The Influence of Traffic Structure on Airspace Capacity

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***Abstract*—Airspace structure can be used as a procedural mechanism for a priori separation and organization of en-route air traffic. Although many studies have explored novel structuring methods to increase en-route airspace capacity, the relationship between the level of structuring of traffic and airspace capacity is not well established. To better understand the influence of traffic structure on airspace capacity, in this research, four airspace concepts, representing discrete points along the dimension of structure, were compared using large-scale simulation experiments. By subjecting the concepts to multiple traffic demand scenarios, the structure-capacity relationship was inferred from the effect of traffic demand variations on safety, efficiency and stability metrics. These simulations were performed within the context of a future personal aerial transportation system, and considered both nominal and non-nominal conditions. Simulation results suggest that the structuring of traffic must take into account the expected traffic demand pattern to be beneficial in terms of capacity. Furthermore, for the heterogeneous, or uniformly distributed, traffic demand patterns considered in this work, a decentralized layered airspace concept, in which each altitude band limited horizontal travel to within a predefined heading range, led to the best balance of all the metrics considered.**

Keywords – airspace structure; airspace capacity; en-route airspace design; air traffic control; air transportation system performance

I. INTRODUCTION

The current en-route airspace design is centred around predefined airways, sectors and ground-based Air Traffic Controllers (ATCo) [1]. Although enhancements to air traffic systems and procedures have led to incremental capacity improvements, the current centralized system architecture has been widely reported to be nearing saturation levels [2]–[4]. To keep pace with the ever growing demand for air transportation, it is necessary to investigate novel methods of organizing and structuring traffic to increase en-route airspace capacity. However, a fundamental relationship between the level of structuring of traffic and resulting properties, such as efficiency and safety, is not well established, and different studies in this field report seemingly contradictory findings.

Free-Flight researchers, for instance, advocate that higher densities can be achieved through a reduction of traffic flow constraints and structure [5]–[7], whereas other studies argue that capacity would benefit more from a further structuring of airspace [8], [9]. This dichotomy suggests that airspace structure and capacity are invariably tied together. The relationship between these two variables, however, is not well understood, i.e., does more or less structuring lead to higher capacity? Or, is there a transition point, where a further increase in capacity will require a switch from one approach to the other?

To answer these questions, in this work, the impact of airspace structure on capacity is investigated as part of the Metropolis project, a research initiative funded through the Seventh Framework Programme of the European Commission. To this end, four airspace concepts, ranging from a decentralized direct routing concept, to a highly structured tube network using 4D trajectory-based operations, are compared using large-scale simulation experiments. The analysis is performed within the context of a futuristic personal air transportation system, to enable exploration of extreme traffic densities that would be impossible to achieve in the current operational context. The goal of the simulations is not to arrive at precise capacity estimations for the four concepts, but rather to consider how the level of structuring affects capacity. Therefore, the concepts are subjected to multiple traffic scenarios with heterogeneous demand patterns, and a relative capacity ranking is performed by measuring how safety, efficiency and stability metrics vary with traffic demand. By including rogue aircraft that ignore concept dependent routing requirements in selected simulation scenarios, the robustness of the concepts to non-nominal conditions is also investigated in this study.

This paper begins with descriptions of the four airspace concepts used to empirically relate airspace structure and capacity in section II. This is followed in section III with the setup of two simulation experiments used to compare the concepts. The results of the experiments are presented and discussed in sections IV and V respectively. Finally the main conclusions are summarized in section VI.

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II. AIRSPACE CONCEPTS

To empirically study the structure-capacity relationship, four en-route airspace concepts of increasing structure, named Full Mix, Layers, Zones and Tubes, have been defined. This section describes the conceptual design of the four concepts.

A. *Full Mix*

The Full Mix airspace concept can be most aptly described as ‘unstructured airspace’. As demand is often unstructured, the Full Mix concept assumes that any structuring of traffic decreases overall system efficiency, and that safety is actually improved by the spreading of traffic over the available airspace. Therefore aircraft in the Full Mix concept use direct horizontal routes, as well as optimum altitudes and velocities, to minimize fuel usage and other related trip costs.

In Full Mix, traffic separation responsibility is decentralized to each individual aircraft. As no level of airspace structure is used to separate potentially conflicting trajectories, safe separation between aircraft is entirely dependent on self-separation automation, see section III for more details. Since Full Mix imposes no restrictions to the path of aircraft, combined heading, speed and altitude conflict resolution maneuvers are used.

