Metropolis II: Investigating the Future Shape of Air Traffic Control in Highly Dense Urban Airspace

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***Abstract*—Metropolis II aims to provide insights in what is needed to enable high-density urban air operations. It does this by investigating the foundation for U-space U3/U4 services. The final goal is to provide a unified approach for strategic deconfliction, tactical deconfliction, and dynamic capacity management. Highly-dense operations in constrained urban airspace will likely require a degree of complexity that does not exist in modern-day air traffic management. The expected high traffic demand will require a shared use of the airspace instead of assigning exclusive use of blocks of the airspace to some flights. A unified approach for traffic management is needed because at high-densities, airspace design, flight planning, and separation management become increasingly interdependent. Metropolis II builds upon the results of the first Metropolis project. Three concepts with a varying degree of centralisation will be compared using simulations. (1) The centralised concept will take a global approach for separation management. (2) The decentralised concept aims to give the individual agents separation responsibility. (3) The hybrid concept tries to combine a centralised strategic planning agent with a robust tactical separation strategy.**

***Keywords*—Separation management, Flight planning, U-Space, Unmanned Traffic Management (UTM), BlueSky ATC Simulator, Urban Airspace, Degree of Centralisation**

I. INTRODUCTION

The overload of ground transportation in urban environments has created the need for research on urban aerial transportation, which should be designed to accommodate an increasing amount of air traffic. Parcel delivery demand is expected to rise in the future to millions of flights per year [1]. Research has been performed in previous projects for urban airspace navigation, most notably the CORUS project [2], which looked at airspace structuring when aircraft would fly above all buildings in a city. However, that might not be feasible in cities with very tall buildings (e.g. New York). On top of that, flying above streets can increase the societal acceptability by lowering the impact on noise, privacy and perceived third party risk, when not part of the traffic.

Thus, the scope of Metropolis II [3] is to study and develop methodologies to provide an Unmanned Traffic Management (UTM) solution for mixed airspace (open and constrained), which includes airspace design, flight planning, and separation management. The main research question of Metropolis II may be summed up as; How does the degree of centralisation of an Unmanned Traffic Management system including airspace design, flight planning, and separation management affects the system's performance? To answer that question three individual concepts have been designed; centralised, hybrid and decentralised, each with a different degree of centralisation. The three concepts are presented in sections II, III, and IV, respectively.

In high traffic densities, we believe that the design of the airspace, the flight planning, and the separation management should not be treated as separate problems. Such a system should include a concurrent design of the three subsystems. Thus, each concept was independently designed from each other, ensuring that the subsystems were best suited to each design philosophy.

All concepts were designed considering a set of common elements and requirements, such that the experimental results may be comparable. The concepts were provided with the basic airspace rules for which to design. The airspace was designed suitable for a realistic city structure and was separated into a constrained area, in which the aircraft were confined to flying above the existing street network, and an open area, in which the aircraft do not need to follow predetermined paths. The concepts are evaluated using the same traffic scenarios. The experimental method employed in Metropolis II is presented in section V.

II. The Centralised Concept

The centralised concept focuses on strategic deconfliction and flight planning, which are conducted pre-flight by a central entity. The central entity has access to global data concerning the information about the requested flights, the planned flights, and the real-time tracking data of en-route aircraft. For that purpose, a centralised deconfliction algorithm was developed, responsible for producing flight plans based on the requested departure time and the origin and destination coordinates. In this concept, a flight plan is a 4-dimensional trajectory describing the longitude, latitude and altitude and time. Each of the produced flight plans has a fixed altitude, with the exception of the take-off and landing segments.

Within the centralised concept, the designed airspace structure may be described as a bi-directional graph. For the constrained airspace the geometry of the graph is set by the street network while for the open airspace the area is divided into hexagonal tiles, each representing one node of the graph, as shown in Fig. 1. Turning costs are added to the produced graph with the method described in [4]. The whole airspace (open and constrained) is divided into 16 flight layers, following the recommendations of the Metropolis project [5]. Each aircraft is assigned to one of the layers for the entirety of its flight depending on its origin and destination (based on the bearing of the 2-dimensional vector connecting the origin to the destination) or a layer selected from the deconfliction algorithm presented below.

Flight planning and strategic deconfliction are conducted using two different methodologies depending on the demand. For low demand, the flight plan for every aircraft is computed initially without considering the other aircraft, using the A* algorithm. Then, flight plans are checked for conflicts using a quick simulation. The detected aircraft pairs causing a conflict are used to create a conflict graph, with the aircraft as vertices and the edges representing the detected conflict between two aircraft. To resolve the conflicts, some aircraft are assigned to different layers, by formulating the problem as a graph colouring problem [6], [7].

