Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)

Metropolis: Relating Airspace Structure and Capacity for Extreme Traffic Densities

Emmanuel Sunil[1], Jacco Hoekstra[1], Joost Ellerbroek[1], Frank Bussink[2],
Dennis Nieuwenhuisen[3], Andrija Vidosavljevic[4] and Stefan Kern[5]

[1]Control and Simulation, Faculty of Aerospace Engineering, TU Delft, Delft, The Netherlands
[2]Cockpit and Flight Operations, National Aerospace Laboratory (NLR), Amsterdam, The Netherlands
[3]ATM and Airports, National Aerospace Laboratory (NLR), Amsterdam, The Netherlands
[4]Laboratory of Applied Mathematics, Ecole Nationale de l'Aviation Civile (ENAC), Toulouse, France
[5]Institute of Flight Guidance, Deutsches Zentrum für Luft- und Raumfahrt (DLR), Braunschweig, Germany

Abstract—**Personal and unmanned aerial vehicles have received increasing media attention over the last decade. As a result of the growing excitement for these two aircraft types, many within and outside the aerospace industry envision a future in which large numbers of small aircraft fly over urban areas. With this vision for the future, the question arises what would be required, in terms of airspace organization, to make this feasible, or indeed, if it will be possible at all. In this context, the Metropolis project aims to investigate the influence of airspace structure on capacity, complexity, safety, and efficiency for high-density airspace. To this end, four airspace concepts, ranging from a decentralized direct routing concept, to a highly structured tube network using 4D trajectory-based operations, have been considered. The four concepts were compared by means of large-scale simulation experiments, for multiple scenarios that are extreme when compared to current air traffic densities. This paper presents an overview of the Metropolis project with a focus on the project objectives, design and implementation of airspace concepts, and preliminary simulation results.**

Keywords - airspace structure, urban airspace design, air traffic control, free flight, 4D trajectory based operations, Personal Aerial Vehicles (PAVs), Unmanned Aerial Vehicles (UAVs)

I. INTRODUCTION

Since the early days of flight, Personal Aerial Vehicles (PAVs) have been proposed as an alternative to automobiles to solve the ever-rising road traffic congestion problems affecting most urban areas [1]. Despite many failed attempts, recent successful test flights of road-able aircraft designs, by PAL-V in the Netherlands and by Terrafugia in the United States, have revived interest towards PAVs [2]. Similarly, Unmanned Aerial Vehicles (UAVs) have become increasingly popular as they can be used for a wide variety of applications that previously required more expensive manned aircraft [3]. At present, however, large-scale commercial UAV operations are still limited by most aviation authorities [4]. This is expected to change in the near future, particularly with companies such as Amazon and Google pushing towards the introduction of automated cargo delivery UAVs [5], [6]. In fact, the rapid emergence of PAVs and UAVs over the last decade has led many within and outside the aerospace industry to view these vehicles as important components of a future air transportation system. However, before this vision can materialize, an airspace system that can safely separate and organize large numbers of aircraft is required [7].

The difficulty of safely separating a large number of aircraft can be reduced through careful design of airspace structure. There is, however, no clear consensus yet on how this should be done. There are, for instance, several studies which argue that a well-defined and structured approach is required to handle high traffic densities [8], [9]. In such an approach, pre-planned conflict free routes are negotiated between the airspace user and the Air Navigation Service Provider (ANSP). In addition to the three-dimensional path that aircraft are required to follow, the negotiated trajectories include arrival time constraints at waypoints along the route. This way, uncertainties regarding the positions of aircraft can be reduced, allowing for closer packing of several trajectories, and thus, increasing capacity levels over current operations.

In contrast, Free Flight studies have found evidence of the opposite: the Free Flight (or unmanaged airspace) concept has been shown to allow for higher traffic densities by reducing traffic flow constraints and structure [10], [11]. Here, aircraft are allowed to fly user-preferred (often direct) routes, while separation responsibility is delegated to each individual aircraft by means of airborne Conflict Detection and Resolution (CD&R) automation. As a result, traffic is more evenly distributed over the airspace, thus reducing the number of potential conflicts, thereby increasing both capacity and safety [12], [13].

The above dichotomy suggests that airspace structure and capacity are tied together. What is as yet unknown, however, is the relationship between these two variables; i.e., does more or less structuring lead to higher capacity? Or, is there perhaps a transition point, where a further increase in capacity will require a switch from one approach to the other? The goal of the Metropolis project, a research initiative funded through the Seventh Framework Programme of the European Commission,

---

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

is to answer these questions within the context of a future urban air transportation system integrating high volume PAV and UAV operations. To study how capacity varies along the dimension of airspace structure, four concepts, ranging from a completely unstructured Free-Flight-inspired concept, to a highly structured tube network using pre-planned 4D trajectories, have been defined. These concepts were compared with the aid of large-scale simulation experiments using four extreme traffic scenarios that ranged up to a density of 30,000 aircraft per 10,000 square nautical miles. Subsequently, the capacity-structure relationship was inferred by comparing the concepts across the four demand scenarios in terms of safety, efficiency and traffic complexity metrics.

This paper presents an overview of the ongoing Metropolis project and is structured as follows. In section II, an outline of the consortium's vision for the future of urban air transportation is described. Next, the design and implementation of the four airspace concepts are discussed in section III and IV respectively. In sections V and VI, preliminary simulation results are presented and discussed. Finally, the main conclusions are listed in section VII.

II. METROPOLIS SETTING FOR 2050 AND BEYOND

To provide sufficient grounding for the scenarios in this project, their definition considered (extrapolations of) current trends in aviation technology, demographics, and societal demand for PAVs and UAVs. In this section, the main assumptions underlining the consortium's expectations for the future, and the resulting influence on simulation scenarios, are discussed.

Assumption 1: Continued population growth and urbanization leads to the formation of mega-cities

According to the United Nations, the global population is expected to increase to over nine billion by 2050 [14]. Moreover, a greater proportion of the population is expected to migrate to cities, leading to rapid urbanization of rural areas, as well as the merging of towns and cities to form vast metropolitan areas. Similar to contemporary cities, these 'mega-cities' of the future will consist of one or more densely populated urban cores that are surrounded by less dense suburban areas, with high levels of commuting traffic and congestion between these two areas.

