This project has received funding from the European Union’s Seventh Framework Programme for research, technological development and demonstration under grant number n° 341508 (Metropolis).

METROPOLIS – Urban Airspace Design

Concept Design (D 2.2)

Document author(s)  Oliver Schneider (DLR), Stefan Kern (DLR), Franz Knabe (DLR), Ingrid Gerdes (DLR), Daniel Delahaye, (ENAC), Andrija Vidosavljevic (ENAC), Pim van Leeuwen (NLR), Dennis Nieuwenhuisen (NLR), Emmanuel Sunil (TUD), Jacco Hoekstra (TUD) and Joost Ellerbroek (TUD)

Responsible Partner  DLR

Dissemination Level

<table>
<thead>
<tr>
<th>PU</th>
<th>Public</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP</td>
<td>Restricted to other programme participants (including the Commission Services)</td>
<td></td>
</tr>
<tr>
<td>RE</td>
<td>Restricted to a group specified by the consortium (including the Commission Services)</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>Confidential, only for members of the consortium (including the Commission Services)</td>
<td></td>
</tr>
</tbody>
</table>
This page intentionally left blank
Document information table

<table>
<thead>
<tr>
<th>Contract number:</th>
<th>ACP3-GA-2013-341508</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project title:</td>
<td>METROPOLIS</td>
</tr>
<tr>
<td>Project Co-ordinator:</td>
<td>Delft University of Technology</td>
</tr>
<tr>
<td>Document Responsible Partner:</td>
<td>Oliver Schneider <a href="mailto:o.schneider@dlr.de">o.schneider@dlr.de</a></td>
</tr>
<tr>
<td>Document Type:</td>
<td>Report</td>
</tr>
<tr>
<td>Document Title :</td>
<td>METROPOLIS Concept Design Report</td>
</tr>
<tr>
<td>Document ID:</td>
<td>D2.2</td>
</tr>
<tr>
<td>Contractual Date of Delivery:</td>
<td>May 2014</td>
</tr>
<tr>
<td>Actual Date of Delivery:</td>
<td>October 2014</td>
</tr>
<tr>
<td>Filename:</td>
<td>Metropolis_D2-2_Concept_Design_Report_v10.pdf</td>
</tr>
<tr>
<td>Status:</td>
<td>Released</td>
</tr>
</tbody>
</table>

Cover illustration:

Tableau of four airspace concept idea illustrations (from METROPOLIS Project Proposal).

Preface

This publication only reflects the view of the METROPOLIS Consortium or selected participants thereof. Whilst care has been taken to ensure that this information is accurate, it may be out of date or incomplete. Neither the METROPOLIS Consortium participants nor the European Community are liable for any use that may be made of the information contained herein.

This document is published in the interest of the exchange of information and it may be copied in whole or in part providing that this disclaimer is included in every reproduction or part thereof as some of the technologies and concepts predicted in this document may be subject to protection by patent, design right or other application for protection, and all the rights of the owners are reserved.

The information contained in this document may not be modified or used for any commercial purpose without prior written permission of the owners and any request for such additional permissions should be addressed to the METROPOLIS coordinator. (Prof.dr.ir. Jacco Hoekstra, Delft University of Technology, Faculty of Aerospace Engineering, Kluyverweg 1, NL-2629HS, Delft, The Netherlands)
This page intentionally left blank
Revision table

<table>
<thead>
<tr>
<th>Version</th>
<th>Date</th>
<th>Modified Page/Sections</th>
<th>Author</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2014-10-03</td>
<td></td>
<td>O. Schneider</td>
<td></td>
</tr>
</tbody>
</table>

Partners involved in the document

<table>
<thead>
<tr>
<th>№</th>
<th>Member name</th>
<th>Short name</th>
<th>Check if involved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Technical University of Delft</td>
<td>TUD</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>National Aerospace Laboratory</td>
<td>NLR</td>
<td>X</td>
</tr>
<tr>
<td>3</td>
<td>École Nationale de l’Aviation Civile</td>
<td>ENAC</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt e.V.</td>
<td>DLR</td>
<td>X</td>
</tr>
</tbody>
</table>

Executive summary

This document contains the results of METROPOLIS Work Package 2: Concept Design. It provides input to other work packages on urban airspace concepts.
This page intentionally left blank
Table of Contents

1 Introduction .......................................................................................................................... 11
   1.1 Goal as Defined in Project Plan for WP 2 ................................................................. 11
2 Scenarios [TU Delft] .......................................................................................................... 13
   2.1 Vehicle Modeling and Traffic Projections ................................................................. 13
       2.1.1 Vehicle Types .................................................................................................... 13
       2.1.2 Traffic Volume ................................................................................................. 13
       2.1.3 Traffic Types and Distribution ....................................................................... 15
       2.1.4 Origin–Destination Algorithm ....................................................................... 16
   2.2 Simulation Physical Environment ............................................................................. 16
       2.2.1 City Map ........................................................................................................... 16
       2.2.2 Infrastructure .................................................................................................. 17
3 Concept Elements ............................................................................................................ 21
   3.1 Common Concept Elements ..................................................................................... 21
       3.1.1 Airspace Limits for PAV/UAV Operations (Airspace Management) ............. 21
       3.1.2 Conflict detection/resolution (Air Traffic Control) ......................................... 22
       3.1.3 Separation requirements (Air Traffic Control) .............................................. 22
       3.1.4 Trip planning / Mission Planning ................................................................. 24
       3.1.5 Weather and abnormal situations ................................................................. 26
   3.2 Batch Simulation Independent Variables and Conditions ........................................ 27
   3.3 Concept specific Elements ...................................................................................... 27
       3.3.1 General Description ....................................................................................... 27
       3.3.2 Flow Management, Separation and Conflict avoidance ............................... 28
       3.3.3 Take-off and Landing Procedures ................................................................. 28
       3.3.4 Handling of abnormal situations ................................................................ 28
4 Concept 1: Full Mix [TU Delft] ........................................................................................ 29
   4.1 General Description ................................................................................................... 29
       4.1.1 Full Mix-Free Flight Relationship ................................................................ 29
       4.1.2 Route Planning and Trajectories .................................................................... 30
       4.1.3 Airspace Usage Restrictions .......................................................................... 30
       4.1.4 Take-off and Landing Procedures .................................................................. 31
   4.2 Flow Management, Separation and Conflict Avoidance ......................................... 31
       4.2.1 Air Traffic Flow Management ....................................................................... 31
       4.2.2 Separation Requirements ............................................................................. 31
4.2.3 Conflict Detection and Resolution ................................................................. 32
4.3 Handling of Abnormal Situations ....................................................................... 35
  4.3.1 Rogue Aircraft and Meteorological Conditions ........................................... 35
  4.3.2 Robustness of Aircraft State Transmission System ..................................... 36
5 Concept 2: Layers [DLR] ....................................................................................... 37
  5.1 General Description ....................................................................................... 37
  5.2 Flow Management, Separation and Conflict avoidance .................................. 40
  5.3 Take-off and Landing Procedures ................................................................... 43
  5.4 Handling of abnormal situations ..................................................................... 44
6 Concept 3: Zones [ENAC] ...................................................................................... 47
  6.1 General Description ....................................................................................... 47
  6.2 Zone topology ............................................................................................... 48
    6.2.1 UAV airspace topology ............................................................................ 48
    6.2.2 PAV airspace topology ............................................................................ 51
  6.3 Flow Management, Separation and Conflict avoidance .................................. 60
    6.3.1 UAV operations and management ............................................................ 60
    6.3.2 PAV operations and management ............................................................ 60
    6.3.3 Flight planning ....................................................................................... 62
  6.4 Handling of abnormal situations ..................................................................... 64
7 Concept 4: Tubes [NLR] ......................................................................................... 65
  7.1 General Description ....................................................................................... 65
    7.1.1 Introduction ............................................................................................ 65
    7.1.2 Preliminary assumptions ......................................................................... 65
    7.1.3 Input ....................................................................................................... 68
    7.1.4 The tube topology .................................................................................. 69
    7.1.5 UAV and PAV tube topologies ............................................................... 72
    7.1.6 Minimum safe altitude .......................................................................... 73
    7.1.7 Optimizing the tube topology .................................................................. 73
    7.1.8 Glossary ............................................................................................... 73
  7.2 Flow Management, Separation and Conflict avoidance .................................. 74
    7.2.1 Ensuring separation ............................................................................... 74
    7.2.2 Transfers between layers ....................................................................... 74
    7.2.3 Joining the topology ............................................................................. 76
    7.2.4 Flight planning ....................................................................................... 76
  7.3 Take-off and Landing Procedures ................................................................... 77
  7.4 Handling of abnormal situations ..................................................................... 79
8 Origin-Destination Algorithm for PAVs [TU Delft] .................................................................81
8.1 Runway Spawn Rate Determination ......................................................................................81
8.2 Traffic Type Selection ..............................................................................................................82
8.3 Vehicle Type Selection .............................................................................................................84
8.4 Destination Runway Selection ..................................................................................................85
8.5 Ensuring Appropriate Traffic Volume Each Simulation ‘Hour’ .............................................86
8.6 Raw Data Needed for O-D Algorithm Implementation .............................................................86
9 List of Abbreviations ...................................................................................................................91
10 Bibliography .............................................................................................................................93
This page intentionally left blank
1 Introduction