The high demand methodology is utilised for aircraft densities in which the low demand approach fails to reach a solution. The high demand methodology is an addition to the low demand methodology and it is called to resolve the remaining conflicts. For the aircraft, for which a solution was not found, the algorithm searches for the optimal path based on the availability of the airspace. A time-expanded network (TEN) [8] is created for each layer, where each possible aircraft movement is represented by an edge. Having removed the edges that would lead to a conflict, the shortest path in the graph may be found. The Dijkstra algorithm is used for the graph search in the time-expanded network. After a flight plan has been produced, it does not incur any changes and it is considered as an obstacle for later-planned flight plans.

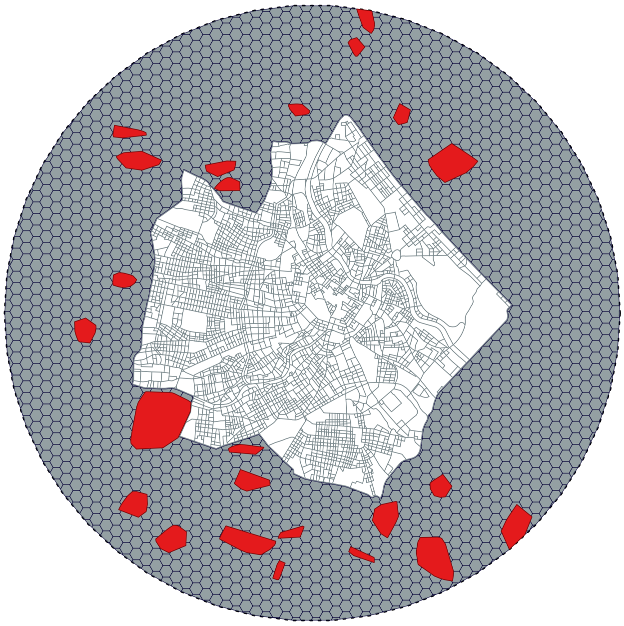

Fig. 1: Centralised concept airspace structure, with hexagonal cells in open airspace. The red polygons are geofences areas of open airspace.

In nominal conditions, a centralised concept, as the one presented here, does not need to contain a tactical separation management system, since all conflicts have been resolved pre-flight. However, different types of uncertainties could cause the aircraft to deviate from their designed paths and create a possible conflict. For this reason, a centralised tactical deconfliction system is included and has the responsibility to detect conflicts and recompute aircraft trajectories to resolve them.

III. The Hybrid Concept

The hybrid concept combines centralised and decentralised components to achieve separation management. The development of the hybrid concept was conducted in three stages: (1) the design of the airspace structure, (2) the design of the centralised pre-flight strategic separation management, and (3) the design of the during flight tactical separation. In ideal conditions, the first two stages should be able to provide a safe and efficient solution for the requested flights. However, due to uncertainties,

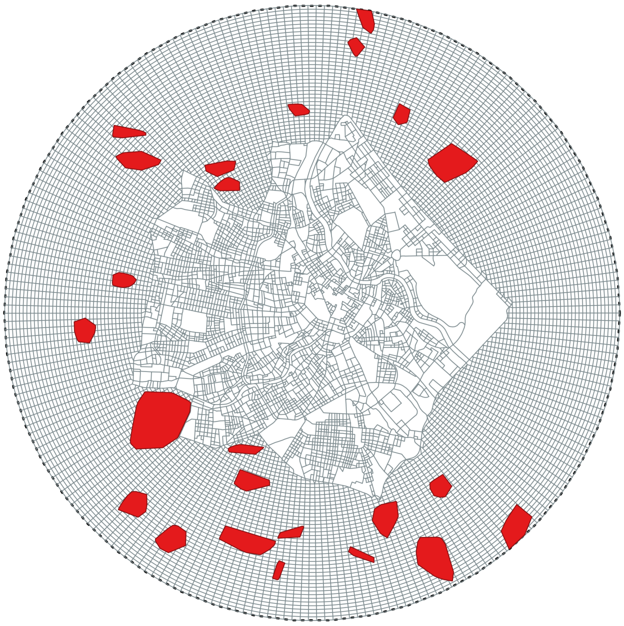

Fig. 2: The radial network used within the hybrid concept for open airspace navigation.