The Metropolis simulation scenarios use population size (and per capita demand) as a starting point to estimate traffic volumes. To this end, a city the size of Paris, with a projected population of 14 million in 2050, is used as a baseline scenario [15]. Three additional scenarios are defined with population sizes of 18, 22 and 26 million inhabitants, such that the relation between airspace structure and capacity can be evaluated by studying multiple traffic demand levels. It should be noted that although these population sizes are not chosen to represent predictions for a particular city, however, they are nevertheless similar to present day populations of the following urban areas: Beijing (18.2 million), Shanghai (21.7 million) and Delhi (26.7 million) [16].

Assumption 2: Vehicles for personal air transport have become widely available

As mentioned earlier, several PAV variants are already under development, with some models currently undergoing flight-testing and certification [7]. Given the current pace of development, the technical challenges to realize a viable PAV are likely to be met within the time frame of the Metropolis scenarios (2050+).

Although the current work does not focus on vehicle-related technical specifications, it is considered likely that both conventional and Vertical Take-Off and Landing (VTOL) PAVs reach the market place. Thus, it is assumed that a small runway will be required for terminal operations, and more importantly, horizontal velocity needs to be maintained to stay airborne, further constraining airspace design. Due to space restrictions in urban areas, raised platforms above existing streets seem the most feasible solution for these 'PAV-ports', and a large number of these will need to be located throughout a city to allow near 'door to door' operations.

For the creation of Metropolis scenarios, accurate market predictions for PAVs are not required. Since the project centers on the influence of airspace structure on capacity, it is only necessary to ensure that sufficient traffic volume is simulated to study this relationship. Nonetheless, it was assumed that one in six cars would be replaced by PAVs. Using the per capita ownership of cars in Paris [17], and a PAV market penetration of 16.7%, approximately 4.0% of the population is expected to use PAVs by 2050.

Assumption 3: Unmanned aircraft will be used for cargo delivery

Autonomous cargo delivery UAVs are already used within the militarily domain [18]. Given the public appetite for ever-shorter order-to-delivery times, commercial introduction of similar UAVs may occur within the near future. In fact, several companies, including Amazon, Google and DHL, are already prototyping quad-copter variants for express delivery of lightweight cargo from existing distribution centers. These UAVs are likely to serve local communities surrounding a distribution center, and improvements in payload capability may allow for multiple deliveries during a single flight.

Future demand for UAV delivered packages is estimated for the Metropolis scenarios using current trends in e-commerce. Literature shows that the average French citizen orders 13.4 parcels per annum, and 48% of these are categorized as express deliveries [19]. Additionally, Amazon estimates that 86% of the orders it receives are suitable for UAV delivery [20]. Taking the net effect of these statistics, the per capita demand for UAV deliveries is taken as 5.5 packages per annum.

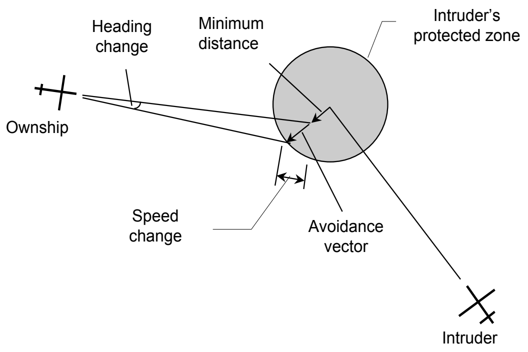

Figure 1: Geometrical conflict resolution approach of the Modified Voltage Potential (MVP) algorithm [21]

III. DESIGN OF AIRSPACE CONCEPTS

The primary goal of this research is to investigate the effect of airspace structure on capacity. To empirically study this relationship, four airspace concepts, named Full Mix, Layers, Zones and Tubes, have been defined using increasing levels of structure to implicitly separate and organize traffic. This section begins by describing some elements that are common to all concepts. Subsequently, the conceptual design of each airspace concept is discussed individually.

A. Common Concept Elements

1) Airborne Separation Assurance System:

In the Full Mix, Layers and Zones concepts, tactical Conflict Detection and Resolution (CD&R) tasks are delegated to each individual aircraft, where they are handled by an automated Airborne Separation Assurance System (ASAS). The current study employs the ASAS implementation as proposed by Hoekstra because of its demonstrated resolution capabilities in several complex multi-aircraft scenarios [12],[21]. While adaptation (or redesign) of an ASAS to make it able to cope with extreme densities would be an interesting study in itself, this was not the goal of Metropolis, as it is focused on airspace design.

In this implementation, conflict detection is performed by state-based extrapolation of traffic positions, within a prescribed 'look-ahead' time, using traffic transmitted state information (position, speed and heading). The Modified Voltage Potential (MVP) algorithm is used to resolve conflicts in a pairwise fashion. This method results in implicit cooperative resolution strategies, where the distance between the conflicting aircraft at the Closest Point of Approach (CPA) is increased to (at least) the minimum separation requirements, see Fig.1. Based on initial test runs, a look-ahead time of sixty seconds was selected, in addition to separation margins of 250 meters horizontally, and 50 meters vertically.

The types of resolution maneuvers (heading, altitude and speed) allowed are airspace concept dependent and is discussed in the relevant subsection below.

2) Common Airspace Limits for Concept Design

To simplify simulations, and to facilitate comparison between concepts, both PAVs and UAVs are assumed to fly above buildings. Due to safety and privacy considerations this might well turn out to be the case. To separate urban air traffic from higher and faster flying commercial aircraft, the lower airspace region between 1100 ft and 6500 ft was selected for designing the airspace concepts. Additionally, the available airspace has been further segmented to separate PAV and UAV operations due to the significant performance and operational differences between these aircraft types (door-to-door vs. local cargo deliveries), as shown in Fig. 2**.**

As a result of the airspace segmentation pictured in Fig. 2, the take-off and landing phases of flight are expected to be common for all concepts, and as such are not expected to cause significant capacity variations between the concepts. The concept descriptions that follow therefore focus on the cruise phase of flight.

B. Concept 1: Full Mix

The Full Mix airspace concept can be most aptly described as 'unstructured airspace', where traffic is subjected to only physical constraints, such as weather, static obstacles and terrain. As traffic demand is often unstructured, the Full Mix concept assumes that any structuring of traffic flows decreases overall efficiency of the system, and that safety is actually improved by the spreading of traffic that results from self-regulation. 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, to reduce fuel burn and other related trip costs. Since Full Mix imposes no restrictions to the path of aircraft, combined heading, speed and altitude conflict resolution maneuvers are used to reduce deviations from the optimal route, for all flight phases.