This document describes the airspace concepts required to perform the batch simulations. The focus will be on the conceptual design, during simulations, minor corrections and adaptations to the concepts might be necessary. These will be described in the final report.

1.1 Goal as Defined in Project Plan for WP 2

Urban airspace for future high-traffic scenarios will require a structure that differs significantly from today’s to accommodate Personal Aerial Vehicles (PAVs) and Unmanned Aerial Vehicles (UAVs) as well as a higher number of landing sites.

Based on the findings of work package 1, four different airspace designs will be detailed into concepts in Work Package 2, to meet the demands of the scenarios as specified in Work Package 1.

Figure 1.1 shows global descriptions of four design options that will be detailed in this report. These will address questions in the likes of

- General airspace structure,
- Separations/conflict avoidance,
- Trajectories,
- Approach/departure procedures.

Many parameters of the concept need to be defined and optimized to allow a batch simulation.

In all concepts, it is assumed that the on-board avionics have the airspace structure implemented, as well as other constraints such as terrain/obstacles and (uplinked) weather information. Advanced automation concepts result in a flight protection mode ensuring that the vehicles stay in the airspaces where they are allowed.
**Full mix**

In this design, all vehicles share the same airspace, without any structure or non-physical constraints, in which via a prescribed airborne separation assurance algorithm, supported by automation, the vehicles avoid each other while flying an optimal route. UAVs and PAVs are mixed. This is a static airspace design, which does not require adjustments based on demand.

**Layers**

In this design, every altitude band corresponds to a heading range in a repeating pattern. The aim is to allow maximum freedom of routing while lowering the relative speeds, facilitating the separation and increasing the safety. A limit to the ceiling of UAVs will be an option on this design. This is a static airspace design, which does not require adjustments based on demand.

**Zones**

Based on the principle of airspace design today, different zones for different types of vehicles, speed ranges as well as global directions have been defined to aid the separation by the structure of the airspace. UAVs and PAVs each have their own zones and are mostly, if not completely, separated. A dynamic adjustment of zones based on demand or observed densities, is an option with this design.

**Tubes**

As a maximum of structuring of airspace, tubes have been defined to provide a fixed, but dense, route structure. Different directions, speeds and vehicle types will use different tubes ensuring safety by separating potentially conflicting traffic. UAVs and PAVs each have their own tubes and are completely separated. A dynamic adjustment of zones based on demand or observed densities, is an option with this design.

*Figure 1.1: METROPOLIS Airspace Concepts*
2 Scenarios [TU Delft]

Four future scenarios were defined for METROPOLIS in deliverable D1.3 [1]. These scenarios assume population and traffic growth when compared to present day Paris levels. The scenarios will be used to evaluate the four airspace concepts discussed in this report. Therefore, a summary of the most important aspects of the METROPOLIS scenario definition is presented in this chapter.

2.1 Vehicle Modeling and Traffic Projections

2.1.1 Vehicle Types

Three types of Personal Aerial Vehicles (PAVs) and one type of Unmanned Aerial Vehicle (UAV) were selected for the METROPOLIS project, see Figure 2.1 to Figure 2.4 [2]. The Terrafugia FT-X and the Agusta Westland AW609 PAVs are Vertical Take-Off and Landing (VTOL) aircraft. On the other hand, the PAL-V One is a gyrocopter and thus requires a short runway for take-offs and landings. In the METROPOLIS scenarios, UAVs are used for express delivery of packages lighter than 2 kilograms and operate from dedicated UAV cargo distribution centers located throughout the city.

2.1.2 Traffic Volume

Traffic volumes for the four scenarios were computed by extrapolating current traffic volumes in Paris [7] to the METROPOLIS population sizes using the following assumptions:
1. Per capita ownership of automobiles remains constant at the 2001 level of 0.257 [1].
2. By 2050, the market share of PAVs is assumed to be 16.7 % [2]. As a result, aerial vehicles are expected to replace 16.7 % of all road traffic.
3. Terrafugia TF-X, PAL-V One and Agusta Westland AW609 are aerial substitutes for cars, motorbikes and minivans. As a consequence aerial vehicles will be divided into these three vehicle types by the same proportion as in 2001 i.e., 82 %, 6 % and 7 % respectively [2].
4. Per capita demand per year for UAV delivered packages is 3.87 in 2050 [1].
5. UAVs deliver 5 packages during each delivery run, and each delivery is not further than 7 kilometers from the UAV cargo distribution center [1].

The resulting average traffic volume per hour for the METROPOLIS simulation area (experiment and background area, see section 2.2.1), categorized according to vehicle type and city zone, is listed below in Table 2.1.

Table 2.1: Average traffic volume per hour in the METROPOLIS simulation area (experiment and background areas)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TF-X</th>
<th>PAL-V</th>
<th>AW609</th>
<th>UAV</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City Center</td>
<td>1,754</td>
<td>128</td>
<td>150</td>
<td>77</td>
<td>2,110</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>3,388</td>
<td>248</td>
<td>289</td>
<td>150</td>
<td>4,075</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>3,986</td>
<td>292</td>
<td>340</td>
<td>176</td>
<td>4,794</td>
</tr>
<tr>
<td>Total</td>
<td>9,129</td>
<td>668</td>
<td>779</td>
<td>403</td>
<td>10,979</td>
</tr>
<tr>
<td>Scenario 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City Center</td>
<td>2,255</td>
<td>165</td>
<td>193</td>
<td>100</td>
<td>2,713</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>4,356</td>
<td>319</td>
<td>372</td>
<td>192</td>
<td>5,240</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>5,125</td>
<td>375</td>
<td>437</td>
<td>226</td>
<td>6,164</td>
</tr>
<tr>
<td>Total</td>
<td>11,737</td>
<td>859</td>
<td>1,002</td>
<td>518</td>
<td>14,116</td>
</tr>
<tr>
<td>Scenario 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City Center</td>
<td>2,757</td>
<td>202</td>
<td>235</td>
<td>122</td>
<td>3,315</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>5,325</td>
<td>390</td>
<td>455</td>
<td>235</td>
<td>6,404</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>6,264</td>
<td>458</td>
<td>535</td>
<td>277</td>
<td>7,534</td>
</tr>
<tr>
<td>Total</td>
<td>14,345</td>
<td>1,050</td>
<td>1,225</td>
<td>634</td>
<td>17,253</td>
</tr>
<tr>
<td>Scenario 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City Center</td>
<td>3,258</td>
<td>238</td>
<td>278</td>
<td>144</td>
<td>3,918</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>6,293</td>
<td>460</td>
<td>537</td>
<td>278</td>
<td>7,568</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>7,403</td>
<td>542</td>
<td>632</td>
<td>327</td>
<td>8,903</td>
</tr>
<tr>
<td>Total</td>
<td>16,953</td>
<td>1,240</td>
<td>1,447</td>
<td>749</td>
<td>20,390</td>
</tr>
</tbody>
</table>

It should be noted that the numbers presented in Table 2.1 are not indicative of the instantaneous number of aerial vehicles in the air at any given point in time. This can be computed from the values in Table 2.1 and assuming an average trip time of 15 minutes (thus by dividing the traffic volume in Table 2.1 by four).
It is well known that city traffic volumes vary throughout the day. Since the primary goal of the METROPOLIS project is to investigate capacity limits of the four airspace concepts, the following three time spans have been selected for study:

1. Morning rush hour (08:00–09:00): 195 % of average hourly traffic
2. Evening rush hour (17:00–18:00): 206 % of average hourly traffic
3. Lunch time (12:00–13:00): 150 % of average hourly traffic

The traffic volumes for these time intervals can be computed by multiplying the above percentages to the traffic volumes given in Table 2.1. This will lead to very high traffic numbers especially in the city center with only very few landing sites. Since the focus of the project is on airspace, it might be necessary to modify the takeoff and landing distributions for the simulations. These numbers will be tuned so the total number of PAVs in the airspace will be reached and the distribution over landing spots will be reasonable.