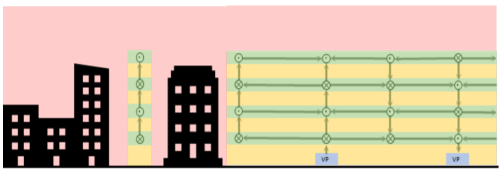

Fig. 3: The layered airspace structure used within the hybrid concept for constrained airspace navigation, with cruise layers (green) and deconfliction layers (yellow).

the aircraft may not be able to follow the designed route in the exact computed time, causing conflicts, which are resolved in the third stage. In order to prevent the tactical separation management from having a negative effect on the efficiency and safety of the flights computed from the strategic plan, the two act on different dimensions; strategic uses horizontal resolution and tactical uses vertical resolution.

The developed airspace structure is described as a 3-dimensional directional graph. In constrained airspace, the graph follows the street network, while in open airspace a radial grid is created, as shown in Figure 2. The vertical axis is separated into layers. Two types of layers are used: cruising layers (mostly used for the strategic separation management) and resolution layers (mostly used for the tactical separation management). The two types of layers alternate and create a stack of layers, as presented in Figure 3. The direction of cruising layers alternates as the altitude increases. The vertical edges of the graph are bi-directional, allowing ascending and descending.

The centralised pre-flight strategic separation management is responsible for computing conflict-free paths while optimising for the length of the path and it obeys to rules imposed from the above presented airspace structure. Since it is centralised, the central entity computing the initial flight plans has access to information concerning all flights to be planned. The strategic conflict resolution algorithm in use is time-based (i.e. the edges and nodes of the graph will appear as occupied for certain time steps if they are in use from previously computed flight plans) and contains four steps:

1) Flight plans with earlier desired departure time are prioritised and computed first.("First come, first served")
2) For each aircraft the shortest route is found using the Dijkstra search algorithm.
3) Search for a conflict-free flight plan in the lowest layer and if that fails repeat the process for higher layers. The length of the route computed at step 2 is used as a baseline to compare the optimality of the solution found.
4) For the aircraft that a solution was not found, a delay in their departure time is imposed.

The decentralised tactical separation management acts during flight and acts in two levels: the conflict detection, resolution and trajectory recovery level and the route replanning level. The conflict detection, resolution and trajectory recovery level is responsible for detecting near-future conflicts, designing a manoeuvre for the aircraft to resolve the conflict and after the conflict has been averted, initialises the trajectory recovery sequence to return the aircraft to its initial trajectory in a safe manner. The resolution layers may be used for the conflict resolution manoeuvres. The route replanning level is requested to recompute a flight plan in case the corresponding flight plan becomes impractical due to airspace closures or changes.

IV. The Decentralised Concept

In the decentralised concept the responsibility of designing the flight plan and taking the actions to maintain the separation distance lies to each individual agent. The agents do not have any information about the flight plans of other agents and they are not able to include strategic separation techniques while designing their flight plans, very similar to road traffic.

The decentralised concept may be broken down into the development of four subsystems: airspace structure, flight planning, flow control (traffic control from central entity) and tactical separation management.

The airspace structure was developed in the scope of minimising the probability of conflicts. In the design of the airspace structure for the constrained airspace an additional objective was considered; a turning aircraft should not have a major impact on the cruise flow. To respect both objectives the constrained airspace structure contains only one-way streets with the traffic being distributed into

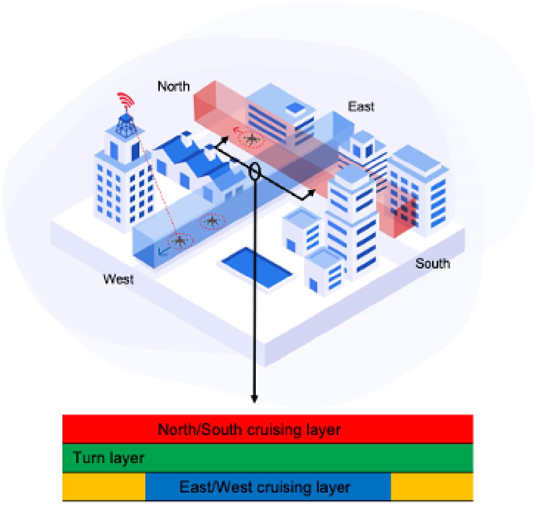

Fig. 4: The layered airspace structure used by the decentralised concept in constrained airspace to minimise the conflicts between cruising aircraft at intersections.

