Metropolis II

Benefits of Centralised Separation Management in High-Density Urban Airspace

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Metropolis II: Benefits of Centralised Separation Management in High-Density Urban Airspace

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***Abstract*—The Metropolis II project aimed to study the impact of centralised separation management for urban aerial mobility. Three concepts were developed in this study: a fully centralised, strategically separated concept, a hybrid concept featuring centralised strategic separation and distributed tactical separation, and a fully distributed tactical concept. A comparative simulation study was performed, using traffic scenarios based on predicted demand in an urban airspace in the city of Vienna. Simulations were performed with varying traffic densities and situations. Results show that the purely strategic and purely tactical strategies perform comparably in terms of safety, and that further improvements can be achieved with a combination of those strategies.**

***Keywords*—Unmanned Traffic Management, Conflict Detection & Resolution (CD&R), Self-Separation, U-space, UAS, UTM**

I. Introduction

Urban air traffic mobility is a subject of high interest across the research community, as the applications of use of aircraft in the Very Low Level (VLL) urban airspace are increasing. The use of autonomous aircraft for delivery transportation has been suggested as a measure to combat congestion in high density ground vehicle traffic in city centres and excessive emissions. Unmanned Traffic Management (UTM) systems need to be designed and tested to investigate methodologies for integrating highly dense air traffic in the urban environment.

Previous research has been conducted with the scope of shaping future operations of small aircraft within VLL airspace. The CORUS project [1] categorised airspace sections, and defined urban airspace as being above the tallest obstacle in a city. However, that might not be feasible for missions such as local small package deliveries, as it would be inefficient for small aircraft to travel at such high altitudes in cities with very tall buildings (e.g., New York).

Furthermore, the question of how to control traffic within U-space operations still remains. Previous research has emphasised centralised, strategic separation management, with tactical separation as a potentially federated or distributed fallback. The question remains, however, to what extent (high-density) drone traffic will be accurate and predictable enough to enable effective strategic separation, and whether proposed business models for urban drone applications would be compatible in terms of required planning horizons.The Metropolis II project aims to investigate the impact of the degree of centralisation of a separation management method on resulting traffic safety, efficiency, capacity and equity. n The project developed three separate separation management concepts with varying degrees of centralisation; a centralised concept including only centralised strategic deconfliction techniques, a decentralised system including only decentralised tactical deconfliction techniques and a hybrid system including both centralised strategic deconfliction and decentralised tactical deconfliction.

This paper presents an overview of the experimental results of the Metropolis II project, regarding safety, efficiency and other performance metrics of three different concepts in highly dense urban airspace. Section II-A presents the design of the urban airspace, missions and operations used in the project. The three concepts are briefly introduced in Section II-B. The experimental and simulation methodology is described in Section III, while the metrics used for concept comparison and the most relevant results are shown in Section IV. Finally, the discussion and conclusion are presented in sections V and VI, respectively.

II. Methods

The following section presents the background information of urban airspace and UTM concept design used in simulations within the Metropolis II project. More detailed information about the developed concept of operations can be found in [2].

A. Urban environment

It is expected that urban air traffic will be fundamentally different from conventional aviation due to the increased presence of physical obstacles, the higher expected traffic densities, the different operational characteristics, and the use of small unmanned aerial vehicles. Globally, several developments are undergoing for creating a concept of operations capable of enabling aircraft operations within cities.

A large volume of these operations is expected to be conducted within Very-Low Level (VLL) airspace, defined by FAA [3] and EU [1] projects as being below an altitude of approximately 500ft. Considering building heights, aircraft flying at such low altitudes might be required to fly above the existing street network for safety, efficiency and privacy reasons. Thus, the Metropolis II project aims to include both constrained (i.e., aircraft are constrained to flying above streets and between buildings) and open (i.e., aircraft can fly freely above obstacles in any direction) airspace within the study. Furthermore, previous research [4] performed within constrained airspace has used orthogonal street networks, which provide an idealised traffic situation. Within the Metropolis II project, a broader scope was taken by also considering organically developed street networks, common in cities in Europe.

For this reason, the city of Vienna was chosen as the basis for the simulation environment, due to the presence of a combination of orthogonal and organic street network topology, and its relatively low street alignment [5]. Vienna also has a low disconnectness index [6], meaning that all areas of the city are reachable without much detours. Lastly, the city has a great amount of open data available for both the buildings [7] and the streets [8], providing the opportunity to create a more realistic simulation area.