### 2.1.3 Traffic Types and Distribution

Four different traffic types are considered for METROPOLIS:

1. Residential–Residential
2. Residential–Commercial
3. Commercial–Residential
4. Commercial–Commercial

Residential–Commercial refers to traffic originating in a residential area and travelling to a commercial area of the city. The other three categories can be understood similarly. The four traffic types are necessary to create a high level of realism for the simulation and the proportion of each type depends on the time of day, see Table 2.2. It should be noted that the values in Table 2.2 are estimates which are based on today’s road traffic distribution.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning Rush Hour (08:00–09:00)</td>
<td>25 %</td>
<td>50 %</td>
<td>15 %</td>
<td>10 %</td>
</tr>
<tr>
<td>Evening Rush Hour (17:00–18:00)</td>
<td>10 %</td>
<td>15 %</td>
<td>55 %</td>
<td>20 %</td>
</tr>
<tr>
<td>Lunch Time (12:00–13:00)</td>
<td>30 %</td>
<td>15 %</td>
<td>20 %</td>
<td>35 %</td>
</tr>
</tbody>
</table>
Most of the traffic is of the Residential–Commercial type during the morning rush hour, whilst Commercial–Residential traffic has the highest proportion during the evening rush hour, similar to real traffic dynamics.

2.1.4 Origin–Destination Algorithm
A stochastic origin destination algorithm has been designed specifically for the Metropolis project. The algorithm is runway centric: during each simulation time step, the algorithm determines whether an aircraft should be spawned at each runway. Subsequently, the algorithm determines the traffic type, vehicle type, and finally the destination of the spawned aircraft. The algorithm takes into account operational constraints, for instance non-VTOL aircraft can only spawn at non-VTOL runways, and can only fly to other non-VTOL runways.

The origin–destination algorithm has been tested and tuned such that an appropriate traffic volume is generated for each scenario. More details about the algorithm, including governing equations and the raw data needed for its implementation, can be found in Chapter 8.

2.2 Simulation Physical Environment

2.2.1 City Map
The 80 x 80 square kilometers portion of the METROPOLIS city, known as the simulation area, is visualized in Figure 2.5. The city is divided into three zones: city center, inner ring and outer ring. All city zones have a ‘grid-like’ street layout. The height of the buildings in METROPOLIS is the highest in the city center (300 meters) and decreases with distance from the city center, see Figure 2.5. Additionally, the city (simulation area) has been divided into an experiment area and a background area. Although traffic will be simulated throughout the simulation area, data will only be logged for the experiment area (to speed up simulations). Through simple offline simulations, the experiment area (1543.5 square kilometers) has been sized such that it is large enough to study conflicts between aircraft pairs, for all potential conflict geometries, and considering conflicts between the fastest vehicle in the METROPOLIS scenario (the AW609).

To ensure realistic simulation conditions, it is necessary to ensure a distinction between commercial and residential city areas. As implied earlier, this distinction is necessary to influence traffic volumes during rush hours; for example, during the morning rush hour, it is expected that the largest proportion of traffic will be of the residential–commercial type.

To create this distinction, a number of so called commercial focus points have been defined for METROPOLIS (for both background area and experiment area). Each focus point is given a ratio value between 0 and 1 to indicate the amount of commercial activity at that focus point. For instance a focus point with a ratio of 1 indicates 100 % commercial activity, while a ratio of 0 indicated 100 % residential activity. To model the sphere of influence of each focus point, a Gaussian Radial Basis Function (RBF) is
used such that commercial ratios always drop off to a value of 0 in 1000 meters\(^1\). The net commercial ratio for a particular point in the city is computed as the maximum commercial ratio of all the focus points that have an influence on that point. This influence depends on the distance of the focus point from the city point under consideration, as described by the shape of the selected RBF.

UPDATE: In D1.3, the office ratios were computed based on the average office ratios of all the focus points that had an influence on a particular building. Since then, it has been decided to modify the computation procedure such that the office ratio of a particular building is taken as the maximum office ratio of all the focus points that influence that point. This results in a better distinction between commercial and residential areas and leads to a better approximation of real cities.

\[\text{Figure 2.5: Map of the METROPOLIS city}\]

### 2.2.2 Infrastructure

The only infrastructure under consideration for METROPOLIS are PAV and UAV landing areas. PAV runways (or landing strips) have been distributed evenly over the METROPOLIS city area at a frequency

\[^1\] 1000 meters was selected as the outer distance of influence for each focus point as it led to a realistic distribution between commercial and residential areas.
of 1 runway per four square kilometers. Hence, there are a total of 1600 runways in the METROPOLIS simulation area. Due to the smaller number of non-VTOL aircraft, it has been decided to define every other runway as non-VTOL capable i.e., 1 non-VTOL runway per eight square kilometers, resulting in a total of 800 non-VTOL runways for the METROPOLIS simulation area. To simplify the simulations, PAV runways (or landing strips) have been defined on raised platforms at street intersections. After landing, PAVs can drive down to the street level by means of a ramp. In reality this would also involve adjusting the traffic light sequences such that all other traffic is stopped while a PAV drives onto the street. The distribution of PAV runways, including each runway’s office ratio, is illustrated in Figure 2.6.

As UAVs are used for package delivery, it has been decided to define UAV landing spots on top of each and every building block. As mentioned earlier, UAVs originate from so called UAV cargo distribution centers. For simplicity, each distribution center’s delivery area is defined as a square area with a side length of 12 kilometers (each UAV can deliver packages up to 6–7 kilometers from the distribution centers). Figure 2.7 displays the distribution centers and their areas of influence.

Figure 2.6: Location, type and office ratio of PAV runways. 'A' = VTOL runways and 'B' = non-VTOL runways.

Note: the size of the runways are exaggerated for effect.
Figure 2.7: UAV cargo distribution centers (black dots). Each distribution center has a square shaped (side length 12 kilometers) area of influence (grey squares).
This page intentionally left blank
3  Concept Elements

A major challenge of the METROPOLIS approach is the organization and the management of PAV traffic in the airspace over a heavily populated city. As the METROPOLIS scenarios will cover a time horizon beyond the year 2050 it is likely that the air traffic management as a whole will completely differ from today.

Due to limited resources the METROPOLIS project will focus on essential elements of an operational concept which are indispensable for the simulation and evaluation of the four different concepts.

3.1  Common Concept Elements

Although the four concepts are very different in their characteristics and implementation there is a set of concept elements that is common to all airspace concepts. This section defines these elements and rules.

3.1.1  Airspace Limits for PAV/UAV Operations (Airspace Management)

Without initiating a fundamental restructuring of airspace, the lower airspace is most suitable for the use of PAVs and UAVs. This will on one hand create a safe separation to the higher and faster flying commercial aircraft and has no critical interaction with the airspace of those aircraft itself on the other hand. In respect thereof and to cope with the demand for PAVs and UAVs in 2050, the following limits or rather conditions represent adequate assumptions.