layers. The design contains cruise layers, turn layers and empty layers, the types of the layers alternate while the altitude increases, as shown in Figure 4. Under nominal circumstances the aircraft cruise along a street using a cruise layer and use turn layers only for turning (changing streets). Cruise layers of intersecting streets should not be allocated in the same altitude, which created the need for the existence of the empty layers. The streets were grouped into two categories based on their bearing, creating groups of semi-parallel streets, in order to allocate the altitude of the cruise layers in each street, seen in Figure 5. After that, the directionality of each street was selected using a genetic algorithm to optimise the graph's connectivity.The airspace structure for the open airspace utilises the results from the first Metropolis project [5] and it vertically separates traffic based on the heading of the aircraft.

For the decentralised concept, the calculation of the flight plans can be described as a path planning problem with known and static obstacles and dynamic costs. To solve the path planning problem, we created a graph describing the whole airspace. For the constrained airspace the graph design was obvious and was based on the streets' structure, while for the open airspace a graph was created using cell decomposition techniques [9]. The outcome of the cell decomposition algorithm is presented in Figure 6. The D* Lite algorithm [10] was selected as the path planning algorithm to compute the shortest path on the designed graph. The main reason D* Lite was selected is the algorithm's ability to recompute the path on-line, which offers a significant advantage for the decentralised concept as the aircraft replan every time a new geovector is imposed from the central entity as described in the next paragraph.

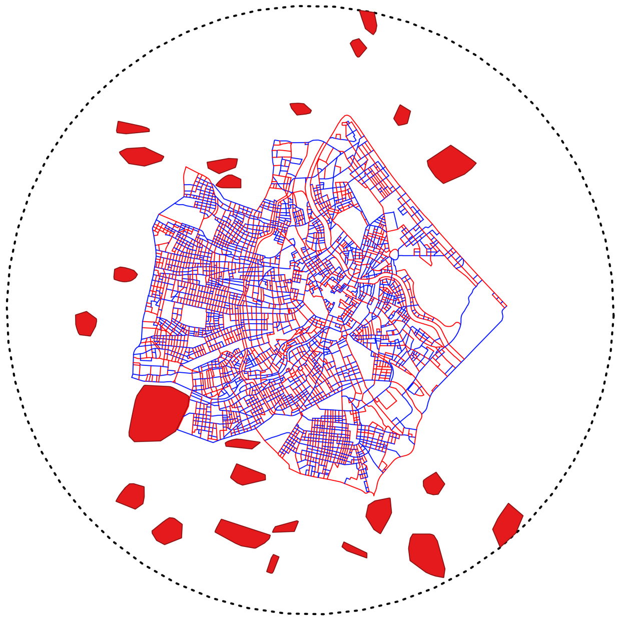

Fig. 5: Overview of the constrained airspace structure used within the decentralised concept, with red and blue streets having different cruise layer height allocations.

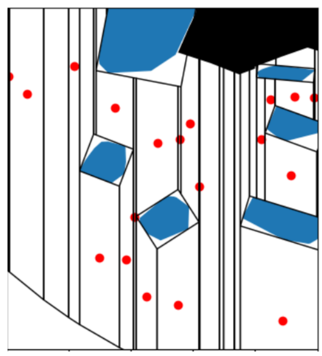

Fig. 6: A section of the open airspace with the cells used from the decentralised concept. The no fly zones are the filled in blue polygons. The cells are delineated with black edges and the centre points of the cells are represented with red dots.

The decentralised concept also contains a central entity, which gathers the aircraft's position data and computes the traffic densities in the traffic groups. Depending on the computed traffic density, the central entity applies geovectors [11] in the traffic groups in the form of speed limits. In a real world implementation the central entity would also be responsible for the authorisation process and for approving a requested flight plan with the agent providing the flight start time, origin and destination coordinates.

As stated at the beginning of the section, the decentralised concept relies only on tactical separation to resolve conflicts, which signifies the importance of tactical separation in this case. The proposed tactical separation algorithm is speed-based and allows only for vertical manoeuvres. The conflict resolution algorithm is called from a conflict detection algorithm which detects the conflicts and classifies them as one of the following three types: overtake, horizontal and vertical.

The main attributes of each concept and the and differences between them are summarised in Table I.

TABLE I: Overview of the main difference between the three concepts and their properties.