Alongside buildings, urban airspace will have to account for areas in which flights will not be permitted, such as parks or other privacy-sensitive locations. Within the Metropolis II project, we chose to enforce these areas using geofencing. Within the experiment airspace designed for Vienna, several geofenced areas were created within open airspace. Thus, although aircraft may freely fly in open airspace, they are not allowed to fly within these restricted areas.

Vertiports and distribution centres were placed within open and constrained airspace to act as origins and destinations for aircraft, based on the municipal demand expected in the future. These demands are based on parcel delivery data from [4], [9]. A linear regression is used that takes into account area, population size, and average annual gross salary per municipality. Fig. 1 shows how the city centre contains more vertiports as it is expected to have more demand. Distribution

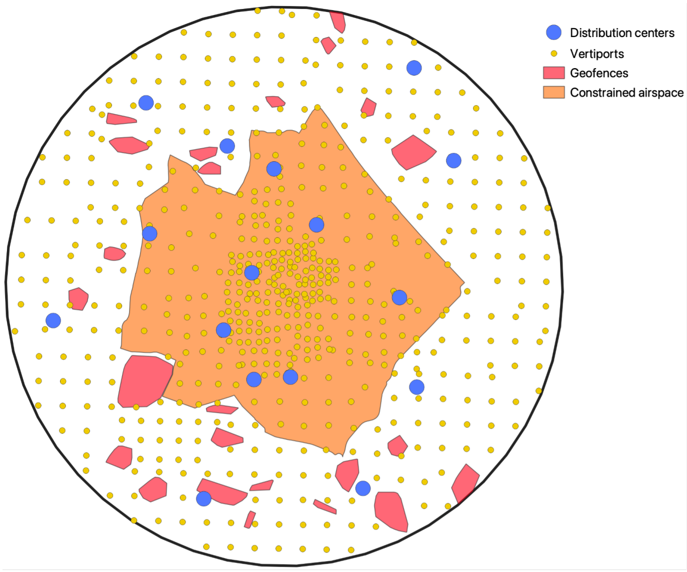

Figure 1. Urban airspace structure used within the Metropolis II traffic scenario simulations.

centres have a higher number of aircraft taking off from the same location, while vertiports have less demand but are more numerous. Within this work, the percentage of traffic originating from vertiports and distribution centres is 40%.

B. Description of concepts

In the Metropolis 2 project, three different separation management concepts were studied, which differed in terms of the degree of centralisation of the separation management task: a centralised, a hybrid, and a decentralised concept. Table I shows an overview of the main differences between the concepts, and the following sections present a summary of the design choices made within each.

TABLE I. Overview of the main differences between the three concepts and their properties [2].

Features	Centralised	Hybrid	Decentralised
Open Airspace	Hexagonal cells	Radial grid	Polygonal cells
Global knowledge of flights	Yes	Yes	No
Main separation management method	Pre-flight Strategic	Pre-flight Strategic and In-flight Tactical	In-flight Tactical

The open airspace design is different among concepts due to the need for it to be compatible with the concept philosophy: in a decentralised concept, the airspace is less structured, while in a more centralised one, structure is beneficial to the global optimisation of trajectories.

1) The Centralised Concept: The Centralised concept aims to strategically deconflict all aircraft prior to take-off. To do this, the open airspace is structured in hexagonal cells and is connected to the constrained airspace street network to enable use of the A* path-finding algorithm [10], [11]. The airspace is divided into 16 vertical layers, where each layer is assigned a heading range, similar to the layers concept created within the Metropolis I project [12].

Flight planning and strategic deconfliction is performed in a two-step approach. In the first step, a relaxed graph colouring model is used to assign flight layers such that the number of unsolved conflicts is minimised. In the second step, the remaining conflicts are solved by delaying the departure slot of flights.

In the centralised concept, a single authority is responsible for planning all flights and ensuring that all aircraft maintain separation throughout their mission. Flight plans are therefore 4-dimensional (latitude, longitude, height tracked in time). UAS agents are responsible for following the flight plan as closely as possible considering their performance limitations and uncertainties. The centralised concept does not include a tactical separation component.

2) The Hybrid Concept: The Hybrid concept attempts to leverage the use of a central entity for flight planning and strategic separation management while letting individual aircraft tactically separate if necessary. In the hybrid concept, the strategic separation component relies on using horizontal separation while the tactical separation component uses vertical and speed-based manoeuvres to solve conflicts not predicted by the central entity. In open airspace, airspace is structured as a unidirectional radial grid that connects to the street network in constrained airspace.

The hybrid concept adds an extra cost to travelling in constrained airspace, to reduce traffic density within the centre of the city. The total airspace is represented as a graph and the paths are solved using the Dijkstra algorithm. When an edge is occupied by an aircraft that edge is removed from the graph for a certain amount of time. This means that if an aircraft is not able to find an adequate solution, it gets delayed.

