Complexity Analysis of the Concepts of Urban Airspace Design for METROPOLIS Project

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[EN-A-062] Complexity Analysis of the Concepts of Urban Airspace Design for METROPOLIS Project

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Abstract: The world population is expected to grow further with a major increase in population living in urban areas. Exploiting the door-to-door concept to the full extent, a considerable part of conventional vehicles may be replaced by personal aerial vehicles. Cargo delivery system will the follow same philosophy using unmanned aerial vehicles. This brings up completely new challenges for future air traffic management in urban environments. The Metropolis research project investigates radically new airspace design concepts for the urban environments 50+ years into the future, which are extreme when compared to today in terms of traffic density, complexity and constraints. This work presents the results of simulation data analysis and a comparison of concepts of urban airspace design regarding organizational (complexity) metrics. The aim was to identify how the structure involved in the concept of urban airspace design influences the complexity of the traffic situation. In this work geometrical metrics, which are only linked to trajectory structure and not to the system used to process them, were used to measure complexity. A robust extension of proximity-convergence metrics as a compound metric has been developed for the ultimate concept evaluation.

Keywords: Future urban airspace design, Traffic complexity, Metropolis, Personal Air Vehicles, Unmanned Air Vehicle

1. INTRODUCTION

According to the United Nation Population office, the world population is expected to grow from 7 billion in 2011 to 9.3 billion in 2050 [1]. What is more critical, it is expected that the population living in urban areas will be doubled by that time reaching 6.3 billion [1]. Exploiting door-to-door concept to full extent, it is expected that a considerable part of conventional vehicles will be replaced by personal air vehicles (PAV) [2]. Amazon, Google, DHL and other's interested in a future delivery system using unmanned air vehicle (UAV) reveals that cargo delivery will follow same door-to-door philosophy [3] [4] [5]. This brings up completely new challenges for the future Air Traffic Management (ATM) in urban environments.

The focus of Metropolis research project has investigated radically new airspace design concepts for the urban environments 50+ years into the future, which are extreme when compared to today in terms of traffic density, complexity and constraints. The fundamental, but still practical, question underlying this research is structure-capacity relation: Does adding structure to the airspace design increase or decrease capacity? How does it influence traffic complexity, safety or efficiency? To have a better understanding of alternatives, four extreme concepts have been designed in the project [6], differing in the terms of structure and control involved. Ranging from a free-flight concept with no structure involved, called Full Mix, the level of structure is gradually increased in the Layers and Zones concept until a fully structured concept is reached in the Tubes concept. Proposed concepts were implemented in a simulation program called Traffic Manager (TMX) [7], a medium fidelity desktop simulation application designed for interaction studies of aircraft in present or future ATM environments, and were evaluated under different scenarios of Metropolis growth. In the end over 6 million flights were simulated for which data was logged for the post-processing.

This work presents the results of simulation data analysis and comparison of concepts of urban airspace design regarding organizational (complexity) metrics. Section 2 contains brief description of the concept of urban airspace design, as seen by the members of the Metropolis project consortium. Next, in section 3 an overview of the existing complexity metrics will be presented with description of the metrics used in this paper for the data analysis. A robust extension of proximity-convergence metrics as a compound metric will be also presented here. In section 4 some results of concept evaluation and analysis, regarding complexity of traffic situation they produce, are presented and discussed. Finally the main conclusions will be listed in section 5.

2. DESIGN OF AIRSPACE CONCEPTS

This section contains a brief description of the airspace concepts design. For the more detailed description please refer to [6].

Since the goal was not to design one ultimate concept, but rather investigate the structure-complexity relation, four concepts have been proposed: Full Mix, Layers, Zones and Tubes, with increasing structure in mind, from the one with no structure involved up to a fully structured airspace.

2.1. Full Mix concept

Underlying assumption of this concept, that any structuring of traffic flows decreases overall efficiency of the system, is justified by the fact that traffic demand in the future urban environment will most likely be unstructured (door-to-door philosophy). Moreover, Free Flight research had shown that today, spreading the traffic in airspace results in fewer conflicts, which are easy to solve by cockpit crew assisted by an Airborne Separation Assurance System (ASAS), which alerts and advises the crew [8].

In the Full Mix concept, aircraft are therefore permitted to use the direct path between origin and destination, as well as optimum flight altitudes and velocities, thus reducing flight costs. Tactical control of the traffic is handled, in decentralized fashion, by an automated ASAS developed in [9], allowing three types of resolution manoeuvres: heading, altitude and speed change, that ensures conflict-free trajectories.

2.2. Layers concept

Based on existing principle of hemispheric flight levels, airspace in the Layers concept is separated into different vertical bands (layers) that limit allowed heading ranges (Fig. 1).