B. *Layers*

In this concept, the airspace is segmented into vertically stacked bands, with each altitude band limiting horizontal travel to within an allowed heading range, similar to the hemispheric rule. The resulting vertical segmentation of airspace is expected to improve safety when compared to the Full Mix concept, by reducing the relative velocities, and thereby reducing conflict probabilities, between aircraft cruising at the same altitude. However, this increased safety comes at the price of efficiency; while direct horizontal routes are still possible, vertical flight profiles are dictated by the bearing between origin and destination, and the corresponding altitude band with the required heading range. Thus, flights might not be able to cruise at their optimal altitude, resulting in higher fuel burn. An exception is made for climbing and descending aircraft; these aircraft are allowed to maintain

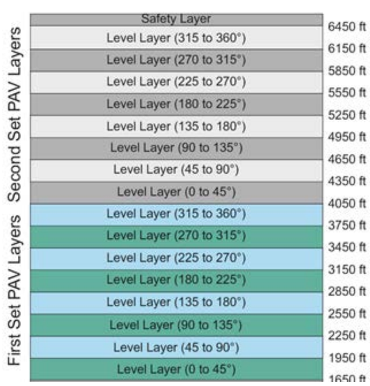


Figure 1: Side view of the Layers concept. Two complete layer sets have been defined within the airspace volume used to simulate traffic.

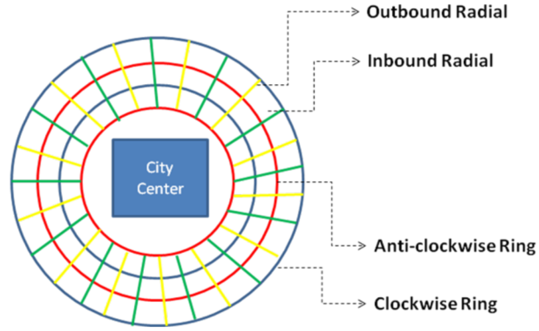


Figure 2: Top down view of the Zones topology. Given the personal air transportation scenario used in this work, the Zone concept is designed to take into account the layout of a modern city.

heading while climbing or descending to their destination altitude.

Figure 1 displays a schematic view of the Layers concept as implemented in this is research. Here, it can be seen that that each layer corresponds to a heading range of 45^{o} and has a height of 300 ft. With these dimensions, two complete sets of layers fit within the airspace volume used to simulate traffic, see section III for more details on the experiment volume. As a result, short flights can stay at low altitudes while longer flights can improve fuel burn by flying at higher flight levels. This is expected to mitigate the efficiency drop of predetermined altitudes in this concept.

The Layers concept also makes use of the same self-separation automation utilized by Full Mix, albeit with restrictions on the allowed resolution maneuvers. While combined heading, speed and altitude resolutions are permitted for climbing and descending traffic, for cruising aircraft, resolutions are limited to combined heading and speed maneuvers for cruising aircraft.

C. *Zones*

Similar to Layers, the Zones concept separates traffic based on similarity of travel direction. However, in this case, a horizontal segmentation of airspace is used to separate traffic along pre-defined trajectories. In this respect, the Zones concept somewhat resembles the airway based airspace design used today.

As a personal aerial transportation scenario is used in this work, the Zones topology takes into account the layout of urban environments in the design of its structure, see Figure 2. Here, two major zone types can be seen: circular and radial zones. Circular zones are used in a similar way to ring roads in contemporary cities, while the radial zones facilitate travel towards and away from the city center, and function as connections between the circular zones. Additionally, both zone types are defined to be unidirectional to further aid traffic separation. As there is no vertical segmentation of airspace in this concept, optimum altitudes are selected based on the planned flight distance between origin and destination.

The Zones concept also uses self-separation to separate aircraft flying within the same zone, as well as to assist with the merging of aircraft between circular and radial zones. Since the zone topology dictates the horizontal path of an aircraft, heading resolutions are not allowed for this concept.

D. Tubes

As a maximum structuring of airspace, the fourth concept implements four-dimensional tubes that provide a fixed route structure in the air. Here, the aim is to increase predictability of traffic flows by means of pre-planned conflict free routes.

The tube topology used in this study can be thought of as a graph with nodes and edges, see Figure 3**.** The nodes of the graph are connection points for one or more routes. The edges are the tubes connecting two nodes. Tubes at the same horizontal level never intersect, except at the nodes, and are dimensioned to fit exactly one aircraft in the vertical and horizontal plane. To provide multiple route alternatives, a total of thirteen tube layers are placed above each other with decreasing granularity. This way, short flights profit from a fine grid at the lowest layer, while at the same time, longer flights benefit from lengthier straight tubes in higher layers. Aircraft are only allowed to climb/descend through one tube layer at a time.