This concept also makes use of 16 layers to vertically separate aircraft. However, there are a reduced number of cruising layers when compared to the Centralised concept in order to provide aircraft with the option of using deconfliction layers for tactical conflict resolution maneuvers.

3) The Decentralised Concept: The decentralised concept only makes use of tactical separation to maintain safe separation between aircraft. The tactical separation algorithm employs both speed and altitude based manoeuvres. In the decentralised concept, open airspace is discretised into polygonal cells in the horizontal plane. In the vertical plane, layers are used to separate aircraft vertically in function of heading range, similar to the centralised concept (16 layers). In constrained airspace, all streets are uni-directional and are assigned a cruise height allocation and direction. The directions are assigned in a way that ensures that the whole airspace is accessible. The directionality allocation aims to minimise the probability of two cruising aircraft intersecting with each other. However, due to the street network containing non-nominal intersections (e.g., 3-way intersections), this will not always be possible. Aircraft that turn can make use of turn layers, located between cruising layers.

The decentralised concept does not use any strategic separation during flight planning. However, there is a central entity that monitors the traffic in constrained airspace and updates the cost of travelling through the airspace. Each aircraft then has the option to replan if the cost has changed due to high traffic, but also has the option to maintain its current route.

III. Experiment

The Metropolis II simulation experiments were designed to see how the level of centralisation influences safety, efficiency, and other metrics. More detailed information about the experiment set up may be found in the Metropolis II reports [13] and in [2].

A. Simulation software

The experiments were simulated through fast-time simulations using BlueSky, an open air traffic simulator [14]. BlueSky has an extensible plugin system, to which different conflict detection and resolution (CD&R) implementations and other modules can be added, allowing for testing of different concepts under similar conditions.

B. Simulation Area

The Metropolis II simulation airspace is an 8 kilometre wide and 500 feet high cylinder centered in the center of Vienna (Fig. 1). It includes open and constrained airspace. Aircraft are allowed to fly without constraints in open airspace unless there is a geofenced area. In constrained airspace, aircraft must fly above streets.

C. Aircraft models

For the Metropolis II project two aircraft types (MP20 and MP30) based on a simplified DJI Matrice 600 Pro hexacopter drone performance model were used in the simulations. The difference between the two is that MP20 cruises at a speed of 20 kts while MP30 at 30 kts.

D. Missions

In order to achieve a diverse and representative set of traffic patterns, and to provide a means to study the use of mission prioritisation, four mission types were defined:

1) **Parcel Deliveries:** These missions start from distribution centers and travel to a vertiport, and thus generate converging/diverging traffic patterns;
2) **Food Deliveries:** These missions travel from vertiport to vertiport, leading to point to point traffic patterns;
3) **Loitering missions:** Point to point missions that activate a dynamic geofence upon arrival;
4) **Emergency missions:** These missions are similar to food deliveries but are announced to the UTM system closer to their desired take-off time.

There are four levels of priority: low, medium, high, and emergency. The parcel, food and loitering traffic is assigned in equal proportion for the first three levels, with emergency missions having the highest priority. These levels are taken into consideration during tactical and strategic deconfliction decisions.

E. Uncertainties and non-nominal situations

Uncertainties and non-nominal events are introduced in the experiments in order to test the robustness of the separation management concepts. These are in the form wind, and rogue aircraft, respectively. Rogue aircraft are vehicles that do not adhere to the rules developed by the concept. They travel from outside the airspace through the center and then back outside the airspace, ignore traffic rules, and do not respond to the presence and actions of other traffic. The number of rogue aircraft in the air is kept constant during the simulation. Note that while rogue aircraft do not follow the rules of the concept, they still travel through constrained airspace by following the streets. The aircraft also randomly vary altitude at several different locations which are not known to the operators. Rogue aircraft do not make any attempts to tactically solve conflicts, and thus should affect the tactical components of the concepts most.

The experiments also include a limited simulation of the effect of wind on UTM operations. The goal of including wind in the experiments was to induce speed and timing uncertainty, which would impact the strategic planning of concepts with a central component. Therefore, a uniform wind field is defined over the whole airspace but only the component parallel to the direction of the aircraft affects the speed of the aircraft. This means that the aircraft will only speed up or slow down and not experience cross-winds.

F. Independent variables

The following independent variables were defined for the experiments:

1) **Degree of centralisation**: Decentralised, Hybrid, and Centralised;
2) **Traffic density**: Very low, low, medium, high, and very high traffic densities are used (see Table II);
3) **Wind level**: The speed of the uniform vector field (0, 1, 3, and 5 knots);
4) **Rogue aircraft**: The number of rogue aircraft at one time in the airspace (0, 33, 66, 100).