Figure 1: Schematic view of the Layers concept

While flights are still allowed to use direct (shortest) routes, traffic segmentation reduces heterogeneity of the relative velocities between aircraft flying at the same layer, therefore reducing conflict rate. Remaining conflicts are solved using the same automated ASAS with combined heading and speed manoeuvres. Increased safety comes at the price of efficiency, as flights might not be able to use their optimal altitude.

2.3. Zones concept

Zones concept takes a further step in segmentation of the airspace compared to the Layers concept. It is based on the principle that traffic is homogeneous in different zones of airspace in which traffic moves at the same speed and follows the same global direction.

A distinction is made between circular and radial zones (Fig. 2). Circular zones are similar to ring roads and allow journeys in the outer area of the city. Radial zones serve as connections between these concentric zones and enables traffic to travel to and away from the city centre. Each zone is unidirectional as shown in the figure. Both types of zones segment airspace only in the horizontal plane, meaning that flights may use their optimal altitude. The horizontal path is computed at pre-tactical level using the A* shortest path algorithm. ASAS manoeuvres consists of speed and altitude change in that order of priority.

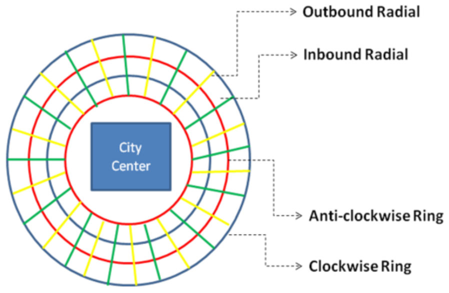


Figure 2: Top view of the Zone topology

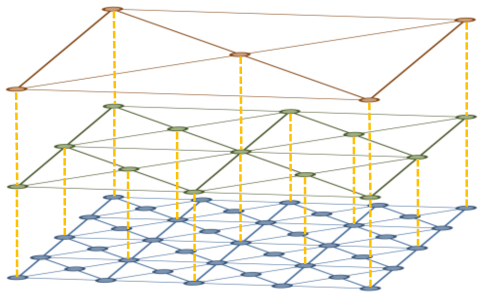


Figure 3: Fixed route Tubes concept topology

2.4. Tubes concept

Finally, the Tubes concept represents a fully structured airspace concept that is based on assumption that by providing conflict-free 4D tubes for each flight at pre-tactical level, both safety and efficiency of the flight could be increased.

In the Metropolis implementation of the Tubes concept a fixed route system has been designed, and time-based separation is used to have pre-planned conflict free routes. Tubes topology is based on a diagonal grid layout consisting of edges (tubes) and vertices (nodes) as on Fig. 3. In order to take advantage of the 3D airspace, a number of tube levels of decreasing granularity are foreseen. For route planning, the A* depth-first search algorithm is used to plan the shortest trajectory from origin to destination, prior to departure.

3. COMPLEXITY METRICS

This section presents the overview of the existing complexity metrics and describes metrics used in the Metropolis project to compare different concepts of urban airspace design.

3.1. Scope

Future urban transport is a safety critical system and maintaining safe separation between vehicles and with other obstacles is imperative for the system. When a conflict is detected, a resolution process is launched which, in certain situations, may generate new conflicts. This interdependency between conflicts is linked to the level of mixing between trajectories. In addition, uncertainty with respect to positions and speeds increases the difficulty of predicting future trajectories. The difficulty to control a system depends on both its sensitivity to initial conditions and interdependency of conflicts [10].

One of the research goals of the Metropolis projects was to identify how the structure involved in the concepts influence the complexity of the traffic situation. Measuring and comparing complexity of the resulting traffic situations, it is implicitly possible to compare how difficult it is to control a given system. In addition measuring the robustness will determine how much the system is invariant to changes in the initial conditions and also external influences.

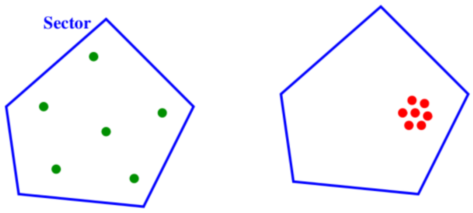
3.2. Overview of existing metrics

Research into air traffic complexity metrics has attracted considerable attention in recent years. Proposed models can be grouped into two groups: the first one focused on the air traffic control officer (ATCo) workload, and the second one focus on traffic complexity using automatic conflict resolution algorithms.