Unlike the other concepts, the Tubes concept uses time-based separation of aircraft to ensure safety within the network. This mode of separation dictates that when an aircraft passes a node, it will ‘occupy’ that node for a prescribed time interval. Within this occupancy interval no other aircraft is allowed to pass through that node, and new flights may only pass through a particular node if the necessary occupancy interval is completely free. To ensure that separation at the nodes ensures separation within the tubes as well, all aircraft within the same tube layer are required to fly at the same velocity. This prescribed speed increases with the altitude of the layer to match the decreasing granularity of the tube network. A major advantage of this method of separation is that it allows the tube network to be bi-directional, as the occupancy at a node is independent of travel direction. This simplifies the design, and enables closer packing of tubes in the topology.

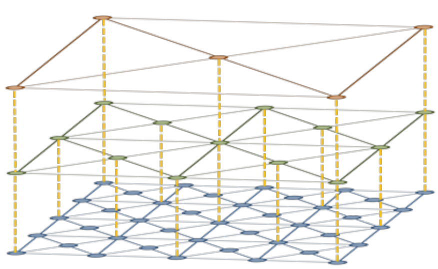


Figure 3: An example tube topology with three layers of decreasing granularity. The dashed yellow lines are used to indicate the placement of nodes above each other. Tubes are bi-directional.

III. Experiment Design

Two large-scale simulation experiments were conducted to compare the four airspace concepts in terms of capacity. This section describes the design of these two experiments.

A. Simulation Development

1) Simulation Platform

The Traffic Manager (TMX) software, developed by the National Aerospace Laboratory of the Netherlands (NLR), was used as the simulation platform in this research. TMX has been extensively validated and has been used for numerous ATM related simulation studies. For more information on TMX capabilities, the reader is referred to [10] .

2) Concept Implementation

Aircraft in the Full Mix concept were programmed to use the direct horizontal route and the most fuel efficient altitude, as determined by the APMs. Layers also used the direct horizontal trajectory. However, altitude was selected based on the bearing to the destination and the matching altitude from a predefined list. Additionally, total flight distance determined the choice between the upper and lower layer sets; flights less than 22 Nmi used the lower layer set, see Figure 1.

For the Zones concept, the A* path planning algorithm was used to determine the shortest route over a predefined horizontal topology, while the most fuel efficient altitude was chosen. Tubes also employed A* to calculate the shortest path, but in this case, it was also used to examine whether the selected path was conflict-free. Here, an instantaneous planning approach was used whereby the occupancy of each node along a proposed route was checked at traffic desired departure times. If any node along a proposed route was found to be occupied by another flight, the corresponding route was discarded, and the A* algorithm backtracked to evaluate the next best solution. If no route could be found, a pre-departure delay was applied in multiples of 10 seconds up to a maximum of 30 minutes. After this period, the tube network was considered to be saturated, and that flight was canceled. A complete description of the A* algorithm can be found in [11].

3) Self-Separation Automation

The Full Mix, Layers and Zones concepts relied on self-separation automation for tactical separation, consisting of separate Conflict Detection (CD), Conflict Resolution (CR) and Conflict Prevention (CP) modules. CD was performed through linear extrapolation of aircraft positions over a prescribed ‘look-ahead’ time. Once conflicts were predicted, the Modified Voltage Potential (MVP) algorithm is used for CR in a pair wise fashion, resulting in implicit cooperative resolution strategies. Finally, the CP algorithm ensures that aircraft do not turn into conflicts, in an effort to mitigate conflict chain reactions. Previous research showed that this three pronged system was highly effective in solving multi-aircraft conflicts. For more details, please consult [5].

Based on initial test runs, a look-ahead time of 60 seconds, and separation margins of 0.135 Nmi horizontally and 150 ft vertically, were selected. Also, aircraft were assumed to have perfect knowledge of the states of neighboring traffic to focus exclusively on the structure-capacity relationship.

4) *Wind*

Wind was modeled as a uniform and time-invariant vector field with random direction and speed. Wind was deliberately omitted from the simulation's trajectory planning functions to study the effect of uncertainties, which could cause deviations from the planned trajectory, on safety. Thus, the wind used in the simulation has a similar effect to wind prediction errors in real life operations.

B. *Traffic Scenarios*

1) *Testing Region*

Given the personal air transport scenario, a fictional city was designed to represent the simulation's physical environment. To create high density traffic scenarios, a small portion of the city, with an area of 1600 square Nmi, was used for traffic simulations, see Figure 4. Here it can be seen that the city is divided into three major districts: city center, inner ring and outer ring. To define origin and destination points for traffic, 1600 ‘PAV-ports’ were evenly distributed over the city in a grid pattern. Although traffic is simulated over the entire city, data is only logged between 1650 ft and 6500 ft, as the focus of this research is on en route airspace design.