- Minimum Altitude (Cruise):
  - 300 ft above ground (minimum safe altitude)
  - 100 ft (UAVs)/500 ft (PAVs) above the highest building
- Maximum Altitude:
  - 6500 ft
- No-Fly Zones:
  - Arrival/Departure sectors of airports (not inside simulation area)
  - Stochastic moving no-go areas during several simulation scenarios.

The specified minimum safe altitude is based on the maximum building height in each part of the city. Table 3.1 outlines the minimum safe altitude for the different city areas.

<table>
<thead>
<tr>
<th>Location</th>
<th>Max Building Height</th>
<th>Minimum Safe Altitude (MSA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PAVs</td>
<td>UAVs</td>
</tr>
<tr>
<td>City Center</td>
<td>1000 ft / 300 m</td>
<td>1500 ft / 450 m</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>330 ft / 100 m</td>
<td>830 ft / 250 m</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>250 ft / 80 m</td>
<td>750 ft / 230 m</td>
</tr>
</tbody>
</table>

Specific airspace usage restrictions may be defined in the individual concepts.
Another aspect to be aware of is the compliance of separation between the PAVs and UAVs itself. Based on the low altitudes, difficulties with vertical separations will occur. The barometric altimeter with its dependence on air pressure does not represent the most satisfactory solution and may be replaced with high probability by some state-of-the-art GPS controlled tool.

3.1.2 Conflict detection/resolution (Air Traffic Control)
PAVs will be equipped with state-of-the-art positioning and ADS-B systems, which will enable them to accurately locate their own position and provide this information to all surrounding vehicles in their vicinity. Furthermore, on-board systems are able to detect possible conflicts and provide resolution trajectories (ad-hoc conflict-detection and avoidance), even so this might not be required for some airspace concepts. On the other hand also an “observation center” on the ground is possible, calculating conflict free trajectories in advance of the flights to eliminate possible conflicts or at least provide traffic balancing (this possibility will not be considered for the simulations). The instrument of Air Traffic Control will be discussed in detail in each concept.

3.1.3 Separation requirements (Air Traffic Control)
Separation requirements in the airspace depend on vehicle type, phase of flight and airspace concept. This section will focus on general separation requirements that will be refined depending on the different airspace concepts in chapters 4–7.

3.1.3.1 Cruise
PAVs are highly automated and it is not possible or required to fly the vehicle manually like an airplane. The user can only interact with the system by defining the intended destination, may have the choice of different possible trajectories to reach this destination or might be able to take over the control in case of an emergency. Since on-board systems provide accurate trajectory data to other vehicles in the vicinity and in most cases no manual steering input is possible, reaction times do not need to be considered to establish minimum separation requirements. A consideration of manually controlled PAVs on one hand makes training and to that effect a special PAV license necessary, which is not comparable with a car license. On the other hand manual control of PAVs makes conflict detection and the calculation of conflict free trajectories more difficult due to several uncertainties. In consequence it only seems to be an option in emergency cases (e.g. avoiding to fly over a fire).

Furthermore, the vehicles are relatively small compared to airplanes, so wake-vortex separation is not necessary. Nevertheless a general separation between aircraft is required for safe operations. Therefore, the general minimum separation corresponds to a 1-second minimum spacing between PAVs with respect to the fastest flying vehicle. The Augusta Westland AW609, with an assumed city cruise speed of 200 kts, needs 206 m spacing to cope with the 1-second separation rule considering the worst case condition of a head-on conflict between two AW609s. Adding a 10% safety margin, and rounding the result up to the nearest multiple of 50, a total horizontal separation of 250 m is established for PAVs. Vertical separation will be assumed as 1/5th of the horizontal separation and thus account about 50 m (150 ft). For UAVs the values for collision avoidance and separation result from multiplying the PAV criteria by 1/10th. To sum up the separation criteria is illustrated in the following Table 3.2.
Table 3.2: Separation requirements for PAVs and UAVs

<table>
<thead>
<tr>
<th></th>
<th>PAV</th>
<th></th>
<th>UAV</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal</td>
<td>Vertical</td>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>Meters</td>
<td>250</td>
<td>50</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Feet</td>
<td>750</td>
<td>150</td>
<td>75</td>
<td>15</td>
</tr>
<tr>
<td>Nautical miles</td>
<td>0.13499</td>
<td>0.02700</td>
<td>0.01350</td>
<td>0.00270</td>
</tr>
</tbody>
</table>

The definition of the separation requirements can be inferred from Figure 3.1 below which displays the PAV requirements. Note that both collision and separation requirements are defined from the aircraft (located in the center).

![Figure 3.1: Separation and collision avoidance for PAVs](image)

The separation requirements define the minimum safe distance between two aircraft. Therefore in Figure 3.2, the two PAVs are safely separated as the distance between them is (at least) 250 meters, even though their protected zones overlap:

![Figure 3.2: Minimum safe distance between two PAVs](image)

If the distance between two PAVs is less than 250 meters, then there is a loss of separation and a collision avoidance maneuver is needed. It is planned to investigate each loss of separation encountered during the simulations to be performed in Work Package 4 to analyze the severity of each protected zone intrusion.

Based on the fact that the METROPOLIS project focuses on the influence of airspace structure on capacity, a decentralized control will be applied in all four concept designs. In this project, PAV traffic is seen as a replacement for road traffic.
Decentralized control comes along with an individual conflict detection and resolution (CD&R). The Modified Voltage Potential (MVP) algorithm will in this case resolve conflicts. Before conflicts can be resolved, flight parameters like heading, position and speed of each PAV or UAV are needed to make a decision. Each aircraft transmits its own flight parameters to all aircraft in its vicinity, so the future position of other aircraft can be extrapolated.

3.1.3.2 Take-off/Landing

Consecutive PAV landing and take-off operations on a landing/take-off spot will require separation in temporal and/or spatial terms. Depending on the usage strategies for the spot, separation values have to be provided for arrival/arrival, departure/departure, arrival/departure and departure/arrival operations. In combination with the demand characteristics, these separation values will determine the capacity of a landing/take-off spot.

Separation between two consecutive take-off and/or landing operations is defined by the service time required to vacate the landing area. The service time should be set in relation to the demand required for one take-off and landing site. Taking the evening rush hour of scenario 4 (see Table 8.4) equipped with the highest demand overall. With a demand of 8731 TF-X PAVs during 15 minutes spread over an area of 6400 km², per minute about 580 PAVs conduct a take-off or landing. Having one take-off and landing sites every four square kilometers, 1600 landing sites (simulation area) are available. In consequence, each site is used every 2.8 minutes.

During climb or descend PAVs have to fly between buildings in each of the concepts. Thus takeoff and landing procedures for all concepts are similar and will be performed with an individual PAV type climb and descend angle. The heading will stay constant until the MSA are vertically passed. Due to this boundary conditions and a constant spawn rate in the simulations, no conflicts during takeoff will occur. In case of landing the simulation is facing some difficulties. If the desired landing site is unavailable, flights need to be delayed to meet the runway availability. Therefore during simulations PAVs will be deleted after crossing the minimum safe altitude for landing. This simplification causes two problems:

- The delay absorption capability of the more structured concepts will not be seen in the simulation.
- If a conflict occurs after the PAV has been deleted, it will not be recorded. This is particularly an issue for conflicts between PAVs and UAVs for some concepts, that aim to adjust UAV zone and tube topologies to allow PAVs to land through the UAV altitude layers.

To reduce the impact of these problems, the arrival times of each PAV will be recorded for each runway in the simulation. A new metric will be developed in Work Package 3 to indicate the ability of each concept to absorb delay by taking the landing sequence recorded into consideration.

3.1.4 Trip planning / Mission Planning

For trip / mission planning two different aspects have to be considered:

- Definition of the pre-departure process and the trajectory coordination phase.
- Determination of possible trip or mission profiles to be considered in simulation runs.
The pre-departure process consists of all actions necessary before a departure from a spot is possible, depending on the type of control used (Centralized: ATC-like trajectory coordinator, decentralized: individual PAV). In case of the centralized control a time interval should be defined for filing a “flightplan” before planned departure time. So, the trajectory coordinator can use the information for the creation of a departure sequence, an optimization of the observed airspace or the selection of a landing strip close to the preferred destination (not necessarily a landing strip). With a decentralized control every PAV user can try to claim a special departure time and strip, trajectory and landing strip. A centralized service for departure sequencing will not be simulated and is just mentioned for description purpose.