TABLE II. NUMBER OF AIRCRAFT CONCURRENTLY IN-FLIGHT FOR EACH TRAFFIC DENSITY.

Density	Average number of aircraft per scenario
Very Low	1660
Low	3340
Medium	4990
High	6650
Very High	8290

For each scenario characterised by a choice of independent variables, nine repetitions were performed using a different set of randomly-generated traffic.

G. Dependent measures

The dependent measures shown in this work are as follows:

- Number of pairwise conflicts,
- Number of intrusions,
- Achieved instantaneous traffic density,

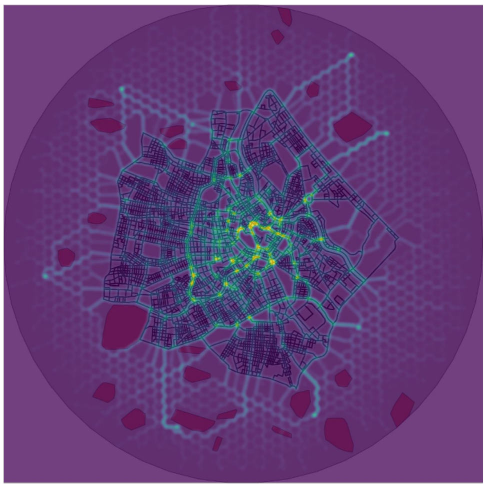

Figure 2. Cumulative density heat map for high density for the Centralised concept.

- Mission duration efficiency,
- Mission delay.

A conflict is counted when there is a predicted intrusion with a certain look ahead-time. This work uses state-based detection, meaning that trajectories are linearly extracted with a certain look-ahead time. The horizontal and vertical minimum separation is set to 32 metres and 25 feet, respectively. The look-ahead time is 10 seconds.

H. Simulation time

Dependent variables were measured throughout the entire simulation in all scenarios. Each scenario ran until all aircraft reached their destinations. Although flight departures are only planned within the first hour, the simulation time varied between 90 min and 180 min.

IV. RESULTS

The current section presents the most important results of the Metropolis II project. The calculated metrics results are presented using boxplot graphs, each boxplot is computed based on the value of the metrics across the 9 scenario repetitions.

A. Traffic density

Figs. 2, 3, and 4 show the cumulative traffic density heat maps throughout the simulations with high density traffic and 40 percent of traffic coming from distribution centers for the centralised, hybrid, and decentralised concepts respectively. Here, lighter color indicates denser traffic.

A comparison of Figs. 2, 3, and 4 reveals several differences in terms of flight planning. In Fig. 2 the hexagonal grid of the Centralised concept is visible in open airspace. Fig. 3 shows the radial grid of the hybrid concept. Since there was a higher cost in travelling through constrained airspace, the traffic tended to form a beltway around the city center. Fig. 4 shows the effects of the absence of strategic planning. As aircraft tend to use the shortest path though the network in

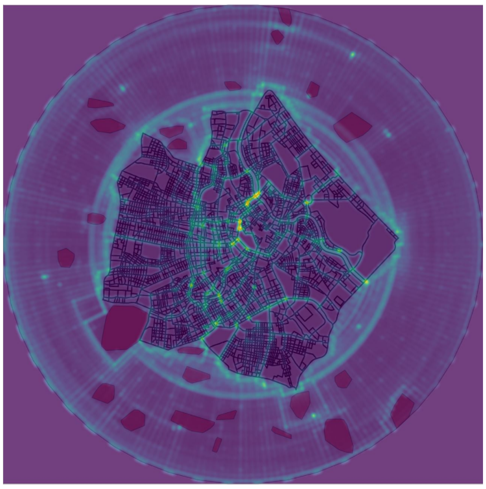

Figure 3. Cumulative density heat map for high density for the Hybrid concept.

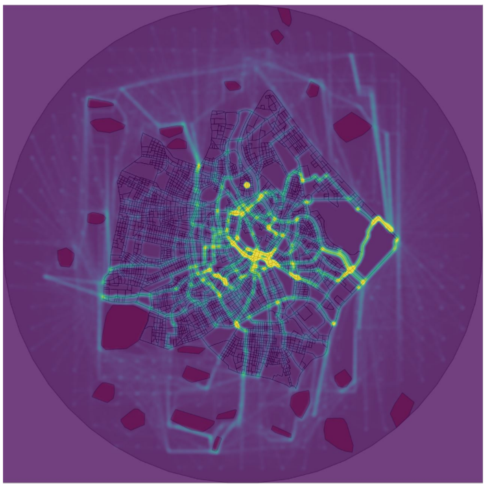

Figure 4. Cumulative density heat map for high density for the Decentralised concept.

constrained airspace, there are certain streets and intersections which are more used than the others. It is also interesting to note that the centralised concept tended to spread the traffic more evenly in constrained airspace.