2) *Traffic Demand*

Four demand scenarios of increasing density were used to compare the concepts, and are defined in terms of instantaneous traffic demand, see Table 1. These scenarios were created by setting the average nominal trip time to fifteen minutes, and rely on assumptions for future population growth and per capita demand for PAVs, see [12] for more details.

In addition to traffic volume, it is also necessary to consider urban traffic patterns. To this end, city blocks were characterized as either commercial or residential, with a greater proportion of commercial buildings near the city center, see Figure 4. This distinction made it possible to simulate morning rush hour as traffic converging towards commercial areas of a city. Similarly, evening rush hour could be simulated as traffic diverging from the city center to suburban residential areas. Therefore, for each traffic volume, scenarios with converging, diverging and 'mixed' traffic flows were created. Also, each scenario had a duration of two hours, consisting of a forty-five minute build-up period, a one hour logging period, and a fifteen minute wind-down period.

TABLE 1: TRAFFIC DEMAND SCENARIOS

Scenario	Low	Medium	High	Ultra
Instantaneous Traffic Volume	2,625	3,375	4,125	4,875

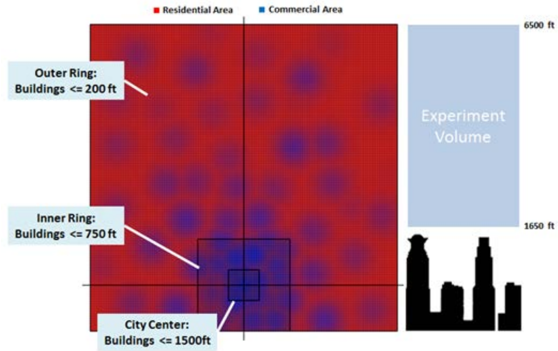


Figure 4: Map of fictional city used as the simulation physical environment. Simulation data is logged for the airspace volume between 1600-6500ft

C. *Independent Variables*

Two separate experiments were performed; the nominal experiment and the non-nominal experiment.

1) *Nominal Experiment*

The nominal experiment focused on the impact of airspace structure on capacity; although traffic was subjected to a uniform wind field, no other detriments to aircraft motion were included. For this experiment, four levels of airspace structure and four traffic demand scenarios represented the independent conditions. Six repetitions were performed for each experiment condition (two repetitions for three traffic demand patterns). Furthermore, the scenarios were simulated with and without conflict resolution, resulting in a total of 192 nominal runs.

2) *Non-Nominal Experiment*

This experiment is aimed at comparing the relative robustness of the concepts to non-nominal situations. For this purpose, the four airspace concepts were compared for simulations with 4, 8, 16, and 32 rogue aircraft. These rogue aircraft were introduced randomly during the logging hour, and flew haphazardly through the airspace. Nominal aircraft were solely responsible for resolving conflicts with rogue aircraft using its self-separation automation, in all concepts. Although time based separation is used in Tubes, the self-separation automation described above is used with speed resolutions to resolve conflicts with rogue aircraft alone. Once again, 6 repetitions were performed, with and without conflict resolution, resulting in a total of 192 non-nominal runs.

D. *Dependent Variables*

Three categories of dependent variables are used to compare the concepts: safety, efficiency and stability. The metrics used to access each category are described below.

1) *Safety*

Safety metrics focus on the ability of an airspace concept to maintain safe separation between aircraft. Separation performance is measured in terms of the number of intrusions and conflicts. Here, intrusions are defined as violations of minimum separation requirements, while conflicts are defined as predicted intrusions, i.e., when two (or more) aircraft are expected to violate separation requirements within a predetermined `look-ahead' time (60 seconds in this research).

Intrusions do not imply collisions. Therefore, in addition to counting the number of intrusions, it is important to consider the severity of an intrusion. The severity of an intrusion is dependent on the path of an aircraft through the protected zone of another, see Figure 5, and is computed using the following expression:

$$\mathrm{Int}_{\mathrm{severity}} = \max_{t_{0_{\mathrm{int}}} - t_{1_{\mathrm{int}}}} \left[\min\left(\hat{I}_H(t), \hat{I}_V(t) \right) \right] \tag{1}$$

Here, $\hat{I}_H$ and $\hat{I}_V$ are the horizontal and vertical intrusions that are normalized with respect to the corresponding minimum separation requirements, while $t_{0_{int}}$ and $t_{1_{int}}$ are the start and end times of an intrusion. Using the above relation, the intrusion severity for the intrusion path shown in Figure 5 is equal to the normalized horizontal intrusion at point 'A'.