The first group of models has the objective to model the control workload associated with given traffic situations. The main approaches are as follows. In the model based on traffic level [11], the workload is defined as the proportion of control time (duration of control actions taken to resolve conflicts) over an hour. The queue-based model [12] considers a control sector as a system supplying service and the queuing theory is used to determine the maximum acceptable arrival rate for a sector. Models based on airspace structure [13] [14] estimate the capacity and complexity of a sector based solely on its structure (flight levels, routes, route intersections, etc.). In the context of operational control, the ideal option would be to find a metric which precisely measures the cognitive difficulty to manage a certain situations. There are various reviews that have been studying factors that impact upon controller workload and their relation to the workload experienced by a controller. The list of factors includes a number of traffic and airspace characteristics like: total number of airplanes, minimum distance between airplanes, number of changes in direction, speed and altitude, number of predicted conflicts, etc. In NASA, the Dynamic density model [15] [16] [17] has been developed as a weighted sum of traffic complexity factors. In [18] a multivariate analysis based upon simulation modelling is proposed. However, the listed models are not generalized and are linked to, and limited to, a specific sector structure and also sensitive to controllers used to infer the model.

Other approaches [19] [20] model the complexity of a traffic situation using automatic conflict resolution algorithms, for which the number of trajectory modifications required in processing a given situation is measured. These methods are highly dependent on the type of algorithm used to resolve conflicts.

Airspace concepts, presented in section 2, differ in the level of structure and in the way how the system is managed and controlled. For this reason, previously listed approaches are not suitable as it is necessary to use an intrinsic traffic complexity metric that is only linked to trajectory structure, and not to the system used to process them. In the next section some geometrical metrics, presented in [10] [21], are studied and a robust extension of proximity-convergence metric will be elaborated.



a) b)

Figure 4: Two situations of spatial distribution of airplanes [10]

3.3. Geometrical approaches

These metrics are calculated at a given instant using the positions and speed vectors of airplanes present in the chosen geographical zone. Each of these geometrical metrics exhibits a particular characteristic associated with the complexity of the situation.

3.3.1. Proximity indicator

The proximity indicator is used to characterize the geographical distribution of airplanes in the given volume of airspace. It allows us to identify spatial zones with high levels of aggregation in relation to their volume. Thus, for a constant number of airplanes in a sector, proximity is used to distinguish whether these planes are distributed homogeneously (Fig. 4a) or in the form of clusters (Fig. 4b).

For two airplanes i and j, the proximity is calculated by weighting coefficient given in formula (1).

$$Pr_{ij} = f(d_{ij}) = e^{-\alpha {d_{ij}}^2}, \tag{1}$$

where α is a parameter fixed by the user, and d_{ij} is normalized distance[1] between airplanes.

3.3.2. Convergence indicator

The convergence indicator is used to quantify the geometric structure of the speed vectors of airplanes in the given volume of airspace. Thus, for identical proximity values, the convergence indicator allows us to distinguish between converging and diverging airplanes (Fig. 5).

For two airplanes i and j, the level of variation of their relative distance is given by the formula (2), and they converge if, and only if, this level of variation is negative.

$$Cv_{ij} = \frac{\partial}{\partial t}(d_{ij}) = \frac{\vec{p}_{ij} \cdot \vec{v}_{ij}}{d_{ij}}, \tag{2}$$

where $\vec{p}_{ij}$ and $\vec{v}_{ij}$ represent relative position and speed vectors respectively.

3.3.3. Proximity-convergence metric

In reality, the risk associated with the convergence of a pair of airplanes also depends on the relative distance between them [21]. We must, therefore, simultaneously account for the speeds and relative distances of each pair of airplanes.

[1] Due to the fact that separation norms are not the same in the horizontal and vertical planes distance is normalized by their value (e.g. 5NM and 1000ft)

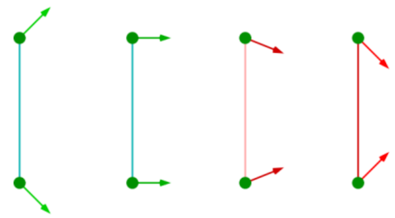


Figure 5: Converging/Diverging airplanes example [10]

For the given time and for each airplane under consideration, we open a spatial weighting window cantered on that airplane. Then, a complexity metric associated with referenced airplane, as in (3), is calculated adding together factors of all pairs of airplanes in the reference window.

$$\mathrm{Cx}_i = \lambda \sum_{j/Cv_{ij} \leq 0} -Cv_{ij} \cdot e^{-\alpha {d_{ij}}^2} \tag{3}$$

3.3.4. Robust extension of the metric

The geometrical approaches presented so far use noiseless observations, allowing us to generate instantaneous metrics. Due to possible changes in initial conditions (delay) and external issues (wind, disruptions, regulations, etc.), the stochastic aspect of observations needs to be taken into account in order to generate reliable (robust) metrics. To do this, trajectory observations, computed through simulation using a set of flight plans, are affected by noise, particularly in the temporal dimension. In the context of stochastic process theory, this phenomenon is known as clock shifting: “the trajectory continues to conform to the flight plan in the spatial dimension, but the position of the vehicles on the trajectory may be subject to significant deviations in the temporal dimension [22]”.