Features	Centralised	Hybrid	Decentralised
Open Airspace	Hexagonal cells	Radial grid	Polygonal cells
Strategic separation	Yes	Yes	No
Main separation management method	Strategic	Strategic and Tactical	Tactical
Central entity responsibility	Flight planning, strategic separation and tactical separation	Flight planning and strategic separation	Traffic density measurement and imposing geovectors
Global knowledge of flights	Yes	Yes	No

V. Experimental Method

The Metropolis II project aims at studying the performance of different centralisation levels on flight management and separation management in the urban airspace. To conduct that study three different concepts have been developed, as presented in the above sections. The three concepts were designed to abide to a set of commonly defined requirements, which remains constant for all tested scenario.

- Cylindrical airspace volume (8 kilometre radius, 500 feet height)
- Constrained airspace street network and buildings.
- Open airspace with geofenced areas.
- Traffic pattern and density including priority and loitering missions.
- Two types of vertical take-off and landing (VTOL) vehicles with 20 and 30 knots cruising speeds respectively.
- Uncertainties (wind and rogue aircraft, not adhering to the rules).

They are tested in a set of scenarios via simulation using the BlueSky Open Air Traffic Simulator [12] and their performance is evaluated using a set of predefined metrics. The following subsections provide an introduction to the simulation software in use and present the scenarios used for the experiment, as well as the experiment variables. The performance of each concept is evaluated using as set of 35 metrics across 5 categories: access and equity, capacity, efficiency, environment, safety and priority.

A. *Simulation software*

The simulations will be performed with BlueSky [12], an open air traffic control simulator, available on GitHub [13]. BlueSky is an open source simulator originally developed for conventional air traffic simulations, and

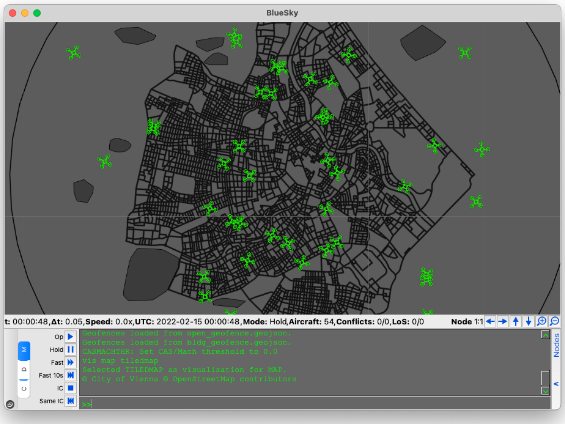

Fig. 7: BlueSky showing simulated traffic in Vienna.

permits the open publication of source code and results. It was essential that the selected simulation software for Metropolis II is open source, to enable project-specific additions and modifications. Therefore, an important part of Metropolis II was to extend BlueSky for urban air traffic simulations. The major developments from Metropolis II are:

1) Autopilot modifications to ensure aircraft closely follow their intended path between buildings and perform turns safely.
2) Inclusion of building polygons as geofences.
3) Bulk waypoint processing.
4) Visualisation of urban maps (Fig. 7).

Each concept has developed their own plugins to ensure that the simulations follow the rules set by the specific concept.

B. *Traffic scenarios*

The selected simulation environment is based on the city map of Vienna and is a mixture of two types of airspace: constrained airspace and open airspace, creating an overall cylindrical experimental area with a radius of 8 kilometres and a height of 500 feet. The constrained airspace represents the city centre and while flying in it the aircraft should follow the street network of the city. The open (unconstrained) airspace surrounds the constrained airspace and represents the outer part of the city. The open airspace includes some no fly zones, which the aircraft are not allowed to use during their flight. Aircraft in the open airspace may fly in any trajectory that does not violate the no fly zones. In order to create a variety of experimental setups, a set of traffic scenarios has been created. These seek to simulate various types of missions (e.g., point to point, hub and spoke), several traffic density levels, as well as vehicles with different cruise velocities. Two vertical take-off and landing (VTOL) aircraft were included, based on the DJI Matrice 600: one with a cruise speed of 20 knots, and another with a cruise speed of 30 knots. The produced traffic scenarios differentiate in the experimental variables described in the next subsection.

C. Experiment variables

Four experimental variables were selected: traffic demand level, mission mix, wind and rogue aircraft. Each traffic scenario is created by selecting a value for each of the experimental variables.

The traffic demand level indicates the number of requested flights and may take one of the five different values, each representing a different percentage of the maximum estimated demand. The number of requested flights corresponding to each of the values was calculated based on the estimated yearly demand of Vienna using a regression and an interpolation analysis with input data for the area, the population, the average annual gross salary and parcel market data [14], [1].