2) *Efficiency*

The efficiency of the concepts is analyzed using the work done metric. This metric considers the optimality of an aircraft's trajectory, and therefore has a strong correlation with fuel/energy consumption. For each flight, the work done is computed as:

$$\mathrm{W} = \int_{\mathrm{path}} \mathbf{T}\, \mathrm{d}\mathbf{s} \tag{2}$$

Here, **T** and **s** are the thrust and displacement vectors.

3) *Stability*

Resolving conflicts may cause new conflicts at very high traffic densities due to the scarcity of airspace. The stability of the airspace as a direct result of conflict resolution maneuvers has been measured in literature using the Domino Effect Parameter (DEP) [6]. The DEP can be visualized through the Venn diagram pictured in Figure 6. Here S1 is the set of all conflicts without resolutions, and S2 is the set of all conflicts with resolutions, for identical scenarios. Furthermore, three regions can be identified in Figure 6 from the union and relative complements of the two sets, with $\mathrm{R1} = \mathrm{S1} \backslash \mathrm{S2}$, $\mathrm{R2} = \mathrm{S1} \cup \mathrm{S2}$ and $\mathrm{R3} = \mathrm{S2} \backslash \mathrm{S1}$.

By comparing R3 with R1, the proportion of additional 'destabilizing' conflicts that were triggered by resolution maneuvers can be determined. Thus, the DEP is inversely proportional to airspace stability, and is defined as [6]:

$$DEP = \frac{R3 - R1}{S1} = \frac{S2}{S1} - 1 \tag{3}$$

IV. RESULTS

The results of the nominal and non-nominal experiments are presented separately in this section. The effect of the independent variables on the dependent variables are analyzed using error bar charts that displays the mean, and the 95% confidence interval of the mean, for each simulation condition. Whenever relevant, the effect of CR is also discussed using separate error bar charts.

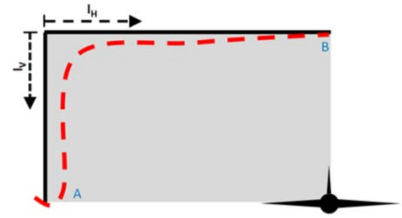


Figure 5: Side view of an intrusion. The red dashed line shows the intrusion path of an aircraft through the protected zone of another.

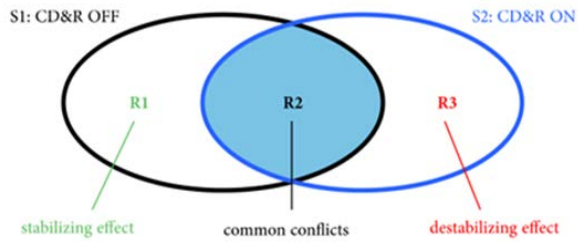


Figure 6: The Domino Effect Parameter (DEP) relates the additional conflicts caused by resolution maneuvers to airspace stability

A. *Nominal Experiment*

Over six million flights were simulated during this experiment. Data from approximately 50% of these flights, which flew during the logging period, are analyzed for these results. The analysis begins by considering the traffic volumes and densities simulated, and the consequent implications on the analysis of the dependent measures.

1) *Traffic Volume and Density*

The total traffic volume and average traffic density per simulation run is displayed are Figures 7 and 8, respectively. For Full Mix, Layers and Zones, traffic volumes and densities were fairly similar. However, in both cases, the Tubes concept deviates significantly from the other concepts. In terms of traffic volume, Tubes simulated significantly fewer aircraft for all demand scenarios. This is because Tubes delayed and cancelled flights if conflict free routes were not available at scenario specified departure times. Despite the lower traffic volume, Tubes caused the highest traffic densities. This inconsistent trend is due to the significantly longer routes of the Tubes concept (see efficiency metrics), which in turn increased flight durations and traffic densities.

These differences in traffic volumes and densities for Tubes need to be taken into account when considering the other dependent variables. Although Figure 7 suggests that the Tubes concept has a lower airspace capacity relative to the other concepts, it should be noted that the figure does not imply that the other concepts are able to, for instance, facilitate the higher volumes safely. Therefore, conclusions with respect to capacity also depend on the other dependent variables discussed below, and cannot be based purely on the amount of traffic simulated. Moreover, whenever appropriate, these metrics are computed relative to the number of flights simulated to allow for a fair comparison between concepts.