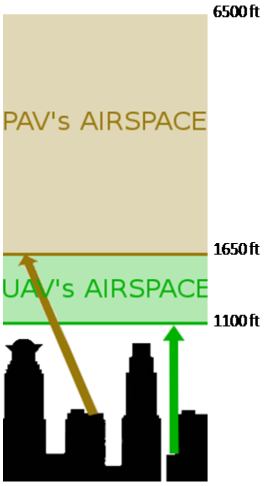

Figure 2: Airspace region available for concept design. PAV and UAV operations are separated by airspace to take into account the performance differences between these aircraft types.

C. *Concept 2: Layers*

The Layers concept can be seen as an extension of the hemispheric rule [22]. Here, the airspace is segmented into vertically stacked bands, where each altitude layer limits horizontal travel to within an allowed heading range. This segmentation of airspace is expected to reduce the probability of conflicts by limiting the relative velocities between aircraft cruising at the same altitude. However, this increased safety comes at the price of efficiency; while direct horizontal routes are still possible, the vertical flight profile is dictated by the relative 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 heading while climbing or descending to their destination altitude.

Fig. 3 displays a schematic view of the Layers concept as implemented in the Metropolis project. It can be seen that that each layer corresponds to a heading range of 45^0 and has a height of 300 ft. With these dimensions, two complete sets of layers fit within the Metropolis airspace. This way, short flights can stay at low altitudes while longer flights can improve fuel burn by flying at higher altitudes. This is expected to mitigate the efficiency drop of predetermined altitudes in this concept.

As mentioned earlier, the Layers concept also uses the MVP conflict resolution algorithm. While combined heading, speed and altitude resolutions are allowed for climbing and descending traffic, for cruising aircraft, altitude resolutions may create new conflicts with traffic in adjacent layers. Resolutions are therefore limited to combined heading and speed maneuvers for cruising aircraft.

D. *Concept 3: Zones*

Similar to Layers, the Zones concept segments traffic based on similarity of travel direction. However, while the Layers concept structures traffic irrespective of city topology (and only vertically), the Zones concept takes into account the layout of the city in the design of its structure.

Figure 3: Schematic view of the Layers concept. Here, each altitude band corresponds to a prescribed heading range, reducing the relative velocities between aircraft at the same altitude. Two complete layer sets have been defined within the Metropolis airspace.

Figure 4: Top down view of the Zones topology, which is designed to take into account the layout of a city.

A top-down view of the Zones concept is illustrated in Fig. 4. Here, two major zone types can be discerned: circular and radial zones. Assuming a concentric shape for a Metropolis city, the circular zones are used in a similar fashion to ring roads in contemporary cities. The radial zones function as connections between these concentric zones and facilitate traffic towards and away from the city center. Both types of zones segment airspace in the horizontal plane, there is no vertical segmentation. Instead, altitude is selected flexibly, based on the planned flight distance between origin and destination, while the horizontal path was computed using the A* shortest path algorithm [23].

For this concept, MVP is used 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.

E. *Concept 4: 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 designed for Metropolis can be thought of as a graph with nodes and edges, see Fig. **5**. 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 one aircraft in the vertical and horizontal plane.

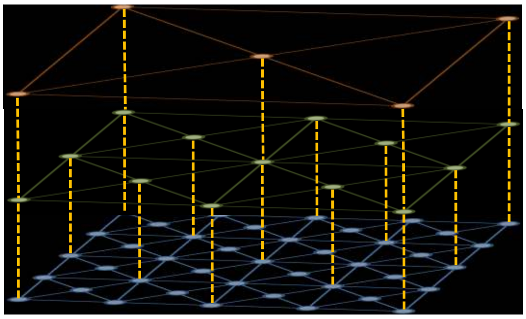

Figure 5: An example tube topology with three layers of decreasing granularity. The dashed yellow lines are used to indicate the placement of nodes above each other. Tubes are bi-directional.

To provide multiple route alternatives, a total of twelve tube layers are placed above each other with decreasing granularity. Short flights profit from a fine grid at the lowest layer, while at the same time, longer flights benefit from longer straight tubes in the higher layers. A lateral offset is used between layers to allow for smooth climb and descent paths. As a result, aircraft are only allowed to climb through one layer at a time.

Unlike the other concepts, the Tubes concept uses time-based (4D) separation of aircraft to ensure safety within the network. This mode of separation dictates that when an aircraft passes a node, it will “occupy” this node for some interval. Within this occupancy interval no other aircraft is allowed to pass this node. For each node an interval list is maintained that keeps track of the times at which a node is expected to be occupied. New flights may only pass the node when its necessary interval is completely free. To ensure that separation at the nodes ensures separation within tubes aswell, all aircraft within the same layer are required to fly at the same velocity, and the prescribed speed increases with the altitude of the layer.

For route planning, the A* depth-first search algorithm is used to plan the shortest trajectory from origin to destination, prior to departure [23]. To ensure a conflict free trajectory, the occupancy of each node along a proposed route is checked. If not, the node is discarded and the algorithm backtracks to find another available solution. If no route can be found, a pre-departure delay is applied in multiples of 10 seconds until a conflict free route is found.

IV. SIMULATION DEVELOPMENT AND EXPERIMENT DESIGN

To compare the four airspace concepts in terms of capacity, large-scale simulation experiments were performed. This section describes the development effort undertaken to implement the concepts onto an existing simulation platform, the generation of high-density traffic scenarios, and the design of two separate experiments.

A. Simulation Platform and Concept Implementation

The Traffic Manager (TMX) software, developed by the National Aerospace Laboratory of the Netherlands (NLR), is used as the simulation platform in this research. TMX is a medium fidelity desktop simulation application designed for the investigation of novel ATM concepts. It is capable of simulating up to 5000 aircraft simultaneously, and has a wide range of features including several CD&R algorithms, 4D Flight Management System (FMS) guidance, and extensive data logging functions. For a complete overview of TMX capabilities, the reader is referred to [24].