A robust complexity metric for a given airplane at a given time is computed taking into account all possible pairs of trajectory samples of observed airplanes existing in spatiotemporal window centred on referenced airplane (Fig. 6). Red lines in the figure indicate all possible pairs of samples for planes i and j. Complexity associated with an airplane i with respect to plane j at a given time t is computed as an time averaging of the proximity-convergence metric over all pairs of samples $(t - \Delta t \leq \tau \leq t + \Delta t)$ and it is given by formula (4).

$$\mathrm{Cx}_{ij} = \frac{1}{m_{ij}} \sum_{\tau_i = t-\Delta t}^{t+\Delta t} \sum_{\tau_j = t-\Delta t / r_{ij}^{\tau_i \tau_j} \leq 0}^{t+\Delta t} -Cv_{ij}^{\tau_i \tau_j} \cdot e^{-\alpha \cdot {d_{ij}^{\tau_i \tau_j}}^2} \tag{4}$$

where $Cv_{ij}^{\tau_i \tau_j}$ and $d_{ij}^{\tau_i \tau_j}$ represent variation of relative distance and normalized distance of airplane i at the time τ_i and airplane j at the time τ_j, while m_{ij} is number of sample pairs.

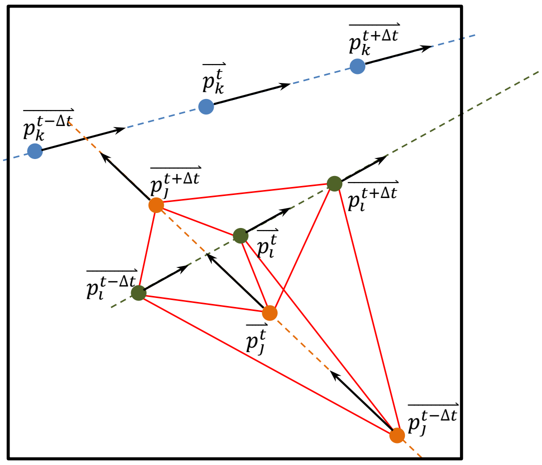


Figure 6: Spatiotemporal window
for the reference airplane $\overrightarrow{\boldsymbol{p}_i}$ and time $\boldsymbol{t}$

A robust complexity metric associated with airplane i is computed as the sum over all pairs of observed planes in the spatiotemporal window by (5).

$$\mathrm{Cx}_i = \lambda \sum_{j/Cx_{ij}\leq 0} \mathrm{Cx}_{ij} \tag{5}$$

Finally, the complexity of the given traffic situation at a given time is then calculated using the sum of the robust complexity metrics of the airplanes present in that geographical zone for the given time.

4. SIMULATION DATA ANALYSIS

To compare the four airspace concepts in terms of complexity, large-scale simulation experiments were performed. Proposed concepts were implemented in a simulation platform called Traffic Manager (TMX) [7], a medium fidelity desktop simulation application designed for interaction studies of aircraft in present or future ATM environments, developed by NLR.

4.1. Experiment design

The Metropolis scenarios were designed for a fictional city based on the present-day Paris 50 years in the future. Similar to other modern cities, the zoning also applies to the fictional Metropolis city that is divided into three major districts: city centre, inner ring and outer ring, with specific land-use.

Based on different predictions of the population growth (14-26 million) and travel demand assumptions, four scenarios were computed differing in the traffic volume: low, medium, high and ultra-high volume scenario. In addition to multiple traffic volumes, using business and residential zones, different traffic demand patterns were experienced during course of the day, respectively: morning, lunch and evening period scenario. Furthermore, the scenarios were simulated with and without the ASAS enabled, in order to study the effect of the airspace structure itself on the operations: structure's vehicle separation ability. Finally, taking into account that a probabilistic distribution function is used for flight's origin-destination pair computation, there were two repetitions of each designed scenario. In the end over 6 million flights were simulated for which data was logged for processing.

For more detail about simulation platform, design of the Metropolis city and traffic scenarios please refer to [6].

4.2. Results

Due to the fact that there are many independent scenario variables: traffic volume, period of the day, usage of ASAS, to analyse their effects it is necessary to perform multiple tests for which all except one variable would be fixed. Following sub-sections present the most relevant results of the concepts evaluation.