Fig. 5 shows that the decentralised and centralised concepts have very similar instantaneous traffic densities. The peak of the hybrid density in constrained airspace is about half of that for the decentralised and centralised concept due to the ring-road strategy used by the former. It is also clear that the hybrid concept took longer to taper off, showing that aircraft were in the air for longer as they avoided constrained airspace.

B. Airspace safety

Fig. 6 shows the number of conflicts per flight for each concept for the different traffic demand scenarios. The effect of strategic pre-take-off deconfliction can clearly be seen: the decentralised concept has the highest number of conflicts at all densities, reaching to an order of magnitude difference at the high and very high densities. The hybrid and centralised

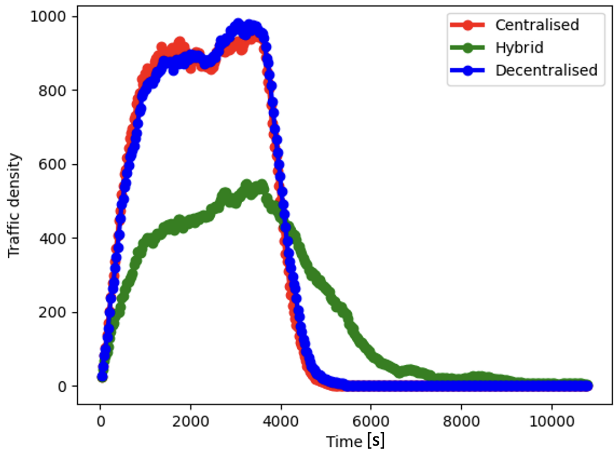

Figure 5. Aircraft density in constrained airspace in function of time for a high-density scenario.

concepts both have similar number of conflicts with the centralised concept having slightly fewer.

Fig. 7 shows the total number of intrusions for each of the concepts in the vertical axis and the scenario density in the horizontal axis. Here it is clear that the hybrid concept has the smallest number of intrusions at all traffic densities. The decentralised and centralised concepts are more comparable in number of intrusions. The levels appear similar at most traffic densities, though at the very high traffic density the decentralised concept has slightly more intrusions than the other concepts.

As the three concepts achieved different densities within constrained airspace, the number of intrusions is not directly comparable. Therefore, the intrusion rate was computed in function of aircraft density in constrained airspace, presented in Fig. 8. The intrusion trend of the centralised and decentralised concepts are nearly identical. Although the hybrid concept achieves the fewest intrusions per minute per number of aircraft in the air, the difference becomes less pronounced

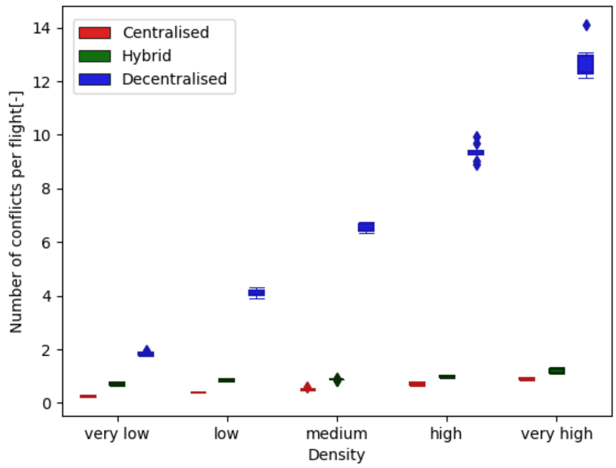

Figure 6. Number of conflicts per flight as a function of the scenario density for the three concepts.

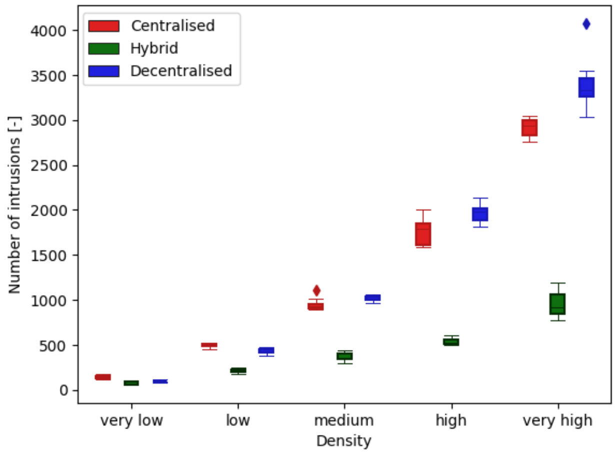

Figure 7. Number of intrusions as a function of the scenario density for the three concepts.