The four airspace concepts were implemented in TMX by modifying the trajectory planning functions taking into account the constraints of each concept. For instance, the direct horizontal path and the most fuel efficient altitude were selected for the Full Mix concept, while the for the Tubes concept, the A* algorithm was used to determine the shortest conflict free trajectory through a pre-defined tube network.

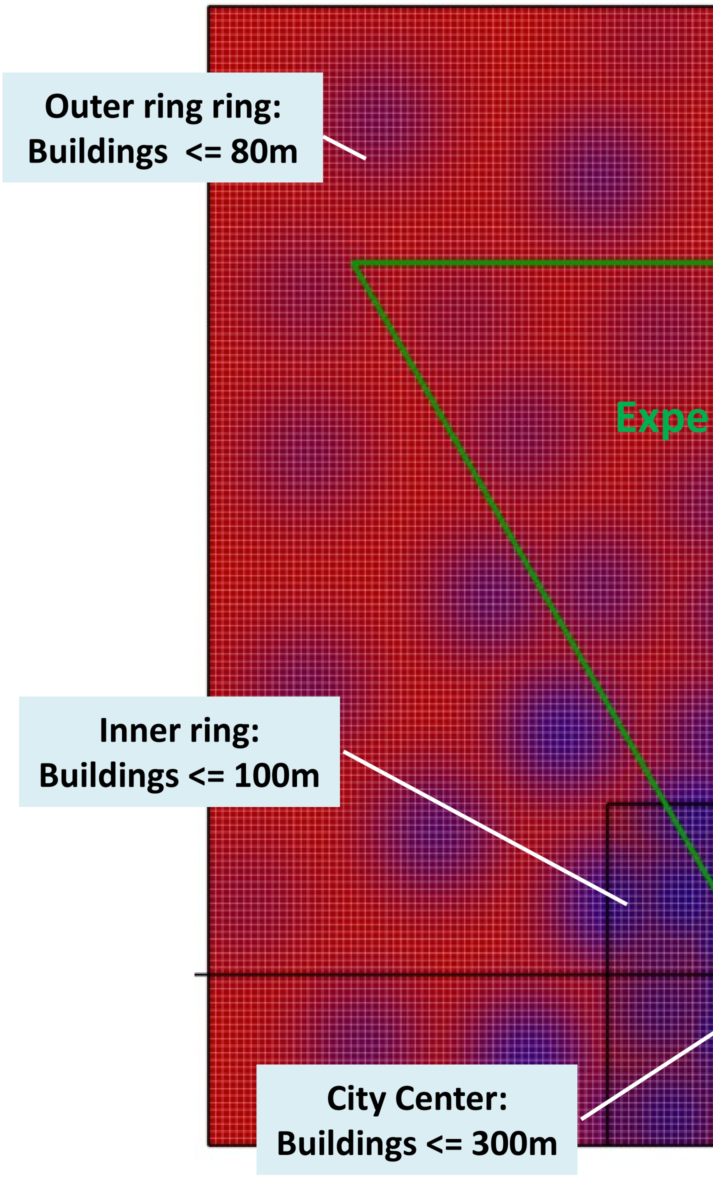

Figure 6: Map of the fictional Metropolis city. Each city block is characterized as either commercial (blue) or residential (red). The green trapezoid represents the experiment area where safety metrics are logged.

Another important aspect of simulation development was the modeling of PAV and UAV vehicle dynamics. For this purpose, parameters of existing vehicle models in TMX were adapted to match the performance specifications available for several current PAVs and UAVs. Additionally, VTOL aircraft were simulated using helicopter dynamics for take-off and landing, while fixed-wing models were used for cruising, climbing and descending flight phases. A total of three VTOL aircraft, two PAVs and one UAV, and a conventional PAV were used in the traffic simulations.

B. Design of the Fictional Metropolis City

As the Metropolis scenarios focus on a future urban air transportation system, a fictional city was designed to represent the simulation physical environment.

1) City Map

To accommodate the population sizes of the four scenarios (14-26 million, see section II), a large fictional city, similar in size to present-day Paris, was designed. A 40 x 40 nautical mile portion of the city, representing approximately 50% of the total city area, was used to simulate traffic, see Fig. 6. Similar to other modern cities, the fictional Metropolis city is divided into three major districts: city center, inner ring and outer ring. Moreover, to simulate realistic urban traffic patterns, city blocks were characterized as either commercial or residential. This way it is possible to, for example, simulate morning rush hour as traffic converging to commercial areas.

While traffic was simulated and performance data was logged throughout the simulation area, safety related metrics were only logged within a trapezoidal 'experiment area', see Fig. 6. This region, with an area of 448 NM^2, has been shaped and sized such that the area ratio between the three city districts are the same for the experiment area and the full Metropolis city (not shown).

2) Infrastructure

The only infrastructure considered were PAV and UAV landing strips, as these served as the origin and destination points for traffic. For PAVs, 1600 runways were evenly distributed over the simulation area, with half defined as VTOL capable. Cargo UAVs originated from dedicated distribution centers, and delivered packages to buildings within a six nautical mile range. As a result of the airspace segmentation illustrated in Fig. 2, interaction between PAVs and UAVs only occurs during the take-off and landing flight phases. Therefore, to study this interaction, two cargo distribution centers were defined near the city center.

C. Traffic Scenarios

The traffic volumes for four scenarios were computed using the population growth and per-capita demand assumptions stated in section II, as well considering the size of the Metropolis simulation area relative to the total city. Subsequently, the instantaneous number of PAVs for each scenario was determined by setting the average nominal trip time to fifteen minutes, see Table 1. Here, the average hourly package demand for the two cargo distribution centers under consideration is also displayed.

In addition to multiple traffic demand volumes, it is also necessary to consider different demand patterns when assessing the airspace concepts. Within the context of an urban environment, the morning rush hour is characterized by a high proportion of commuting traffic originating from residential areas and converging towards commercial regions of a city. On the other hand, during the evening rush hour, the opposite is true, and a vast majority of the traffic is of the commercial-residential type. 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.

D. Simulation of 'Real-World' Phenomena

To prevent a deterministic comparison of concepts, wind and rogue aircraft were added to the scenarios to improve the realism of the simulation results.

1) Wind

Wind was modeled as a uniform and time-invariant vector field with random direction and speed. Although predicted wind information is often used for trajectory optimization in real-life operations, its effects on aircraft flight paths was deliberately omitted from the simulation's trajectory planning functions. In fact, wind was added to study how uncertainties in aircraft operations, which result in deviations from the planned trajectory, affect the safety of a concept.