Origin and destination are not necessarily fix departure or landing strips, but a normal address and could therefore be part of the trajectory negotiation process for cases where the PAVs are able to taxi on ground. With this option the trajectory can be redirected e.g. to a spot less close to the origin when it is possible to match the preferred departure time instead (same for destination). A prerequisite for this would be at least a global departure management system where all planned departure and arrival activities are administrated. It can be assumed that the traffic will consist of a mixture between PAVs which are flexible with their departure spots and those which are parked directly at a departure spot (connected parking lot).

The departure time should be considered as a fix value for each calculated trajectory but – if possible – an interval around this time where a departure with this trajectory is also feasible should be calculated and declared to the user (not part of the simulation runs).

If a user intends to make a PAV flight he/she has to hand over the relevant data mentioned before within the prescribed time frame in relation to the preferred departure time to a control system. Afterwards a flight trajectory for this flight will be created by the system. When he/she gets his trajectory he/she has to stick to the advised departure time (interval) and spot.

To allow maximum flexibility, it should not be mandatory to plan trips well in advance. When using a centralized trajectory coordinator, several modifiers can be used for the calculation of the number in the queue of aircraft waiting for trajectory calculation:

- The earlier you plan your trip, the higher your priority to get the optimal route (First Come, First Served).
- Instead of a fixed departure time as most important parameter a time range could be given and a priority list of the user (e.g. as early as possible, lowest flight time, arrival at a specific time).
- Negative impact on priority for persons / PAVs with a lack of plan adherence in the past.
- Influence of the number of passengers on the priority.

In case of a decentralized trajectory calculation only “First come, First Served” will be used. Nevertheless an overview about the already planned departures and arrivals at specific times for the desired spot should be accessible for each user to facilitate an appropriate trip planning.
Furthermore, it can be supposed that all PAVs will be able to follow the planned trajectory precisely and to calculate their proper position data for distribution to other airspace users or the trajectory coordinator. Especially for departure and landing a clearance from the operators of the affected spots must be given before using these spots. If a connected parking deck should be used a confirmation for a reserved parking lot must be given as well.

When in-flight there are several cases when a re-calculation of the trajectory will be necessary. Reasons for this can be:

- PAV Emergency (System failure / other PAV out of control).
- Emergency PAV / UAV (medical or safety staff on their way to an emergency).
- Ad-hoc closing of airspace.
- Spontaneous destination changes during flight (bakery, visit a friend, forgotten something at the office etc.).

Especially because of the first emergency case all systems used for the calculation of flight trajectories either on-board or centralized have to be able to carry out a re-calculation within seconds. This is necessary to make sure that a conflict-free trajectory exists in time. In case of spontaneous destination changes the PAV user can follow his existing trajectory until a new one was created. For a centralized trajectory coordinator this means that a clear priority list must exist for all cases of trajectory requests with emergencies as highest priority.

Note: Situations where a PAV / UAV will decide ad hoc to change the destination or to insert an additional landing will not be part of the simulation.

3.1.5 Weather and abnormal situations
PAVs are highly automated and will not be manually controlled like an airplane. Therefore visual conditions have no impact on PAV/UAV traffic and visual minima are not required. Wind in comparison has to be handled differently. Restrictions on wind maxima for a specific PAV/UAV-type will be established during vehicle certification. So in consequence UAVs will most likely face lower wind maxima than other vehicles due to the low weight. Also for snow, hail, heavy rain or other precipitations limits need to set during the certification of the different vehicles.

So in the end the certification limits decide about the permission of flying under certain weather conditions. However for weather phenomena like thunderstorms occurring mostly in combination with gusts and lightning strikes airspace needs to be closed for safety reasons. To have the same starting position the weather conditions have to be identical in all scenarios.

For validation reasons each concept has to comply with the same initial situation, embodied by implementing a Wind component and a dynamic no-go area into the simulation. Wind will be included in all scenarios and represent randomness in the experiment. Additionally a stochastic no-go area is selected as abnormal situation and will be part in one of the scenarios. No-go areas can be established based on different safety reasons like thunderstorms, volcanic ash or wind shear. For simulating dynamic no-go areas the following assumptions are made:
• First of all, to simplify all dynamic no-go areas are assumed to retain their shape in time (i.e., only the position of the area changes in time, not its shape)
• Second, it is assumed that no forecast can be given about the future location of the dynamic no-go area. This will certainly be true for rogue aircraft; for weather systems or volcanic ashes, however, forecasts of varying probability might be given. To simplify, these probabilistic forecasts will not be taken into account.
• Third, it is assumed that all dynamic threats including rogue aircraft, weather systems or natural disaster areas can be modelled as no-go areas composed of one or more 3D rectangles.
• Finally, all PAVs are assumed to be ADS-B In, ADS-B Out, and TCAS equipped. Hence, the position and velocity of e.g. rogue aircraft is visible (either through ADS-B, or TCAS, or both) to all other aircraft and automatic conflict resolutions exist to resolve any potential conflicts that would occur in case below re-planning of PAVs cannot be performed in time.

Due to increase of complexity no dynamic adjustments of airspace concepts like load balancing will be considered during validation. For simulations of dynamic no-go areas only the case of a rogue aircraft will be taken into account.

3.2 Batch Simulation Independent Variables and Conditions

To analyze the influence of airspace structure on airspace capacity, the following three independent variables are defined for the batch simulations (that are to be performed in WP4):

1. Airspace Structure: 4 levels, corresponding to the Full Mix, Layers, Zones and Tubes concepts described in this document.
2. Traffic Volume: 4 levels, corresponding to the four population scenarios defined in D1.3
3. Abnormal Conditions: 2 levels, corresponding to the case with and the case without ‘dynamic no-go areas’. Here dynamic no-go areas are a manifestation of abnormal conditions that occur in the natural world, e.g.: a moving storm cell.

A total of 32 simulation conditions are realized through factorial combinations of the different levels of the three independent variables.

3.3 Concept specific Elements

Beside the common elements every concept has individual aspects causing the differences to other concepts. The following sections will give an overview about the structure of the concept elements in general and the individual aspects.

3.3.1 General Description

To start with, the general structure of the used Airspace shall be introduced. An important question which should be answered in the first stage is how PAVs and UAVs are separated from each other or if they are using the same airspace. Also aspects of airspace usage restrictions, e.g. minimum and
maximum allowed speed or what kind of equipment is needed, will be part of the general description. Furthermore specific elements cover at least issues of route structure, trajectory calculation/prediction, organization of Air Traffic Management or possible capacity adjustments due to high or changing demand in dependence of the time of day.

3.3.2  **Flow Management, Separation and Conflict avoidance**
In a more specific manner the section concerning flow management and separations will – if necessary – go into more detail with reference to:

- Trajectory Calculation/Planning,
- PAV/UAV separation,
- Demand Capacity Balancing over Time,
- Flow Management (before Departure),
- Look Ahead Capability of ATM/ATC during flight,
- Conflict Detection and Solution during flight (lateral, vertical, speed) by PAV or ATC or
- ATC responsibility

3.3.3  **Take-off and Landing Procedures**
Beside the common procedures used in all concepts and the fact of not simulating them, there still will be a description on individual aspects of each concept. Especially capacity limiting factors have to be taken into account as well. High Demand can result in delay, but there need to be options for compensation of necessary waiting times in flight. Thus it is to discuss which options are feasible and most practical. Possible options are:

- speed adjustments,
- path stretching,
- holdings patterns, or
- hovering.

In principle it is also necessary to address the process of integrating PAVs into airspace itself and which factors have to be considered in this regard.