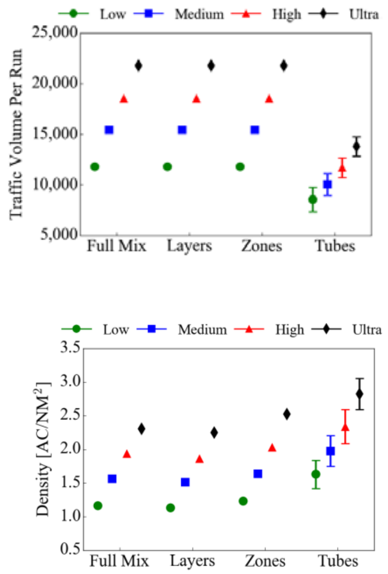
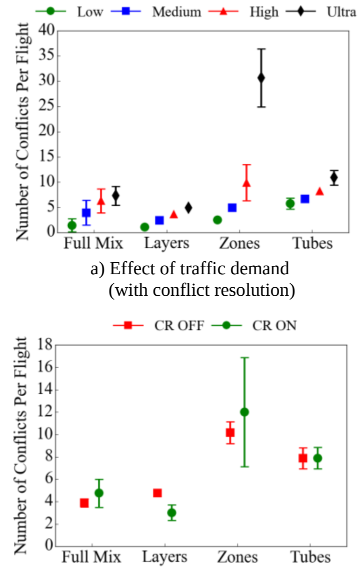


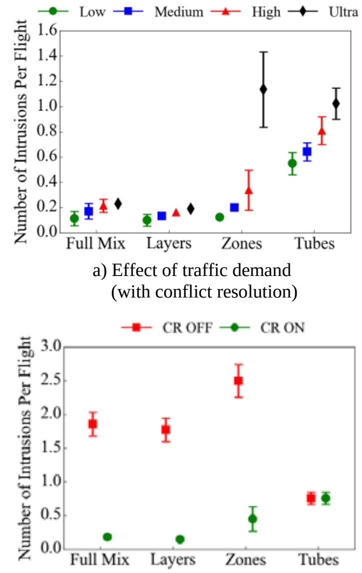
Figure 8: Traffic density per simulation run



a) Effect of traffic demand (with conflict resolution)

b) Effect of Conflict Resolution (CR)

Figure 9: Number of conflicts per flight



a) Effect of traffic demand (with conflict resolution)

b) Effect of Conflict Resolution (CR)

Figure 10: Number of intrusions per flight

2) *Safety*

The number of conflicts and intrusions per flight for all simulation conditions are displayed in Figures 9 and 10, respectively. As expected, the number of conflicts and intrusions increased with traffic demand for all concepts. Furthermore, the figures also show that the more structured Zones and Tubes concepts led to significantly higher numbers of conflicts and intrusions compared to the less structured Full Mix and Layers concepts.

The effect of tactical CR on the number of safety incidents is also pictured in Figures 9 and 10. As Tubes did not use tactical CR, there were no differences between the ON and OFF conditions. For the other three concepts, the number of intrusions was considerably reduced with CR ON. However, the effect of CR on the number of conflicts did not follow the same trend. For Full Mix and Zones, the number of conflicts increased with CR ON. This was expected, as resolution maneuvers increase flight distances and the consequent probability of encountering other aircraft. However, for the Layers concept, the opposite was found, with CR ON leading to a lower number of conflicts. This unusual result is further analyzed using stability metrics.

It is interesting to note that the Tubes concept, which aimed at deconflicting flights prior to take-off, resulted in a very high number of conflicts and intrusions for all scenarios. This is because the trajectory planning functions used by Tubes did not take uncertainties, such as wind, into account. These uncertainties caused aircraft to deviate from their planned flight paths during the simulation, resulting in a large number of conflicts due to the tight packing of the Tubes topology. As no tactical CR was used by Tubes, the conflicts also resulted in a large number of intrusions.

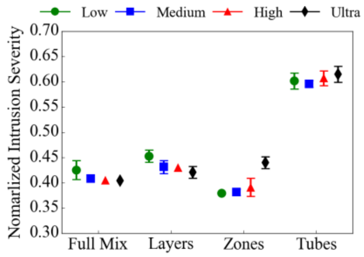
Figure 11 shows that intrusion severity is not significantly dependent on traffic demand, and is fairly similar for the three concepts using tactical CR. This suggests that intrusion severity is more a function of the selected CR algorithm than airspace structure. Due to the resolution maneuvers initiated by the MVP algorithm, intrusion severity was reduced when CR was enabled for Full Mix, Layers and Zones.