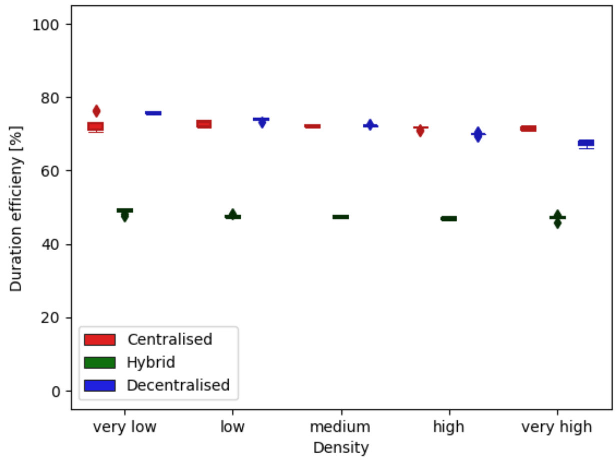

Figure 9. Flight duration efficiency as a function of the traffic density for the three concepts.

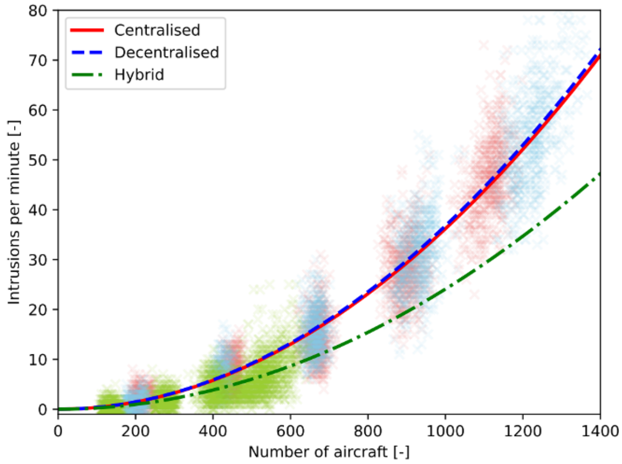

Figure 8. Intrusions per minute as a function of the number of aircraft in constrained airspace for the three concepts.

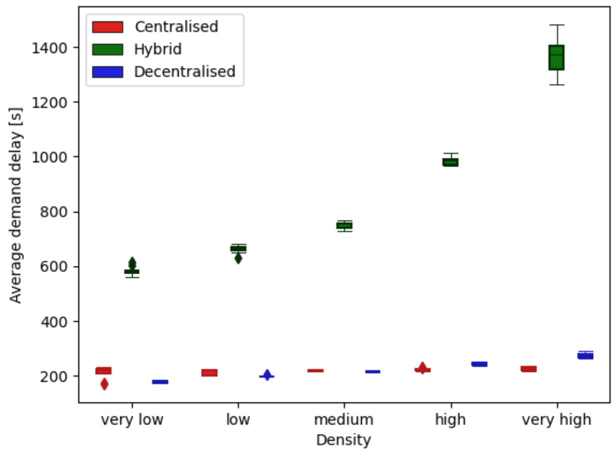

Figure 10. Average demand delay as a function of the traffic density for the three concepts.

when compared to the total number of intrusions presented in Fig. 7.

C. *Mission efficiency*

The duration efficiency is an estimate of how much longer the simulated route took versus an ideal route, presented in Fig. 9. The centralised and hybrid concepts both have relatively constant efficiencies across densities. The hybrid concept achieved a lower overall efficiency due to the beltway airspace structure, which made missions last longer. The decentralised concept is similar in magnitude to the centralised concept, however the efficiency tends to decrease with the density due to aircraft having to resolve more conflicts tactically.

D. *Mission delay*

The average demand delay is measured as the mean of the delay of all the flights in a scenario, presented in Fig. 10. The centralised and decentralised concepts present similarly low values of delay, with the decentralised concept showing a slightly increasing pattern with increasing density. The hybrid concept induces notably higher delays for all densities and presents a rapid raise in the delays with increasing density. Three main factors contribute to demand delay. The first is the departure delay applied by the concepts to the aircraft as an effort to increase safety. The second is the route length, as the hybrid concept discourages aircraft from using the constrained airspace and plans longer routes to avoid it. The last one is the flight time with lower speed limit or hovering while resolving conflicts as a part of the tactical separation.