3.3.4  **Handling of abnormal situations**
Weather is a factor influencing air traffic every time and everywhere. Therefore it is essential to reflect the impact of weather in the sense of general restrictions to the individual concept. Solutions for abnormal situations need to be found and discussed to have the lowest impact of weather or other situations on flight operations. In case of emergencies also fall back routines are required, which may be different in each concept due to airspace structure.

Furthermore, rogue aircraft that are entering the airspace without obeying to the traffic rules need to be considered.
4 Concept 1: Full Mix [TU Delft]

This chapter presents an overview of the Full Mix concept, the concept with the lowest structuring of traffic flows in the METROPOLIS project.

4.1 General Description

The Full Mix airspace concept can be most aptly described as “unstructured airspace”, where traffic is subjected to only physical constraints, such as weather and terrain height, see Figure 4.1. The philosophy is that, as the demand in this scenario is unstructured, any structuring of the airspace will reduce the efficiency of the flights. It is hoped that this design philosophy will simultaneously increase capacity as well as system-wide safety by allowing self-regulation of air traffic. In this concept, there is no separation by airspace structure between Personal Aerial Vehicles (PAVs) and Unmanned Aerial Vehicles (UAVs). A minimum Air Traffic Flow Management (ATFM) is applied to prevent excessive loitering of aircraft, thereby increasing the efficiency and decreasing the environmental impact (in terms of sound and air pollution) of the largely unregulated concept.

![Figure 4.1: Artist impression of the Full Mix concept](image)

4.1.1 Full Mix-Free Flight Relationship

The Full Mix concept adopts the Free Flight principles of Airborne Separation Assurance (ASA) and direct routing [8]. With ASA, Air Traffic Control (ATC) maintains overall strategic control over the traffic to manage the capacity of the airspace, while tactical Collision Detection and Resolution (CD&R) tasks are delegated to each individual aircraft, see section 4.2.3 for more details. This decentralized, or distributed, control architecture is expected to result in higher robustness when compared to centrally controlled airspace designs as failure of the central node does not affect the safety of the entire system [1]. The principle of direct routing reduces distances traveled by aircraft, thus reducing fuel burn and associated trip costs.

ASA and direct routing have also been shown to decrease the effective conflict rate when compared to traditional centralized ATC with rigid airway based route structures [1]. This is because the (theoretical) frequency with which conflicts occurs increases linearly with traffic volume for ASA and quadratically for centralized ATC [9], see Figure 4.2. As a consequence of the reduced conflict rate for ASA and direct
routing, traffic capacity for the Full Mix concept is expected to be significantly higher than for centralized airspace designs, without significantly affecting safety.

![Conflict rate in case of decentralized (Air) and centralized (Ground) separation responsibility depending on traffic volume](image)

**Figure 4.2: Conflict rate in case of decentralized (Air) and centralized (Ground) separation responsibility depending on traffic volume**

### 4.1.2 Route Planning and Trajectories

As mentioned above, the direct routing principle is used in the Full Mix concept. Consequently, the path planning algorithm for PAVs has to compute the shortest trajectory between the origin and destination runways. For UAVs, the path planning algorithm has to compute the shortest trajectory between a maximum of four cargo delivery locations, as well as the trajectory between the first and last cargo delivery location to the distribution center. Inputs necessary to implement the path planning algorithm are the origin and destination runways for each PAV, and the cargo delivery/demand locations for each UAV.

As centralized ATC is not responsible for separation of aircraft, ATC does not require flight plans to be filed prior to take-off. A centralized responsibility role in reality will be a safeguarding of the total capacity of the airspace, if there is a risk that this will be exceeded. This means that a flight plan might still be required for ATFM purposes. As we do not know these limits right now (as a matter of fact this project aims to produce data to contribute to this ability) this aspect can be ignored in the scenarios used in this project.

### 4.1.3 Airspace Usage Restrictions

**Altitude Restrictions**

Similar to all other airspace concepts, PAVs and UAVs must cruise at least 150 meters and 30 meters, respectively, above buildings to prevent traffic from colliding with buildings, as well as to reduce the need for CD&R with buildings during cruise. The consequent minimum safe altitude above buildings for each zone of the city is listed in section 3.1.1. All air traffic must stay below 6500 ft, to separate local
urban air traffic from commercial aircraft overflying the city. Apart from the above stated lower and upper airspace limits, there are no other altitude restrictions in the Full Mix concept.

**Velocity and Heading Restrictions**

For the Full Mix concept, aircraft are free to fly at their design cruise velocity for maximum efficiency. Above the minimum safe altitude, there are no heading restrictions. Below the safe altitude, aircraft must fly the heading of the runway they are landing at (or took-off from) to avoid collisions with buildings. As all landing strips are located on raised platforms above streets, see section 2.2.2, runway headings are equal to the heading of the street over which the runway is located.

**4.1.4 Take-off and Landing Procedures**

As PAVs and UAVs must fly between buildings during the climb and the decent phases of flight, common take-off and landing procedures have been defined for all concepts, see section 3.1.3.2.

**4.2 Flow Management, Separation and Conflict Avoidance**

**4.2.1 Air Traffic Flow Management**

The Full Mix concept is a static airspace design, hence no adjustments are made to the airspace design as traffic volume varies throughout the day. However, in reality, all PAVs must receive take-off clearance before departure. This is to prevent unnecessary loitering at destination runways. This granting of take-off clearance represents the sole flow management task for ATC in the Full Mix concept.

Since the landing phase of flight is not simulated in this project, see chapter 3, neither take-off clearance nor take-off queuing will be considered for the Full Mix concept for the batch simulations conducted in WP4. Consequently, aircraft will take-off as soon as they are spawned in the simulation. Although this deviation from reality will affect absolute airspace capacity measured during the simulation, by considering aircraft arrival sequences at each runway, the effect of loitering can be taken into account when analyzing the simulation results.

**4.2.2 Separation Requirements**

**Structural Separation of Aircraft Types**

As mentioned earlier, there is no structural separation between PAVs and UAVs in the Full Mix concept. Thus both aircraft types are free to use the same airspace. However, performance differences (particularly cruise velocity) between the PAVs and UAV selected for the METROPOLIS project are expected to separate these two vehicle types in practice. Nonetheless, the same CD&R algorithm applies to both types of aerial vehicles, albeit with different parameter values for minimum separation requirements.
Minimum Separation Requirements

The minimum separation requirements between vehicles are common to all airspace concepts in the METROPOLIS project, see section 3.1.3. These requirements are particularly important for the Full Mix concept as PAVs and UAVs are allowed to use the same airspace. For conflicts between PAVs and UAVs, the PAV separation requirements apply.

4.2.3 Conflict Detection and Resolution

Conflict Detection and Resolution (CD&R) is the most important aspect of airspace design as it has a direct influence on safety. The CD&R approach used for Full Mix can be classified into short term and long terms strategies. Additionally, a third procedure is defined for unlikely emergency situations.

Short Term CD&R

The Modified Voltage Potential (MVP) algorithm developed for Free Flight will be used to resolve short term conflicts [8]. MVP computes conflict resolutions using a geometrical state based approach. Here, no intent information is exchanged between aircraft. Instead, each aircraft transmits its own instantaneous altitude, position, velocity (horizontal and vertical) and heading to all other traffic by means of Automatic Dependent Surveillance-Broadcast (ADS-B). Using this data, future aircraft positions can be estimated by extrapolating the transmitted state information over a predetermined look-ahead time.

As stated above, MVP uses a geometrical approach for conflict resolution [8]. Here aircraft have to maneuver such that the distance between two conflicting aircraft at the Closest Point of Approach (CPA), is equal to the minimum separation requirements [9]. This geometrical resolution method is illustrated by Figure 4.3. For conflicts involving multiple aircraft, the MVP algorithm will be applied sequentially, starting with the closest conflict pair.

![Figure 4.3: Geometrical conflict resolution method of MVP](image-url)
The Full Mix short term CD&R approach uses implicit cooperative maneuvering i.e., when a conflict occurs between two aircraft, both aircraft maneuver until the conflict is resolved. Subsequently, both aircraft fly their resolution, or avoidance, vector until the CPA, after which they are free to return to their original trajectories. A major advantage of implicit cooperative conflict resolution is that safety can be assured as it requires only one of the two aircraft in a conflict pair to act to resolve that conflict. Implicit cooperation also implies that all aircraft have equal priority for short term CD&R.