3) *Efficiency*

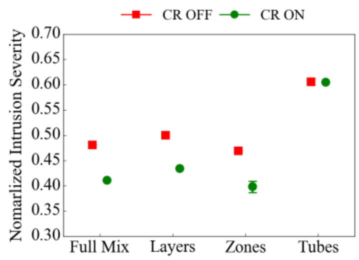
Efficiency, measured using the work done metric, is shown in Figure 12. Here, a positive correlation between work done and the degree of airspace structure, as well as between work done and traffic demand, can be seen. The Full Mix concept led to the lowest work done, closely followed by the Layers concept. Conversely, the Tubes concept led to the highest work done, implying that aircraft flew significantly longer distances in this concept. As conflict resolution maneuvers increase flight distances, work done was increased with CR ON (not shown).

4) *Stability*

The stability of the airspace is analyzed using the DEP, see Figure 13. A negative DEP implies a net stabilizing effect of tactical CR whereby conflict chain reactions are outweighed by those that are solved without pushing aircraft into secondary conflicts, whereas positive values indicate a large number of conflict chain reactions, and thus airspace instability. Figure 13 shows that DEP is consistently zero for Tubes as it did not use tactical CR. For the other three concepts, the DEP for the Low demand scenario is similar and negative. However at higher demand levels, the DEP increases to positive values for the Full Mix and Zones concepts. This suggests that the maneuvering room available to solve conflicts decreases rapidly with increasing airspace density for these two concepts, making it progressively more difficult to



a) Effect of traffic demand
(with conflict resolution)



b) Effect of Conflict Resolution (CR)

Figure 11: Intrusion severity

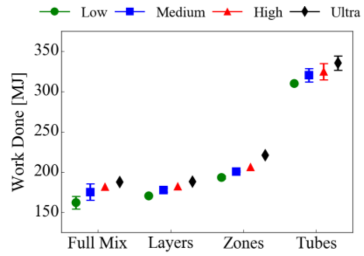


Figure 12: Work done per flight
(with conflict resolution)

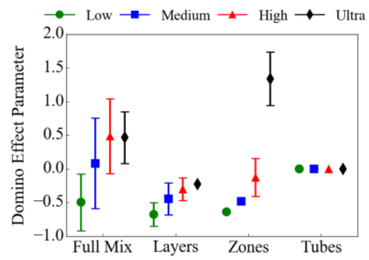
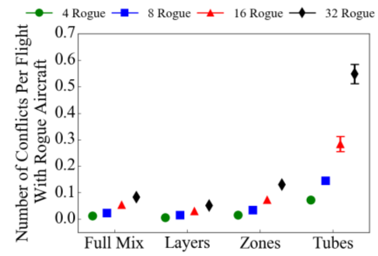
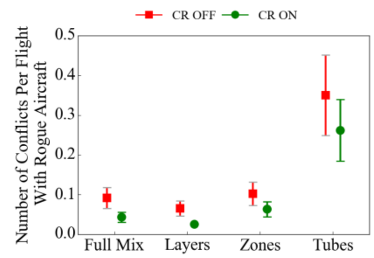


Figure 13: Domino Effect Parameter



a) Effect of traffic demand
(with conflict resolution)



b) Effect of Conflict Resolution (CR)

Figure 14: Number of conflicts per flight
with rogue aircraft

avoid intrusions without triggering additional conflicts. This is particularly true for the Zones concept which experienced a very large DEP increase between the High and Ultra demand scenarios.

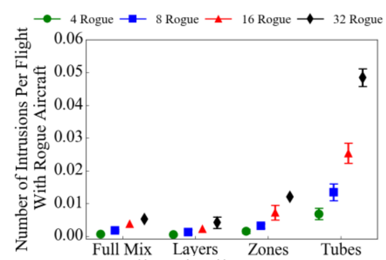
Although the DEP also increased with demand for Layers, it remained negative for the range of densities considered in this work. Thus the Layers concept is more able to prevent conflict propagation from occurring, and is better at assisting the MVP CR algorithm in solving the conflicts that do occur, by reducing conflict angles and relative velocities between aircraft cruising at the same altitude. This result explains the reduction of the number of conflicts noted earlier for Layers with CR ON.