4.2.1. Comparison according to traffic volume

For this analysis all concepts have been compared according to four different traffic density levels: low, medium, high and ultra-high density, with ASAS enabled. Resulting complexity, for each concept-density pair, is the average of the six scenarios: three periods of the day with two repetitions.

Number of flights for each traffic density slightly differs depending on the period of the day and simulation repetition as a result of different demand patterns. Flight plans on average had 11,790 flights in low, 15,416 flights in medium, 18,550 flights in high, and 21,784 flights in ultra-high density scenario. Due to Tubes concept ability to delay or cancel a flight before take-off, in cases where there is no available space for a route clearance with sufficient spacing to ensure a conflict-free route, number of flights for Tubes concept is always lower compared to other concepts. To be able to compare the results of different concepts, computed complexity metric is divided by the total number of flight of respected scenario.

Fig. 7 shows the full complexity distribution (min, max, median values and interquartile range – IQR) for four airspace concepts and four traffic volumes.

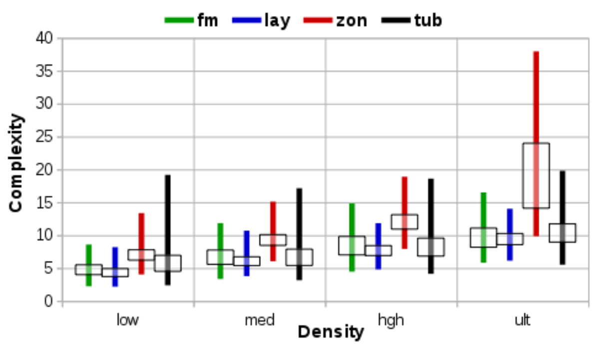


Figure 7: Complexity min, max value and IQR
in function of traffic volume

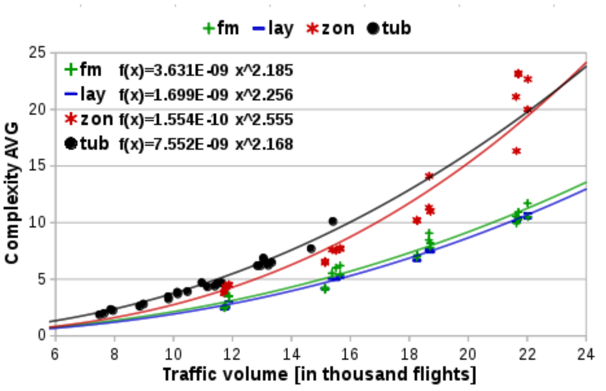


Figure 8: Complexity metric average value in function of traffic volume

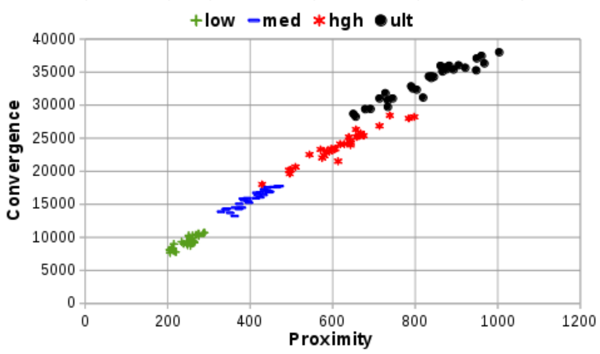


Figure 9: Layers concept convergence-proximity graph for the lunch period and different traffic volumes

The main conclusion, drawn from Fig. 7, is that traffic complexity, as expected, increases with traffic density for all concepts. The relationship between complexity and density is described by power function as on Fig. 8. Figure shows almost quadratic relation between complexity and density for all concepts except Zones concept. Zones has a steeper complexity function as a result of the Zones structure saturation at the higher traffic volumes. The complexity increase for all concepts is caused by increase of both: proximity and convergence, as shown in the Fig. 9 for the Layers concept[2]. This is explained by the fact that, with increase in traffic volume for the same airspace volume, vehicles come geographically closer increasing proximity metric, while trajectory intersections, that are greater in number, increase convergence metric.

Another observation from the Fig. 7 is the order of concepts sorted by the increasing level of complexity: Layers, Full Mix, Tubes and Zones, that is preserved with traffic volume. The order is based on comparison of average and median complexity values, which is relevant taking into account size of the confidence intervals that are rather small.

Layers and Full Mix concepts are both based on direct routing principle, with the difference that in the Layers concept cruising altitude is prescribed for a given heading. The fact that at each flight level, in the Layers concept, flights are homogeneous in flight direction reduces flight convergence compared to Full Mix concept. In addition, choice of cruising level, based on flight direction, increases the usage extent of the vertical dimension of the airspace. Additional vertical separation of flights reduces the traffic proximity, which in combination with lower convergence result in lower traffic complexity for Layers concept than Full Mix concept.