Simulations were conducted to determine the minimum look ahead distance for short term CD&R. These simulations revealed that a look ahead distance of 2500 meters (ten times the separation minima) is needed to stay within the performance capability of the AW609 (the fastest PAV in the METROPOLIS project) for all possible horizontal conflict geometries. Figure 4.4 and Figure 4.5 display the resulting velocity and heading changes necessary (for the maneuvering AW609 in a conflict pair) at a look ahead distance of 2500 meters.

![Figure 4.4: Speed change necessary for the maneuvering aircraft in a conflict pair, at a cruise velocity of 275 knots, and an intruder distance of 2500 meters, for all horizontal conflict geometries. The red dashed line represents the maximum speed change capability of the AW 609 during cruise.](image)

![Figure 4.5: Heading change necessary for the maneuvering aircraft in a conflict pair, at a cruise velocity of 275 knots, and an intruder distance of 2500 meters, for all horizontal conflict geometries.](image)

The maximum acceleration and turn rate needed to apply the speed and heading changes displayed in Figure 4.4 and Figure 4.5 are 0.34 m/s² and 0.71 deg/s, respectively. This is within the performance capability of the AW609. Simulations for the other PAVs in the METROPOLIS project revealed that the maximum acceleration and turn rates needed for each aircraft, at a look ahead distance of 2500 meters, was within their capabilities.

Using the same simulation structure, albeit with different separation requirements, it was determined that a minimum look ahead distance of 250 meters is needed for conflicts involving a pair of UAVs, such that the resulting acceleration and turn rates are within the capabilities of the selected Microdrones MD4-3000 UAV.

A 20 % safety margin was applied to the above mentioned look ahead distances for both PAVs and UAVs to account for three dimensional conflicts. The resulting look ahead times for short term CD&R,
assuming a velocity of 103m/s for the AW609 and 16 m/s for the MD4-3000, are listed in Table 4.2 below.

The MVP algorithm is already implemented in TMX, the simulation software used in the METROPOLIS project. For short term CD&R, the conflict resolution method selected depends on whether an aircraft is climbing/descending or if it is in level flight. Table 4.1 below lists the preferred order of conflict resolution methods to be used for the Full mix concept.

Table 4.1: Conflict resolution for Full Mix

<table>
<thead>
<tr>
<th>Climb/Descent</th>
<th>1. Vertical Speed</th>
<th>2. Speed</th>
<th>3. Heading</th>
</tr>
</thead>
</table>

Long Term CD&R

To reduce the number of conflicts that need to be solved using the MVP conflict resolution algorithm, the Full Mix concept also uses priority rules that are active at twice the look ahead time for short term CD&R. Long term conflict resolutions are applied by means of altitude changes alone. Here, the aircraft with the lower priority is required to climb or descend 'out of the way'. This is because altitude changes have been shown to be the most energy efficient way of resolving conflicts. A choice between climbing or descending is made based on the instantaneous traffic situation such that no new conflicts are created. The priority of different vehicle types is in the following descending order:

1. Non-VTOL aircraft
2. VTOL aircraft
3. UAVs

Non-VTOL aircraft have the highest priority as they have more constrained flight envelopes when compared to VTOL aircraft. As UAVs are unmanned, they are defined to have the lowest priority. Furthermore, cruising aircraft have priority over climbing/descending aircraft.

Preliminary simulations will be conducted to ensure that priority rules do not interfere with short term CD&R. For instance, priority rules should not trigger additional conflicts that need to be solved using short term CD&R. If interferences are found, the look ahead time for priority rules will be adjusted heuristically. However, if no optimum look ahead time can be found, priority rules will be removed from the CD&R procedures for Full Mix.
Table 4.2 summarizes the look ahead times recommended for short and long term CD&R.

<table>
<thead>
<tr>
<th></th>
<th>PAVs [s]</th>
<th>UAVs [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short term CD&amp;R</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Long term CD&amp;R</td>
<td>60</td>
<td>30</td>
</tr>
</tbody>
</table>

**Emergency CD&R**

In the unlikely event that two aircraft are in conflict at very close proximity due to the complete failure of (redundant) short term CD&R equipment (on both conflicting aircraft), automated TCAS (Traffic Collision Avoidance System) is used to avoid collisions. TCAS is designed such that it is completely independent from the other CD&R systems, including separate sensors and computers. The TCAS resolution maneuver is automatically implemented by the aircraft autopilot, thus overriding the commands of the aircrew (should they attempt to manually steer into a conflict).

For emergency CD&R, the look ahead time is defined as half that of short term CD&R, i.e., 30 seconds and 15 seconds for PAVs and UAVs respectively.

NOTE: The batch simulations to be conducted in WP4 assume robust communication of aircraft positions and speeds. Therefore, both short and long term CD&R will be implemented for the simulations. Emergency CD&R procedures will not be addressed in the simulations, but are described above to provide the complete range of CD&R possibilities that would be available in reality.

### 4.3 Handling of Abnormal Situations

#### 4.3.1 Rogue Aircraft and Meteorological Conditions

Just as with road traffic, it is reasonable to expect that a certain number of aircraft will not conform to CD&R procedures, for a wide variety of reasons (including deliberate rule-breaking and/or technical failures). It is necessary to consider how the airspace concepts investigated in the METROPOLIS project will handle these ‘rogue aircraft’, and their impact on overall capacity and safety of each concept.

Thanks to the co-operative maneuvering strategy of the MVP CD&R algorithm, see section 4.2.3, in Full Mix, conflicts can be easily avoided if a nominal aircraft interacts with a rogue aircraft. If two rogue aircraft interact with each other, TCAS can be used as a last resort to resolve the conflict. Therefore, it is anticipated that the unstructured and unconstrained nature of Full Mix, combined with MVP, allows rogue aircraft to be handled without much difficulty.

Meteorological phenomena, such as wind and precipitation, will primarily affect the minimum separation requirements needed to maintain safety levels, as well as the availability of take-off and
landing sites. This in turn will have a direct effect on the capacity of the airspace. Furthermore, aircraft may require rerouting for high intensity meteorological phenomena.

Only rogue aircraft will be simulated in Work Package 4 using dynamic no-go airspace volumes that move stochastically across the METROPOLIS simulation area. In the simulation, the location and speed of the no-go volumes will be communicated to all the aircraft over the METROPOLIS city. Using this information, the path planning algorithm will simply re-route aircraft around these no-go volumes such that the deviation from the optimum direct route between the origin and destination of each aircraft is as little as possible. As there are very few airspace restrictions for Full Mix, these no-go areas should (in theory) be easily handled by this concept.

4.3.2 Robustness of Aircraft State Transmission System
The MVP CD&R algorithm requires knowledge of speed, heading and altitude states of aircraft within the look ahead time. Therefore the quality and robustness of the state information transmitted between aircraft has a significant impact on the ability of the MVP algorithm to satisfactorily resolve conflicts. Current airborne surveillance methods, such as ADS-B and GPS, have latencies and inaccuracies that may be too high for the accurate maneuvering needed in obstacle rich urban environments. However, the accuracies of these systems have improved significantly over the past decade, and these improvements are expected to continue. Consequently, the METROPOLIS project assumes that by 2050, aircraft surveillance technology has matured to a point such that the MVP algorithm can be implemented with high confidence in urban areas.
5 Concept 2: Layers [DLR]

This chapter presents an overview of the Layer concept, this concept structures the traffic flows by limiting the direction of flight depending on the altitude.

5.1 General Description

As a general condition only the airspace between 300 (minimum safe altitude) and 6500 feet will be used for the definition of layers.