B. Non-Nominal Experiment

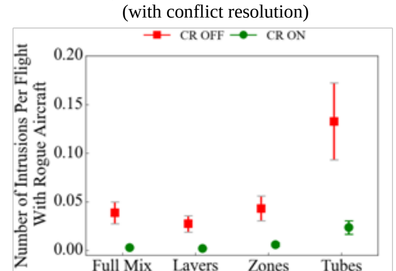
As stated earlier, the purpose of the non-nominal experiment is to compare the relative robustness of the different airspace structuring methods when subjected to increasing numbers of rogue aircraft. Since rogue aircraft primarily affect safety metrics, the following paragraphs discuss the properties of conflicts and intrusions between rogue and 2.7 million normal aircraft. Thus only incidents between rogue and normal aircraft are considered.

Figures 14 and 15 display the number of conflicts and intrusions per flight with rogue aircraft alone. Here, it can be seen that increasing the number of rogue aircraft increases the number of conflicts and intrusions for all concepts. The figures also show that the Tubes concept is considerably more affected by rouge aircraft than the other three concepts.

As the trajectories of rogue aircraft were not known in advance, aircraft in the Tubes concept used the MVP CR



a) Effect of traffic demand
(with conflict resolution)



b) Effect of Conflict Resolution (CR)

Figure 15: Number of intrusions per flight
with rogue aircraft (with conflict resolution)

algorithm to avoid conflicts with rogue aircraft alone. Since Tubes specified the horizontal and vertical flight profiles, speed resolutions were used. Figure 14b shows that these resolutions did reduce the number of conflicts with rogue aircraft for Tubes. Similarly, Figure 15b shows the number of intrusions for all concepts (including Tubes) improved significantly with CR ON. Finally, it is noted that intrusion severity was unaffected by the number of rogue aircraft for all concepts, although it did decrease with CR ON (not shown).

V. DISCUSSION

In this work, four concepts of increasing structure, named Full Mix, Layers, Zones and Tubes, were compared using fast time simulations to study the influence of traffic structure on capacity and robustness.

In contrast to previous research, which focused on either fully structured or fully unstructured concepts, the current results clearly indicate that the moderately structured Layers concept led to the best overall performance. Although unexpected, this result can be explained by the heterogeneous, or uniformly distributed, traffic demand scenarios used in this work. For such demand patterns, strict structuring of airspace, as for Zones and Tubes, increased flight distances and caused traffic concentrations at intersection points of the predefined topologies. On the other hand, the vertical structuring used by the Layers concept separated traffic with significantly different headings, without constraining the horizontal path of aircraft. This improved safety and stability by reducing relative velocities, compared to the unstructured Full Mix concept, without unduly affecting efficiency metrics. Therefore, it can be concluded that the optimum level of structuring is dependent on the traffic demand pattern, and for heterogeneous demand scenarios, a moderate degree of structure, as exemplified by the Layers concept, results in the highest capacity.

For the range of densities considered, the results also show that a switch between structuring methods is *not required* to maximize capacity. In fact, the results indicate the opposite, with a clear distinction between the two less structured and the two more structured concepts; while performance degraded with increasing demand for all concepts, it did so at a higher rate for Zones and Tubes. Furthermore, the results of the non-nominal experiment showed that the rigid topology and preplanned routes used by the Tubes concept reduced its resilience to the haphazard motion of rogue aircraft, while the flexible structuring of Full Mix and Layers revealed higher robustness to non-nominal events.

The poor performance of the Tubes concept stands in contrast with the positive results of structuring traffic using pre-defined trajectories found in literature. However, those `TBO' concepts generally used globally optimum trajectories, based on current airspace status and expected future demand. The Tubes concept, on the other hand, used an instantaneous planning approach that selected the shortest available route at the time of departure, to meet the high flexibility of operation needed to realize a future personal aerial transportation system. Regardless, the results of the current study show that pre-planned trajectories, which are common to both TBO and Tubes, are negatively affected by uncertainties. In the case of Tubes, these uncertainties, such as those caused by wind, made it difficult for aircraft to follow RTAs at waypoints along a planned route, resulting in a large number of unintended conflicts and intrusions.

VI. CONCLUSIONS

The results of the simulation experiments suggests that the structuring of traffic must take into account the expected traffic demand pattern to be beneficial in terms of capacity. For the heterogeneous demand patterns used here, a segmentation into altitude bands with similar headings, as for Layers, showed safety and stability benefits when compared to the unstructured Full Mix concept, while the strict structuring and predefined routing of the Zones and Tubes concepts only reduced performance. For the traffic densities considered, no reversal can be observed for this trend.

As a large number of conflicts and intrusions were found for all concepts, it is recommended to investigate novel conflict detection and resolution algorithms that cope with the limited maneuvering room available at extreme traffic densities. It is also recommended to further investigate the effects of parameters of the Layers concept, such as heading range per altitude band, on capacity.

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