TABLE 1: INSTANTANEOUS PAV TRAFFIC VOLUME AND AVERAGE HOURLY PACKAGE DEMAND FOR THE METROPOLIS SCENARIOS

Scenario	Instantaneous PAV Traffic Volume	Average Hourly UAV Package Demand
Low	2,625	1,380
Medium	3,375	1,780
High	4,125	2,180
Ultra	4,875	2,580

2) Rogue Aircraft

Just as with road traffic, it is reasonable to expect some aircraft to not conform to airspace routing requirements for a wide variety of reasons, including technical failure and/or deliberate rule-breaking. To model this effect, for selected scenarios, 'rogue aircraft' were introduced at random time intervals. These aircraft were simulated to be seven times larger than other PAVs, and flew haphazardly through the airspace with continuously varying heading and altitude. By comparing simulations with and without rogue aircraft, it is possible to determine the effect of structure on the robustness of an airspace concept to non-nominal occurrences.

E. Simulation Simplifications

To reduce the complexity of the simulation development effort, two simplifications were made. While these simplifications are not expected to affect relative comparisons between concepts, they are stated below for completeness.

1) Take-off and Landing Simulation

Since take-off and landing procedures were considered to be similar for all concepts, the focus of the simulations was on the cruise, climb and descend flight phases. Furthermore, due to the complexity of managing runway capacity, it was decided to delete aircraft at a pre-determined time prior to the Expected Time of Arrival (ETA) at the destination runway. However, to take into account the effect of airspace structure on approach sequencing, the time interval between two successive arrivals was logged for all runways, and analyzed for unacceptably short intervals. It should be noted that all other flight phases were simulated.

2) UAV Operations

As mentioned earlier, UAVs are expected to operate within the vicinity of cargo distribution centers. Given the short flight distances, it was decided to use the Full Mix concept to simulate UAV operations regardless of the airspace concept used for PAV traffic. Consequently, safety metrics are not considered for UAV-UAV incidents. Nonetheless, it should be noted that all aspects of PAV-UAV interactions are simulated and analyzed. In particular, UAVs are expected to affect PAV trajectories near the PAV-UAV airspace boundary, as well as entry trajectories into PAV airspace. Moreover, it is reasonable to assume that conclusions drawn from the PAV results are also applicable for UAVs.

F. Experiment Matrix

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. For this experiment, four levels of airspace structure and four traffic demand scenarios represented the experiment 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 runs.

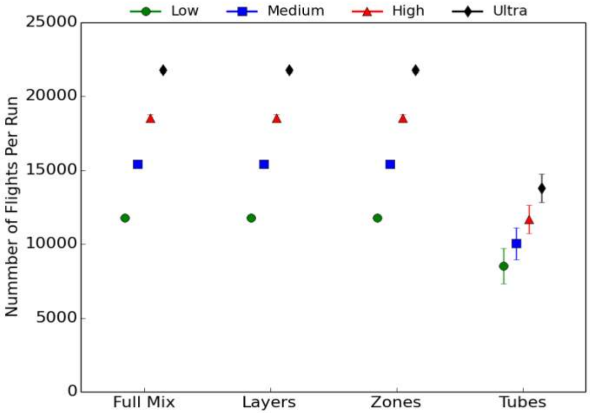

Figure 7: Means and 95 % confidence intervals of the number of flights per simulation run

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 zero, four and eight rogue aircraft introduced randomly during the logging hour. Once again, six repetitions were performed, with and without conflict resolution, resulting in a total of 144 runs.

V. RESULTS

More than six million flights have been simulated, of which approximately three million flights have been analysed for these results. Although all simulation runs had finished at the time of writing this paper, analysis is not yet complete, and the results shown here are still preliminary. A selection of the data has been made, of which there is high confidence that they will remain as shown in this paper. Future analysis may, however, still have an influence on some of the figures.

In this paper, the concepts are compared for nominal conditions, in terms of capacity, safety, and efficiency metrics. In the follow-up study, results from the non-nominal experiment as well as the further analysis should provide additional insights, on which a final conclusion can be based.

A. Demand Versus Capacity

In the simulations, the four concepts were compared in four different scenarios, where *traffic demand* varied between *Low, Medium, High and Ultra* settings, see Table 1. Fig. 7 shows the number of flights simulated during the logging hour, per simulation run, for all combinations of airspace concept and traffic demand. It can be seen that the Tubes concept deviates from the other concepts for all traffic demand conditions, which indicates that traffic demand could not be met by the Tubes concept. This can be explained by the fact that the Tubes concept has the ability to delay a flight before take-off in cases where no conflict free routes could be found between an origin and the desired destination.

The difference in the number of flights simulated for the Tubes concept has to be taken into account when considering the other metrics. Although Fig. 7 suggests that the Tubes concept has a lower airspace capacity than the other concepts, it should be noted that the figure does not imply that the other concepts were able to facilitate the higher volumes safely. For instance, if the other concepts resulted in many more intrusions that the Tubes, it should still be concluded that capacity is less than the Tubes concept. Conclusions with regard to capacity will therefore also depend on other metrics such as safety and efficiency. Moreover, safety and efficiency metrics should be computed relative to the number of flights simulated to allow for a fair comparison between concepts.

To be able to compare the results in Fig. 7 with current-day airspace use, some conversions are required. As a unit for air traffic density, often the number of aircraft per 100 x 100 NM (so 10,000 NM^2) is used. Our simulation area was only 1600 NM^2. To arrive at comparable density figures the number of aircraft would have to be multiplied with 6.25 to arrive at this reference unit. It should be noted, however, that the protected zone dimensions have also been reduced, and that travel speeds also deviate from current operations. Each of these factors complicates comparison of these density numbers with todays' airspaces.

B. Safety

The degree of safety of an airspace can be assessed by the number of separation violations. Here, the airspace design can be seen as a first layer of protection, where structure is used to either reduce the number of conflicts and possibly improve conflict geometries (which is the aim of the Layers and Zones concepts), or to provide full protection by preventing conflicts altogether (the Tubes concept).