E. *Service access and equity*

Demand delay dispersion metric is used as an indicator of equity and access to UTM services. This metric gives an indication of how delay is distributed over airspace participants. A low value indicates that delay was evenly distributed, and a higher value means that some aircraft were delayed disproportionately more than others. It is computed as the standard deviation over the arrival delay of all aircraft which arrived at their destination, where the arrival delay is the

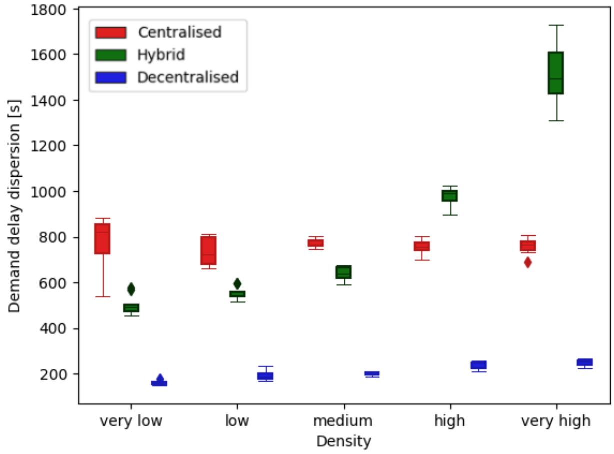

Figure 11. Demand dispersion delay as a function of the traffic density for the three concepts.

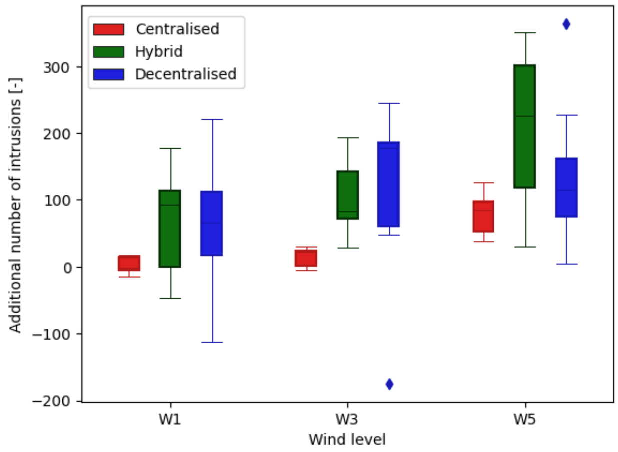

Figure 12. Additional number of intrusions as a function of the wind level for the three concepts (1, 3, and 5 kts wind speed).

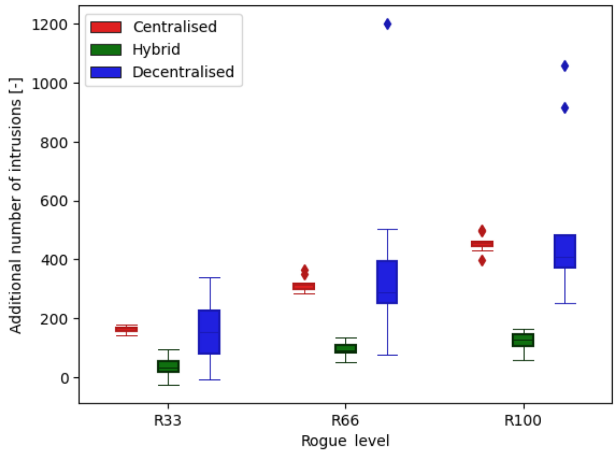

Figure 13. Additional number of intrusions as a function of the number of rogue aircraft for the three concepts (33, 66 and 100 aircraft).

difference between realized arrival time and ideal expected arrival time.

The demand delay dispersion can be seen in Fig. 11. The decentralised concept had the lowest demand delay dispersion which means that most aircraft were similarly delayed. In the very low, low, and medium densities the hybrid concept had a lower dispersion delay than the centralised concept. However, for the high and very high the effect is reversed and the hybrid concept achieves values above those of the centralised concept, indicating that for those densities the hybrid concept applies significantly longer delay to a subset of aircraft.

F. Effect of uncertainties and non-nominals on safety

Fig. 12 shows the additional number of intrusions due to the presence of wind for all three concepts in a high density scenario. The centralised concept shows a very low number of additional intrusions at 1 and 3 knots. However, it is higher at 5 knots. For the hybrid concept the additional number of intrusions is similar at 1, and 3 knots and then increases at 5 knots. For the decentralised concept, the number of intrusions is similar across all wind speeds. However, the spread of the number of intrusions moves to the positive side of the vertical axis for the 3 and 5 knots case.