Having in mind the initial idea of the Tubes concept to design conflict-free 4D route of the flights at pre-tactical level (when flights are spawned), one could expect that Tubes concept performs the best in the terms of the traffic complexity. Taking into account absolute values of the complexity, indeed, Tubes concept result in traffic situation with lowest complexity. Due to flight cancelation, however, Tubes had the lowest traffic volume, which in turn results in higher complexity value per flight.

Finally, the Zones concept had significantly poorer performance regarding complexity compared to other concepts. The explanation for this is in the Zones concept structure design that consists of concentric rings and radials. The radials converge to the city centre causing higher concentration (higher proximity) of the traffic in the core city area. In addition, traffic is structured only in the horizontal dimension and not separated in the third dimension creating high convergence areas around structural crossing points (ring and radial intersections). This effect is more expressed at the higher traffic densities. It is expected that a different Zones concept design might result in a better traffic complexity. However, a general conclusion is that the introduction of the higher structure into airspace without the involvement of traffic management in general results in the higher traffic complexity.

The order of the concepts sorted by the increasing level of complexity doesn't change when robustness is included, as in Fig. 10. Results show a correlation between traffic density and robust complexity that increases with density, similarly to the general metrics case. Although order of concepts is not changed, Tubes concept complexity increases the most when robust metric is used. This leads to conclusion that Tubes concept has lower level of robustness compared to other concepts and therefore is more influenced by changes in the initial conditions (delay in particular). Additionally, performance of the Layers concept is decreased at the higher traffic volumes compared to Full Mix concept, and the two concepts are very similar when robustness is considered.

[2] Similar figures are found for other concepts and other period of day.

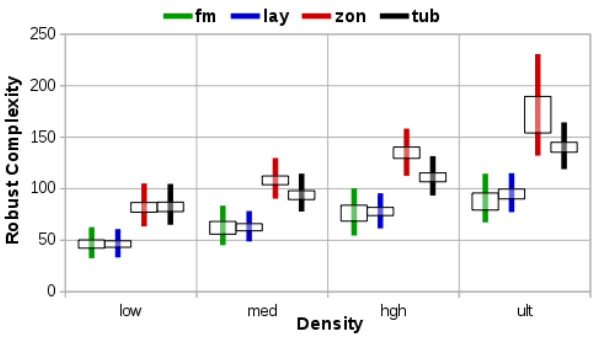


Figure 10: Robust complexity min, max value and IQR in function of traffic volume

4.2.2. Comparison according to period of the day

For this analysis, all concepts have been compared according to three rush-hour periods of the day: morning, lunch and evening period with ASAS enabled. As in previous analysis, complexity value for each concept-period pair is the average of the eight scenarios: four densities with two repetitions. In order to scale it, final complexity metric is divided by the total number of flight of respected scenario.

Morning period is characterized by a high demand for the commercial areas (people going to work) 60% of flights. This cause high inbound traffic in the morning as business areas are mostly located in the core city centre. As a difference, evening period is characterized by a high supply of commercial areas: commercial-residential (e.g. people going home) 55% of traffic and commercial-commercial (e.g. people going shopping after work) 20%, causing high outbound traffic. Finally lunch period has a more balanced demand patterns compared to other two periods.

Fig. 11 shows full the complexity distribution (min, max, median values and interquartile range – IQR) for four airspace concepts and three periods of the day. The first conclusion is that the order of the concepts sorted by the increasing level of complexity doesn't change with the period of the day and is the same as the order shown in previous analysis: Layers, Full Mix, Tubes and Zones. However complexity for all concepts changes with the period of the day caused by different traffic demand patterns.