For each of the concepts, the Conflict Resolution (CR) function could be either on or off. Here, results with CR on are used to indicate the safety of each concept as a whole, whereas the results with CR off show how well each concept is able to prevent conflicts from occurring, i.e., illustrate the primary function of structure.

Safety in terms of the number of separation violations and the number of conflicts is illustrated in Figs. 8-10. Fig 8. shows the average number of separation violations per flight for all concepts and densities. To illustrate the influence of the conflict resolution function in each concept, Fig. 9 shows the average number of intrusions for simulations with and without CR. Finally, Fig. 10 shows the average number of conflict alerts per run, for all concept-scenario combinations.

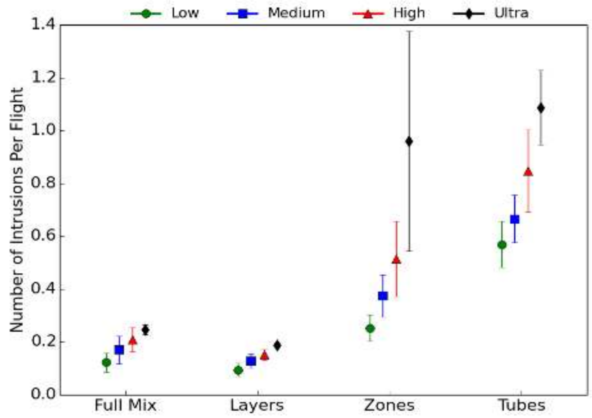

Figure 8: Means and 95 % confidence intervals of the number of intrusions per flight (with conflict resolution on)

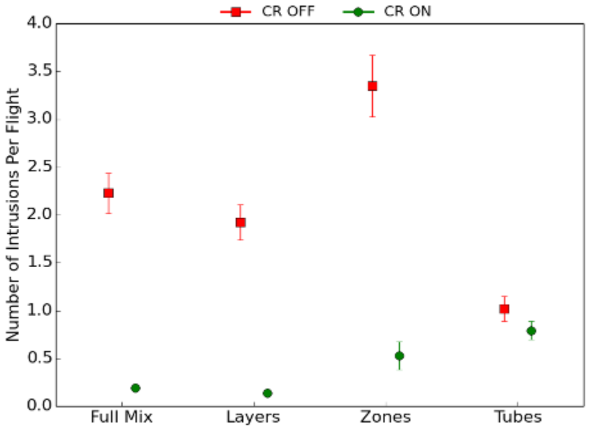

Figure 9: Means and 95 % confidence intervals of the number of intrusions per flight with and without Conflict Resolution (CR)

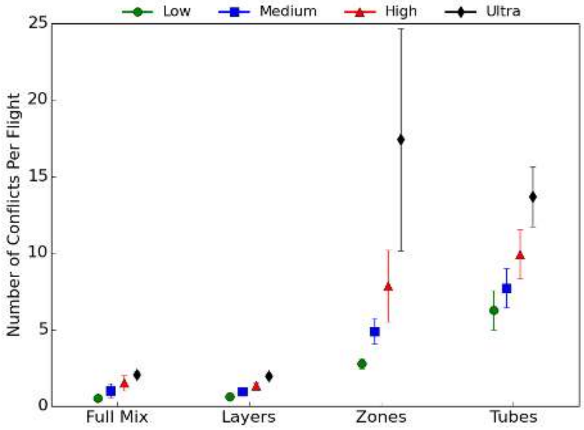

Figure 10: Means and 95 % confidence intervals of the number of conflict alerts per flight (with conflict resolution on)

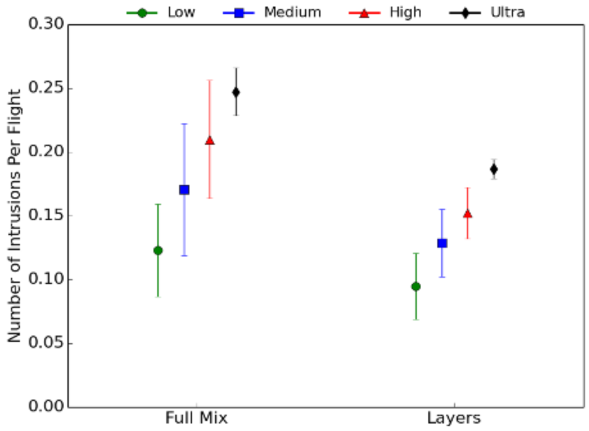

Figure 11: Mean and standard deviation of the number of intrusions per flight for the Full Mix and Layers concepts (with conflict resolution on)

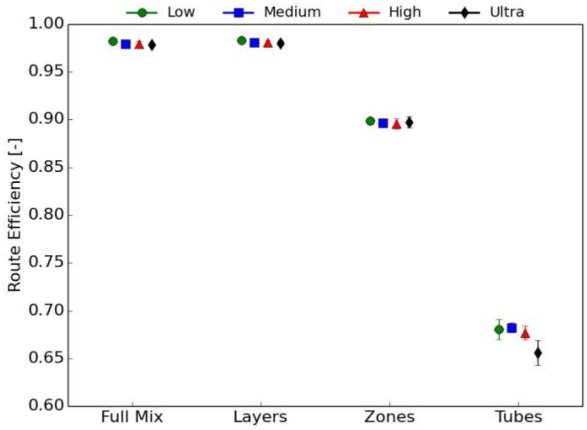

Figure 12: Mean and standard deviation of route efficiency (with conflict resolution on)

As the CD&R implementation was not optimised for these densities and concepts, there were still many conflicts and intrusions. Despite the goal of de-conflicting traffic, the resulting high traffic concentrations of the Zones and Tubes concepts apparently has a larger effect than the reduction of relative velocity. Both the Full Mix and Layer concepts distribute traffic over the available airspace, which significantly reduced the number of conflicts and intrusions relative to the more structured concepts. The difference between these two concepts is shown in more detail in Fig. 11. Here it can be seen that the Layers concept has the lowest number of intrusions with increasing traffic density, a trend that is also visible in the conflict alert plot. This may be due to the lower relative speeds within the Layers as all aircraft fly in generally the same direction at each altitude level. A lower relative velocity lowers the conflict rate, as aircraft will, on average, meet fewer vehicles per unit time.