The mission mix describes the allocation of the mission types as a percentage of the overall flight number of the scenario. The main mission types considered are parcel delivery and food delivery. Food delivery missions have a higher variety of origins and destinations, while parcel deliveries tend to origin from a smaller set of distribution centres. In every mission mix a small number of loitering and emergency missions are added. The particularity of the loitering mission is that they apply dynamic geofences (no fly zones) around their area of mission, while the emergency missions are announced shortly before the requested departure time.

The wind and rogue aircraft variables are described as uncertainties, as they are the ones generating non-nominal conditions. These experimental variables have two values ON or OFF.

VI. Discussion

Metropolis II is currently ongoing, however, some points of interest have already appeared from our research so far. Here we intend to present the main challenges we encountered while developing the three concepts and some remarks generated from the progress of our research.

Constrained airspace poses challenges not present in open airspace. It severely limits the total airspace volume since aircraft must fly between streets to avoid buildings. This severely reduces the total capacity as compared to open airspace. One goal of the simulations is to create traffic densities that stress the capacity to their limit. This is meant to stress the strategic planning capacity of both the centralised and hybrid concepts. Moreover, the limited vertical space makes tactical conflict resolution more difficult because of the reduced space. This will stress the tactical separation solutions of the hybrid and decentralised concepts. However, it is expected to affect the decentralised concept more as aircraft do not have a globally deconflicted path.

Another interesting discussion is about how the concepts will respond to the uncertainties of wind and rogue aircraft. Wind uncertainties are expected to disturb the strategic plan of the centralised and hybrid concepts. Wind uncertainty will slow and speed up drones across the airspace and potentially create conflicts that the strategic planning did not foresee. The wind will stress the tactical separations solutions of the centralised and hybrid concepts. For the decentralised concept, the wind is expected to have a smaller effect on the number of conflicts because the task of solving conflicts is designed to be originally in the tactical side. Rogue aircraft may have similar effects on the safety of all the concepts. Also, rogue aircraft have the potential to create head-on conflicts that the concepts try to avoid with their airspace structure.

The last remark to mention is the time and memory complexity required for each concept implementation. To start with the decentralised concept, the concept was designed to allocate most of the computational load to separate agents according to common decentralised architectures. In order to evaluate the concept, it had to be tested in simulation, which runs using one core of one computer. It quickly become clear that testing an initially designed distributed system in one computational unit as a single thread program requires a great amount of time and memory optimisation. To resolve that problem, the decentralised concept's code was greatly optimised and a part of the data required as simulation input was pre-computed. While the computational cost of the decentralised concept was a hurdle to overcome for the simulation requirements, it would not be presented while designing for a real-world system in which the computational load could actually be allocated among agents. So, reduction of the computational load might not be of the same importance for the decentralised concept as it is for the centralised and hybrid. Both of the later concepts when applied to a real-world situation, they would be required to conduct the total of the flight planning and strategic separation management in one central entity. When designing such a system, someone should consider the time limitations set from the system requirements and the memory limitation set from the computational unit in use and the effect on the capacity of the system.

VII. Conclusion

The use of the urban airspace for transportation purposes is anticipated to be in high demand in the near future. Operational concepts and airspace configurations need to be researched, in order to design safe and efficient urban UTM systems. Metropolis II seeks to contribute to the research for U-space U3/U4 services that are crucial to support high urban air traffic densities. This paper presents the main research goals of the Metropolis II project and the experimental methodology followed to achieve them. Three concepts with varying levels of centralisation regarding flight planning and separation management have been designed as part of the project. The concepts have been introduced in sections II, III, and IV and each of them includes an airspace structure design, flight planning and separation management (strategic and/or tactical depending on the type of concept). The concepts were developed for a city which contained open and constrained airspace. The evaluation of the performance of the concepts will be conducted with simulations on a variety of traffic scenarios, as explained in section V.

As described in this paper, several lessons have been learnt already from designing, implementing and prototyping the concepts. The simulations planned are likely to generate a great amount of measurements, which will be used to create the data for around 35 metrics. These will be used in a trade-off analysis to select the most promising of the three concepts. As the final part of the project, the selected concept will be presented in a real-world demonstration.

The final results of the simulations conducted for the project are still under the processing stage and will be uploaded at https://doi.org/10.4121/19700002 when finalised.

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