Fig. 13 shows the additional number of intrusions due to rogue aircraft for all three concepts in the high density scenarios. Overall, the number of intrusions increases as the number of rogue aircraft increases. The hybrid concept resulted in the lowest number of additional intrusions. The number of intrusions for the decentralised and centralised concepts is similar across rogue levels, although the decentralised does show more spread in its results.

V. Discussion

There are a number of observations that can be made from the results of the Metropolis 2 concept comparison. The first is that the hybrid concept managed to achieve the lowest number of intrusions of the three concepts, even when considering intrusion count as a function of instantaneous traffic density. However, when looking at, e.g., flight efficiency and demand delay it can be seen that the safe performance of the hybrid concept comes, in part, at the cost of flight efficiency and capacity. This shows the potential benefit of the combination of strategic and tactical separation management measures. However, not all of these differences can be attributed to the difference in degree of centralisation between the concepts. The design of the airspace was also a large factor in the observed differences between the three concepts.

Firstly, because the hybrid concept made use of dedicated deconfliction layers, it only has half of the allowable cruising space compared to the centralised concept, which can have an impact on capacity. This means that the strategic planner has half the vertical space available. From Fig. 11 it can be seen that at lower densities the dispersion of the delays of the hybrid concept was below the centralised concept. However, as the traffic density increased the availability of cruising space became denser and the hybrid concept was not able to match the centralised concept.

Secondly, the beltway-like structure of the hybrid concept for unconstrained airspace had aircraft in the air for longer because the strategic algorithm tended to prefer these beltways over flying in constrained airspace. This can be seen in the density heat maps (Fig. 3) and the instantaneous density plot in Fig. 5. This behaviour causes longer flight distances, but because of its high degree of traffic alignment (on any point along a roundabout all vehicles are going in approximately the same direction at the same speed) conflict probability can be reduced by a large amount. This shows that the airspace structure can have a significant impact on safety, especially if traffic is better aligned and spread out (albeit at the expense of route efficiency).

The decentralised concept does not globally optimize the paths of the aircraft. It does attempt to spread traffic through flow control but local hotspots can still be seen within the airspace. Moreover, the number of conflicts in the decentralised concept are an order of magnitude higher than both the centralised and hybrid concepts. However, when comparing the number of resulting intrusions to the centralised concept results, it can be seen that the decentralised concept is able to maintain similar levels of intrusions to the centralised concept. The higher number of conflicts, therefore, achieve *reactively*, what a pre-departure optimisation algorithm does proactively. It is interesting that by only using strategic separation or tactical separation, the number of intrusions remains comparable. The centralised concept was able to reduce network bottlenecks and maintain path efficiency. However, it is not able to plan completely for all circumstances, therefore a tactical element remains indispensable. However, it can be difficult to effectively trade-off between both as it is seen from the performance of the hybrid concept in the duration efficiency (Fig. 9) and the demand delay (Fig. 10).

Another interesting result is the similarity between the centralised and decentralised concept in the safety results within constrained airspace (Fig. 8). This can be attributed to the nature of constrained airspace, where the action and solution space are limited. Thus, when the separation methods are limited (i.e., using either tactical or strategic), the airspace network structure itself has a greater influence on the safety.

The results in terms of robustness to rogue aircraft show that the hybrid concept is able to have the least number of intrusions for all rogue levels. This can be related to the fact that the hybrid concept distributes traffic efficiently in the strategic phase, and that its tactical resolution algorithm proved more effective in solving the type of conflicts that occurred with rogue vehicles.

VI. Conclusion

The hybrid concept was able to achieve the highest level of safety by combining centralised strategic and decentralised tactical separation management. The "ring road" routing method helped increase safety by a large factor in the hybrid concept as there were fewer aircraft in constrained airspace. The strategic planning of the hybrid concept distributed traffic and mitigated network bottlenecks. Moreover, the tactical separation strategy further improved the safety by resolving the conflicts that the strategic planning did not detect, due to uncertainties regarding the positions of all aircraft. However, this came at the expense of route efficiency and demand delay.

The decentralised concept provided the most equitable access to the airspace. In terms of safety and demand delay, the decentralised concept was on par with the centralised concept, resulting in a similar number of intrusions for both. However, the centralised concept was able to redistribute traffic more efficiently than the hybrid concept due to allowing more aircraft in constrained airspace.

To answer the question on the degree of centralisation of an urban air traffic management system, we propose an improved hybrid system with more elaborate path planning and less strict strategic planning that allow higher aircraft densities.

Acknowledgment

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