C. Efficiency

There are many ways to look at the efficiency of each concept. One way is to log the amount of distance travelled. Both resolution manoeuvres as well as rerouting due to the airspace structure will increase the length of the route and hence provide an indicator of the efficiency in terms of fuel. Fig. 12 shows route efficiency for each concept, where efficiency is defined as the shortest (great circle) distance between origin and destination, divided by the actual distance travelled. Therefore, a value high numeric value implies high route efficiency. A similar trend to the previous metrics can be observed, where the concepts with little structure (Full Mix and Layers) clearly outperform the highly-structured concepts (Zones and Tubes). The largest difference is observed between the Full Mix and the Tubes concepts, where the Tubes concept performs 1.5 times worse, compared to the Full Mix concept.

VI. DISCUSSION

In the current study, fast-time simulations of extreme traffic densities have been performed in an effort to study the relationship between airspace structure and capacity. In total six million flights have been simulated of which about 50% has been used in the data analysis (the remainder consisted of background traffic).

The capacity, safety, and efficiency results presented in this paper suggests that that a good way to structure high-density traffic would be one that *suffices*, i.e., one that aids in traffic separation, without unduly affecting system efficiency. While the segmentation into altitude bands with similar headings, as seen in the Layers concept, still shows a beneficial effect when compared to the unstructured Full Mix concept, the strict structuring as employed in the Zones and Tubes concepts only reduces performance. For the traffic densities simulated in the current study, no reversal can be observed for this trend.

When looking at the results for demand versus capacity, it was observed that the pre-planed approach of the Tubes concept required a lot of airspace to provide separation. A complete route clearance, free of conflicts, requires a prediction horizon that spans the entire (planned) flight duration. Prediction uncertainties, further aggravate this. The discretized tube topology was therefore easily occupied, with a high frequency of delayed take-offs and a lower airspace capacity as a result. Because the other concepts did not incorporate these pre-takeoff constraints, they do not show this behavior. This difference is further emphasized by the results in terms of safety and efficiency. A consistent improvement of Full Mix and Layers over Zones and Tubes indicates that capacity at extreme densities benefits from little structuring of the airspace.

In terms of safety, the number of conflicts and intrusions increased proportionally with traffic density, even for the Tubes concept, which aimed to avoid interactions through pre-planned conflict-free routes. A possible reason for this is that the uncertainty margins were inadequate. Simulated uncertainties such as wind, for instance, could have created trajectory offsets large enough to lead to unanticipated conflicts. As tactical resolution algorithms were not used for the Tubes concept, the conflicts also resulted in a large number of intrusions. Since real-world uncertainties are constantly changing and hard to model, this result indicates that variations between planned and actual flight trajectories can have a large impact on the safety of highly structured airspace concepts.

So from the results of the nominal experiment, the Layers concept was found to result in the best balance between safety and efficiency metrics. When comparing the concepts with present day operations, then today's ATM could be seen as a variation of the Zones concept. The future –more trajectory-based– design is similar to the Tubes concept. The Layers concept can essentially be seen as an extension of the hemisphere rule. Based on the above results, an obvious question would be whether they can be translated to today's operations? Next to the lower traffic densities, two other things need to be noted. First, due to the personal air traffic scenario, the traffic demand was almost uniformly distributed except for some daily patterns. Today, there is a clear demand beween hubs, resulting in predominant traffic flows with a similar heading, which would, in the layers concept, all be forced to fly at the same levels. Second, in non-nominal situations, such as a small opening between weather systems, or one between Special-Use Airspaces, the scarcity of airspace will be high. The current implementation of the layers concept would, however, still force all traffic that need to go through the corridor to fly at the same level, leaving other altitudes in the corridor unused. Simulations with more comparable properties would be required to make reliable statements about the applicability of these results to current operations.

VII. CONCLUSIONS

The results have shown that extreme traffic densities can be achieved by spreading the traffic over the airspace, while keeping structure relatively flexible. As there are still losses of separation in all concepts, it cannot yet be concluded that the densities simulated in this study are feasible. More conclusive results would require an adaptation of the separation assurance system and the flight rules. This was, however, not the focus of this study.

From comparison of the concepts, it can be concluded that for the nominal situations of a spread demand such as provided by personal air transport or delivery drones, a layered concept is optimal. For the described scenario, a further investigation of this concept is recommended to investigate both the effect of the parameters (like number of layers per heading segment) and to investigate how CD&R/the flight rules should be optimised to function better in this scenario.

For today's ATM, especially for a free routing sector, this extension of the hemisphere rule could be considered as an enhancement for safety. This especially applies to concepts such as sectorless ATM [25], and delegated separation assurance. It will, however, also increase the safety of other more traditional concepts. As there are some caveats in translating the results of this study to today's ATM, it is recommended to investigate the effects of applying the Layers concept on scenarios similar to today's high density airspaces.

ACKNOWLEDGMENT

The authors would like to thank Pim van Leeuwen (NLR) for his valuable contribution to the design of the Tubes concept, Roalt Aalmoes (NLR) for his work on metrics definition, Oliver Schneider for his efforts towards the design of the Layers concept, professor Daniel Delhaye (ENAC) for his insights on air traffic complexity measurement, Georges Mykoniatis (ENAC) for helping with project management tasks and Marieke Suijkerbuijk (NLR) for assisting with the implementation and execution of the simulation runs.

REFERENCES

[1] T. Truman and A. de Graaff, "Out of the box: Ideas about the future of air transport (Part 2)," European Commission Services, Brussels, 2007.

[2] E. Kolawole, "The flying car: are we there yet?," *The Washington Post*, 20-Apr-2012. [Online]. Available: http://www.washingtonpost.com/

[3] Z. Sarris, "Survey of UAV applications in civil markets," in *Proceedings of the 9th IEEE Mediterranean Conference on Control and Automation*, 2001.

[4] G. Warwick, "Unmanned Community Making Progress On Airspace Access," *Aviation Week and Space Technology*, 05-Aug-2013. [Online]. Available: http://www.aviationweek.com.

[5] C. Arthur and T. Editor, "Amazon seeks US permission to test Prime Air delivery drones," *The Guardian*. 11-July-2014. [Online]. Available: http://www.theguardian.com.

[6] J.Stewart, "Google trials drone deliveries," *BBC News*. , 28-Aug-2014. [Online]. Available: http://www.bbc.com/news.

[7] M. Cummings, "A Drone in Every Driveway," *Scientific American*, vol. 308, no. 1, pp. 28–29, Jan. 2013.

