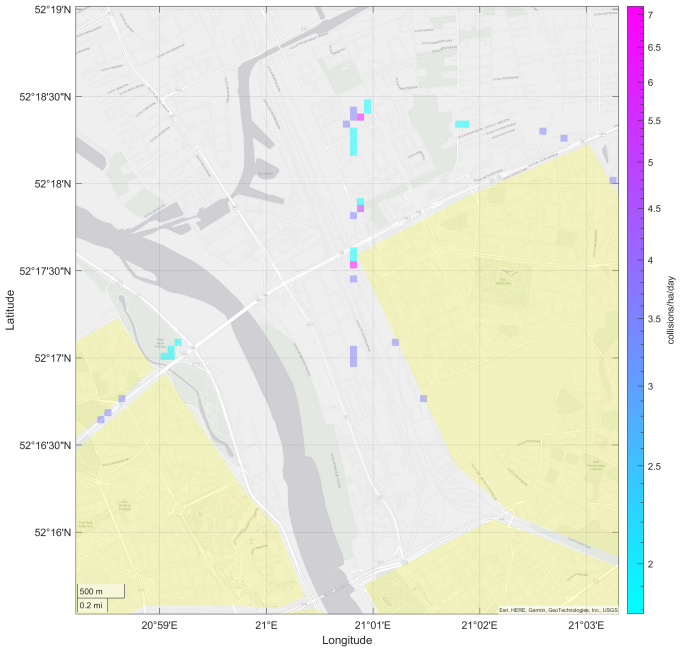


Fig. 9. Case 4 VTOL conflicts heatmap – close-up.

E. Case 5

To minimize the likelihood of a conflict resulting in a collision, especially in naturally occurring narrow air corridors, an air traffic management scheme was proposed to associate flight altitude with the current VTOL's course. This should ensure that the VTOLs flying at the same altitude would fly in the same direction, and the possibility of conflict would be limited only to a case when one VTOL catches up with the other due to a difference in speed. The approach did not prove successful; the total number of conflicts remained at the same level, with 228 conflicts resulting in a collision. Fig. 10 present conflicts distribution - not significantly changed compared to Cases 3 and 4.

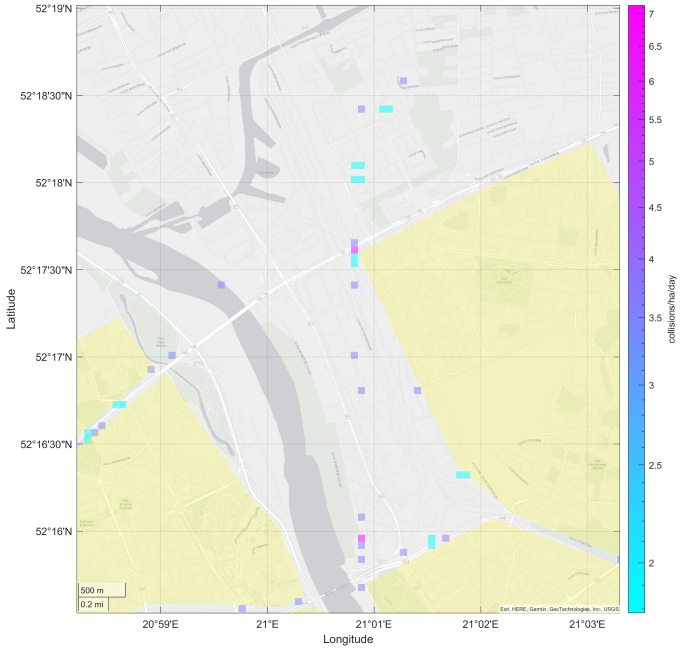


Fig. 10. Case 5 VTOL conflicts heatmap – close-up.

IV. Results

A. Case 1 and 2

The selected cases were chosen to underline some crucial elements of the simulation. Cases 1 and 2 show that the results could be distorted due to some simplifications - for example, too small vertiports. Changing the vertiport area from point to defined area makes a difference. The reduction of conflicts resulting in a collision from 832 to 52 is a significant improvement. Thus, the tool could be used to calculate the capacity of the vertiports or area needed to handle a certain number of operations. If one considers more constraints (e.g., real size of the vertiports, real schedule of take-offs and landings, etc.), it may clearly indicate how much VTOLs the user could implement within one hub.

B. Case 3 to 5

The simulations presented show that it is important to implement proper route selection algorithms. Each one has its own characteristics and provides different results. There are also other factors that may be important regarding the ATM approach such as – noise, air visibility, or some technical limitations. The simplest solution to set the airspace from 200 [m] to 1000 [m] and with some no-fly-zones. The approach will enable the full spectrum of airspace use. The number of

conflicts resulting in a collision in this Case (2) refers to 53. However, from some reasons the U-space operator might want to group VTOL families into zones so they operate in the same altitudes. This may be forced due to limited VTOL capabilities such as range or max altitude. Such an approach clearly makes the selected operation airspace narrower – thus the number of collisions increase. The result of airspace narrowing can be seen in Case 3 in which there are 244 conflicts resulting in a collision. That number was slightly reduced by implementing an altitude control so the altitude is related to the takeoff time. That modification resulted in collision reduction to 220. Case 5 presents a different solution with binding the altitude to heading course. This simulation resulted in 228 events. Case 4 and 5 represent two possible methods of traffic management further implementation and testing of additional methods can be tested in the presented UAM TAT simulation.

V. Summary

The presented simulations demonstrate that there are challenges still to be resolve before the various ATM approaches would be implemented. Selected cases showed that by changing some constrains other issues arises and need to be fixed.

The presented cases are basic scenarios introduced to show the general use of the UAM TAT as currently developed. Further upgrades and improvements will extend the usefulness of the tool. However, regardless of the specific results it evident that such a tool will benefit in the design of UAM operations, including but not limited to vertiports designers, VTOL manufacturers, ATM, regulators, aviation and city authorities, and U-space operators.

In presented analysis only one parameter was implemented to assess the safety of the operations - conflicts resulting in a collision. However, this parameter might not be the right choice as in reality, from the point of view of air traffic management, the number of collisions should be zero. Therefore, it is planned to evaluate collision likelihood in terms of probability rather than number of actual events. Another interesting aspect to be assessed is adding the total distance covered by the UASs within one simulation. This would directly translate to energy consumption which may be a significant parameter right after the safety. Thus, some ATM approach could be compared to see and calculate the UAV efficiency. Another significant factor that should be considered is the noise impact. That parameter may be important especially over the areas where people sleep/rest. Thus, the UAS traffic may be regulated not only by its trajectory but also within the time periods.

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