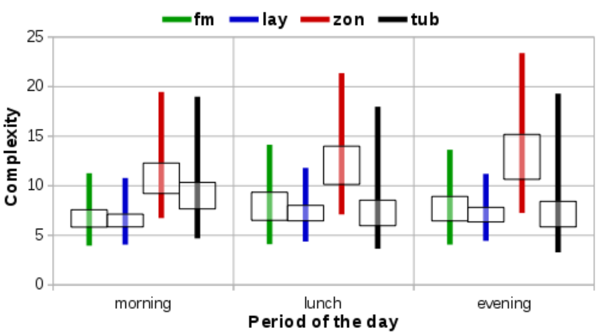
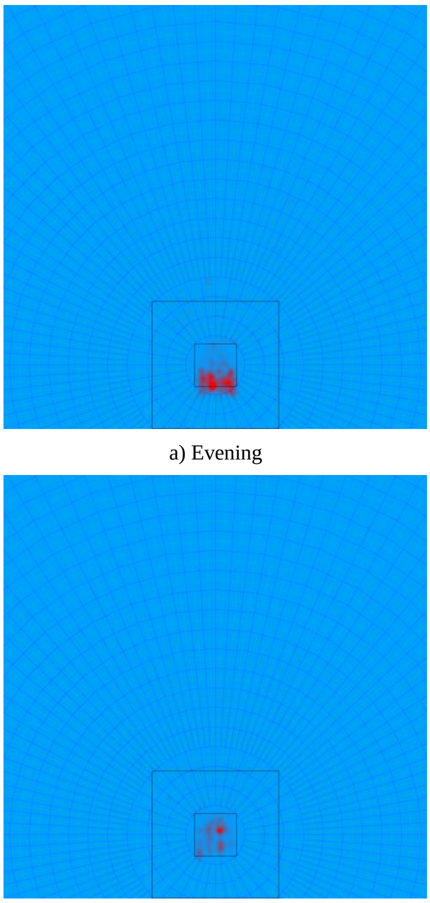


Figure 11: Complexity min, max value and IQR in function of period of the day

Concepts that doesn't regulate flights before take-off (ground delay program), like Full Mix, Layers and Zones, experience, in general, higher traffic complexity with the increase of supply of commercial areas. Due to inability to separate flights before take-off, high commercial areas supply results in high traffic density in the city centre immediately after flight departure, increasing complexity of traffic situation. This is even more expressed for the Zones concept with a fixed structure that reduces set of allowed conflict resolution manoeuvres types. Although there is a high demand for the commercial areas in the morning period, the resulting traffic complexity for the Zones is lower compare to the evening period as flights are partly sequenced by the structure before reaching the core city area (Fig. 12).

As opposite, the complexity of the Tubes concept doesn't increase with increase of commercial areas supply. This is explained with the ability of Tubes to delay a flight before take-off in order to ensure a conflict-free route. However, decrease of the Tubes traffic complexity is the result of rejected flights for which a conflict free 4D route wasn't available at the time when they had been spawned.



a) Evening

b) Morning

Figure 12: Zones concept complexity map of the most complex traffic situation

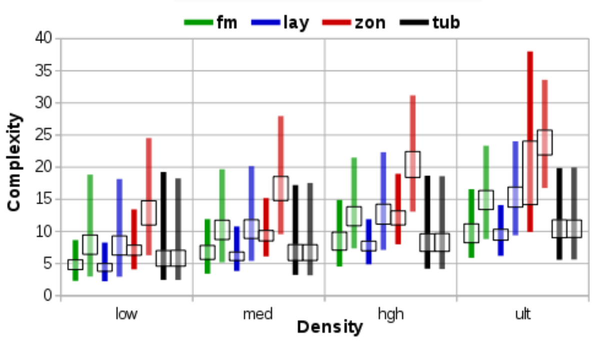


Figure 13: Complexity min, max value and IQR with/without ASAS enabled for different traffic volumes

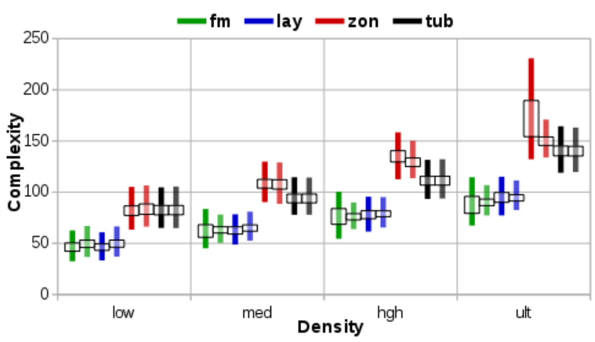


Figure 14: Robust complexity min, max value and IQR with/without ASAS enabled for different traffic volumes

4.2.3. Effects of the ASAS

All the previous analyses are based on simulated data with ASAS enabled. This section studies the effects of ASAS itself on the traffic complexity. Concepts are compared according to traffic density with and without ASAS enabled. Darker colours in the figures (left bars) represent scenarios with ASAS enabled; while lighter (right bars) represent scenarios without ASAS enabled. Complexity values are averaged over different periods of the day and repetitions.

Fig. 13 shows a summary of the concept comparison using general complexity metric. The general conclusion is that complexity increases if conflicts remain unsolved. This is expected as in conflicts aircrafts come closer together which the increases traffic proximity. Also intersecting routes in conflicts cause higher convergence of the traffic. In total this results in a higher traffic complexity.