[8] T. Prevot, V. Battiste, E. Palmer, and S. Shelden, "Air Traffic Concept Utilizing 4D Trajectories and Airborne Separation Assistance," in *Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit*, 2003.

[9] J. W. Andrews, H. Erzberger, and J. D. Welch, "Safety analysis for advanced separation concepts," *Air Traffic Control Quaterly*, vol. 14, no. 1, pp. 5–24, 2006.

[10] J. M. Hoekstra, R. N. H. W. van Gent, and R. C. J. Ruigrok, "Designing for safety: the 'free flight' air traffic management concept," *Reliability Engineering and System Safety*, vol. 75, no. 2, pp. 215–232, Feb. 2002.

[11] J. Krozel, M. Peters, and K. Bilimoria, "A decentralized control strategy for distributed air/ground traffic separation," in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, 2000.

[12] J. M. Hoekstra, R. C. J. Ruigrok, and R. N. H. W. van Gent, "Free Flight in a Crowded Airspace?," in *Proceedings of the 3rd USA/Europe Air Traffic Management R&D Seminar*, 2000.

[13] M. R. Jardin, "Analytical Relationships Between Conflict Counts and Air-Traffic Density," *Journal of guidance, control, and dynamics*, vol. 28, no. 6, pp. 1150–1156, 2005.

[14] Department of Economic and Social Affairs, "The World Population Situation in 2014," United Nations Population Division, New York, 2014.

[15] National Institute of Statistics and Economic Studies (INSEE), "En résumé - Ile-de-France," Oct-2014. [Online]. Available: http://www.insee.fr.

[16] Department of Economic and Social Affairs, "World Urbanization Prospects," United Nations Population Division, New York, 2014.

[17] Service Interdépartemental de la Sécurité et de l'Exploitation de la Route, "Statistiques de traffic sur le reseau sirius en 2003," Préfet de la région d'Ile de France, Sep. 2003.

[18] G. Warwick, "Unmanned K-Max Gets Cleverer," *Aviation Week and Space Technology*, 12-Aug-2013. [Online]. Available: http://www.aviationweek.com.

[19] R. Ducret and L. Delaître, "Parcel delivery and urban logistics - changes in urban courier, express and parcel services," in *Proceedings of the 13th World Conference on Transport Research, 2013.*

[20] D. Tam, “Amazon drones: Bold experiment or shrewd publicity stunt?,” *CNET*, 02-Dec-2013. [Online]. Available: http://www.cnet.com.

[21] J. M. Hoekstra, “Designing for safety: the free flight air traffic management concept,” Ph.D. dissertation, Delft University of Technology, Delft, 2001.

[22] International Civil Aviation Organization, “Rules of the Air, Annex 2,” Jul. 2005.

[23] W. Zeng and R. L. Church, “Finding shortest paths on real road networks: the case for A*,” *International Journal of Geographical Information Science*, vol. 23, no. 4, pp. 531–543, Apr. 2009.

[24] F. Bussink, J. Hoekstra, and B. Heesbeen, “Traffic manager: a flexible desktop simulation tool enabling future ATM research,” in *Proceedings of the Digital Avionics Systems Conference, 2005.*

[25] B. Korn, C. Edinger, S. Tittel, D. Kugler, T. Pütz, O. Hassa, and B. Mohrhard, “Sectorless ATM; A concept to increase en-route efficiency,” in *Proceedings of the Digital Avionics Systems Conference, 2009*

AUTHOR BIOGRAPHIES

Emmanuel Sunil received the MSc degree in Aerospace Engineering (cum laude) from TU Delft in 2014, for his work on a haptic interface for unmanned aircraft collision avoidance. He is currently working as PhD student at the Control and Simulation section of the faculty of Aerospace Engineering, TU Delft. His work focuses on airspace design and capacity modeling.

Jacco Hoekstra has obtained his MSc, PhD and a private pilot’s license from the TU Delft. He has worked at the Dutch National Aerospace Laboratory NLR for 16 years. He co-operated with NASA, the FAA and many European organizations. The topics of his ATM research include 4D Trajectory based ATM, airborne separation assurance and controller-pilot data link communication. He founded the Association for Scientific Development of ATM, was the founding director of AT-One and head of NLR’s Air Transport Division. After serving two terms as Dean of the Aerospace Engineering faculty of the TU Delft, he is now a full professor at this faculty and holds a chair in CNS/ATM in the Control & Simulation section. Next to his research, he currently teaches CNS/ATM, Programming in Python and Aeronautics.

Joost Ellerbroek received the MSc (2007) and PhD (2013) degrees in Aerospace Engineering from TU Delft, The Netherlands, where he is currently working as an Assistant Professor. His research interests lie in the field of Communication, Navigation and Surveillance (CNS) and Air Traffic Management (ATM), and in human-automation interaction.

Frank Bussink started working at NLR in 1999 as an operational research engineer. While at NLR he worked on different international ATM R&D projects related to airborne self-separation. In January 2002 he joined NASA Langley Research Centre as a research scientist to support the NASA “Distributed Air/Ground Traffic Management” (DAG TM) and the Small Aircraft Transportation System (SATS) programs. In 2007 he re-joined NLR as a subject matter expert on Aircraft Surveillance Applications Systems (ASAS), which he continued his research on. Mr. Bussink holds a B.Sc. in Aeronautical Engineering and a B.Sc. in Computer Engineering.

Dennis Nieuwenhuisen completed his M.Sc. degree in Computer Science (algorithmic design) at Utrecht University in 2002. In 2007, he received his PhD in Theoretical Robotics at the same university. Since 2007 he works at NLR as an R&D engineer at the ATM and airports department on a range of different topics both as engineer and as project leader.

Andrija Vidosavljevic graduated from the Faculty of Transport and Traffic Engineering, University of Belgrade (UB-FTTE) in 2007 in the field of Air Transportation. He received a PhD at the Division of Airports and Air Traffic Safety from UB-FTTE in 2014. He is currently post-doctoral researcher at ENAC/MAIAA lab.

Stefan Kern completed his Master degree in Aerospace engineering at the Technical University of Berlin. Since 2013 he is working at DLR at the Institute of Flight Guidance focusing on analysis of runway capacity enhancement measures as well as development and assessment of new air traffic concepts.