Therefore Tubes concept is unaffected by the ASAS, since traffic separation is maintained in the route planning phase and therefore there are no additional conflicts left to be solved by the ASAS. The order of remaining concepts sorted by the increasing level of complexity remains almost unchanged when ASAS is disabled: Layers, Full Mix and Zones. For all three concepts, there is around 70% increase of traffic complexity without ASAS for the low traffic volume and the percentage decreases with increase of traffic volume. This means that efficiency of the ASAS is decreased with increase of traffic density (once volume approaches airspace capacity).

Additionally, it is observed that Full Mix concept performance is improved compared to Layers with the increase of traffic density without ASAS. This is reasonable, since the traffic is more distributed over available airspace in the fully unstructured concepts (like Full Mix) compared to structured concepts, when there is no control of the traffic (pre-departure delay, ASAS, etc.).

Fig. 14 shows a summary of the concept comparison using robust complexity metric. The most distinct difference compared to general metric case is that traffic complexity increase slightly, if at all, without ASAS. The explanation is in the fact that although the flight intrusions are more severe without ASAS, due to domino effect (new conflicts that are result of previous conflict resolution manoeuvres) there is greater number of conflicts detected when ASAS is enabled. Greater number of conflict resolution manoeuvres results in traffic situation that is less predictable therefore harder to control. This increases complexity with ASAS enabled when robustness is included. Traffic situation without ASAS is more predictable and therefore more robust.

Further, at the higher traffic densities, robust complexity for the Zones without ASAS is even lower than when ASAS is enabled. There are two reasons for this behaviour. The first is Zone structure that reaches its limits at the higher densities. And the second is CD&R algorithm that is unable to properly solve conflicts, due to limited set of available manoeuvres for the Zones, and fault coordination with traffic merging algorithm.

5. CONCLUSIONS

Based on the different scenarios and the different complexity metrics the following conclusions are made.

When general metrics are considered, list of the concepts ordered by increasing level of complexity is as follows: Layers, Full Mix, Tubes and Zones concept. This order is preserved at all periods of the day and for all traffic densities.

The traffic complexity increase due to traffic density shows an almost quadratic relation for all concepts except Zones. Concepts without flight regulation before take-off (Full Mix, Layers and Zones) experience higher traffic complexity with the increase of commercial areas supply (evening period).

Tubes performance apparently increases with increase of commercial areas supply due to increased number of rejected flight for which a conflict free 4D route wasn't available at the time when they had been spawned.

The order of the concepts is not changed when robust complexity metric is considered. Even thought, Tubes concept is the most influenced by the robust complexity metric. This is due to the fact that robustness considers the stochastic aspect of observations which are affected by the noise, particularly in the temporal dimension. Since time is the main method of flight separation in the Tubes concept, the fixed 3D structure causes an additional convergence of the flights rather than separating flights. This leads to conclusion that Tubes concept has lower level of robustness compared to other concepts and therefore is more influenced by changes in the initial conditions (delay in particular). Additionally, performance of the Layers concept is decreased at the higher traffic volumes compared to Full Mix concept.

The Full Mix, Layers and Zones concepts show an almost proportional increase (around 70%) in complexity when ASAS is disabled. The efficiency of the ASAS is decreased with increase of traffic density (once volume approaches airspace capacity). Due to domino effect, there is greater number of conflict detected when ASAS is enabled, and accordingly there is greater number of conflict resolution manoeuvres. As a result traffic situation is less predictable with ASAS, therefore less robust and harder to control. On the other hand, traffic situation without ASAS is more predictable and therefore more robust.

The final conclusion is that, regarding complexity, the less structured concept, like Layers and Full Mix, performs better than structured concepts. This result is independent to the test scenarios and the complexity metrics used in the analysis. Taking into account performed tests, the Layers concept was chosen as the best concept regarding complexity. Its performance remains stable for all periods of the day and all traffic densities. Therefore, it represents a good balance between a fully unstructured and a structured concept, where the structure involved separates flights compared to the unstructured concept (Full Mix) but doesn't cause a traffic concentration as in structured concepts (Zones, Tubes). However it shows less robustness at higher traffic densities compared to Full Mix concept, which requires further testing.

ACKNOWLEDGMENTS

This research received funding from the Seventh Framework Programme of the European Commission under grant number 341508 (Metropolis).

The authors would like to thank other participants in the Metropolis project: Bruno Lamiscarre, Georges Mykoniatis (ENAC), Joost Ellerbroek (TUD), Dennis Nieuwenhuisen, Pim van Leeuwen, Roalt Aalmoes, Marieke Suijkerbuijk (NLR), Oliver Schneider, Stefan Kern (DLR) for their valuable contribution to: the design of the concepts and their implementation, assistance with the execution of the simulation runs, metrics definition, and helping with project management tasks.

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