![Figure 5.1: Schematic design of a layer concept](image)

This strategy can be influenced by the following boundary conditions:

- Usage of prescribed main cruise flight directions per layer and the angle of these directions (e.g. semicircular cruising layers, quadrant cruising layers with 90 degree angle or eighth layer with 45 degree angle).
- UAV level layers will be separated from the PAV level layers by a separation layer.
- Transition through level layers for climb, descend and vertical conflict avoidance manoeuvres is always allowed.
- Implementation of a feeder layer, which is used by UAVs and PAVs to reach MSA after takeoff and for landing (The Heading inside the feeder layer stays constant with the direction of the runway)

The portioning of the airspace into the feeder layer and level layers separates higher altitude traffic areas with homogenous traffic from traffic with divergent directions or flight altitudes. The feeder layer is the lowest layer and will be used in general for continuous climbs and descents with constant heading after takeoff or before landing. On top of the feeder layer, starting at an altitude of 1100 ft a level layer system for UAVs is located, followed by a separation layer and a PAV level layer system (at 1650 ft).

The lowest part of the airspace above the minimum altitude of 300 ft consist of the feeder layer that is mainly used to offer enough space for climbing and descending PAVs and UAVs. Especially in the city center buildings can reach heights of up to 1000 ft. In the dimensioning of the feeder layer flying over buildings, with a safety buffer for collision avoidance for UAVs, is also taken into account. In consequence the feeder layer is extended to 1100 ft.
Based on the fact, that UAVs and PAVs have to stick to their heading until MSA, PAVs will also use the UAV level layers as “feeder layer” to reach the PAV level layer system. Under these circumstances PAVs have priority and UAVs are in charge of conflict resolution.

After passing MSA at 1500 ft, there is a Separation Layer located, which is first used for PAVs to turn to their designated heading to reach its destination and further climb. On the other hand it is also used to have a safe separation between UAVs and PAVs. For this purpose the minimum vertical PAV separation of at least 300 ft is applied. The normal UAV and PAV traffic will take place in separated level layers, whose vertical dimension comply with the required vertical separation minima. Layers for PAVs are separated by 300 ft and for UAVs by 50 ft. Every level layer can be transited for climb and descend.

For general aviation aircraft the airspace is vertically divided into so-called semicircular cruising levels with an angle of 180 degree. But it must be assumed that today the number of GA aircraft using a predefined part of the airspace at the same time will be considerably lower than the number of PAVs in the year 2050 for a similar area. Therefore, it is much more important to demerge the expected traffic by an advanced segmentation of the airspace using smaller angle ranges.

A segmentation of the airspace into layers of 300 ft vertical dimension with eighth cruising layers will lead to 16 possible levels in addition to a feeder layer. Whereat the highest level layer called “safety layer” has a reduced vertical extent of 50 ft. When using 16 level layers together with an angle of 45 degree there will be two layers for each flight angle. The advantage of this is that two sets of layers can be used for separating the traffic further depending on special flight parameters like the possible flight altitudes which can be handled by the different PAV types, the planned flight distance or speed restrictions. So, in this case the layers are separated into two layer groups (lower and higher layer see Figure 5.2). Another possibility can be the restriction of one layer group to PAVs with a certain minimum number of passengers (compared to “fast lanes”), which might be an option for further developments.
Looking ahead, the trajectory planning in the year 2050 will be able to calculate highly accurate results, taking into account many factors like performance data, weather characteristics or other parameters. This fact makes it possible to have a mixture of aircraft equipped with different performance characteristics, especially speeds. Nevertheless the two different sets of PAV Layers makes it possible to separate fast flying AW609 from slower flying PAL-Vs. In consequence the AW609 will always use the upper layer system, while PAL-V only fly in the lower layer system. The TF-X will use both layer sets depending on the travel distance to be flown. If the distance exceeds a minimum of 15 NM the TF-X will use the upper layer system and for short distances below 15 NM the lower layer system will be used.

Above take-off and landing sites there is the need to implement tubes or cones, which enables the PAVs to transit through the feeder layer and level layers to reach their preferred level layer. Based on the fact that PAVs have to accelerate to a certain speed to enter the level layer, take-off procedures will not completely be vertical. The same applies to landing procedures, since PAVs won’t be able to reduce their speed close to zero in the level layer for safety reasons to vertically land on a site. In this case it is to be assumed that TF-X or even the PAL-V will climb and descend inside an angle range of 3 to 20 degree. So for take-off and landing procedures there will be several tubes or rather laying cones to reach the first set of level layers, meeting the requirements of each PAV and the wind regime. These “cones” are implemented only to pass the UAV layer system safely. It represents a protected zone which is prohibited for UAVs. After reaching MSA at 1500 ft PAVs can transit through the layer system freely.

**Figure 5.2: Layer system for UAVs and PAVs.**
For better understanding an example flight shall help to illustrate the basic layer concept in a more detailed way. A PAV will depart on Runway 27 at its origin and fly a southerly heading of 190° to land on Runway 09 at its destination. After takeoff the PAV will have a constant heading of 270 degrees as long as the MSA is passed. Climbing through the UAV layer system always takes place without interruptions caused by UAVs due to a temporary cone surrounding the climbing path, representing a prohibited zone for UAVs. Above MSA the PAV will start to change its heading to at least 180 degrees to enter the level layer (180° to 225°) at an altitude of 2850 ft. While the aircraft reached the PAV level layers, it has to keep on climbing up to the layer leading south (190 degrees). Therefore it climbs freely to pass 4 level layers and reach its final level Layer with heading restrictions from 180 to 225° (see Figure 5.2). Getting close to the destination the PAV will leave the cruise phase by descending with a heading of 90° through the layer system. Reaching the UAV system a protected zone separates UAVs from PAVs.

Based on the fact that the METROPOLIS project focuses its studies on the influence of airspace structure on capacity, a decentralized control will be applied in all four concept designs. Therefore each PAV or UAV will take care of conflict detection and resolution individually. The PAV calculates its trajectory, taking parameters like airspace restrictions, cost effectiveness or travel time/distance into account. Furthermore the resulting level layer for the cruise phase depends on the main flight direction. The passenger is able to choose between different options concerning the routing. As a possible approach the shortest connection between origin and destination is always a possible option for the user. This means that the direct connection between origin and destination is considered and the PAV climbs to the respective layer that allows the flight in this direction, resulting in the PAV to have to take a short detour since it may have to fly in different directions during climb and descent due to the runway direction. In case of potential conflicts the level for the avoidance is restricted to flight angles which are allowed inside the respective layer. The lower the allowed flight angle of the used level will be, the less possibilities for conflict solving procedures exist without violating the restrictions. Detection of possible collisions is triggered by the defined look-ahead-time. Conflict resolution in the next step can be achieved by introducing the strategy of speed and heading changes, climb or descend. To enable conflict detection and resolution to PAVs or UAVs an exchange of information among each other is an indispensable fact.

5.2 Flow Management, Separation and Conflict avoidance

Centralized vs. distributed CD&R

There are two different possibilities for the responsibility for Conflict Detection and Resolution during flight (CD&R). It can be carried out by

- ATM / ATC or
- PAV (-User).

In the first case ATC will carry out the CD&R for all flights in the responsibility area. They will have a complete overview about all other movements and in case of flight plans of the intentions of the other PAV users. Therefore, they are able to identify possible conflicts in advance with a high time horizon and
can solve them by adapting the flight trajectory lateral, vertical or by speed adjustment. ATC has a very high look-ahead capability during flight. In the second case the look-ahead capability will depend on the type of CD&R system onboard the PAVs.

In 2050 it will be possible to install a similar system with complete information like the one ATC would use, sending every known PAV trajectory to all moving PAVs together with all trajectory updates. Furthermore, a sequence for the calculation of new trajectories for affected PAVs will be defined to avoid situations where the CD&R system calculates the trajectory on the basis of outdated information. Another possibility for PAV-based CD&R could be the use of protected zones around each PAV. It should have a dimension which allows the PAV to avoid conflicts by climb, descend or turn in sufficient time. In this case the PAVs should have information about the trajectories of all other PAVs within a certain distance. In case of conflicts the affected PAV-CD&R-systems have to negotiate the necessary evasive movements.

In consequence just like the Full Mix Concept decentralized control will be applied. In this case the main focus on capacity studies will be comparable among the different airspace concepts.

Each aircraft takes care of conflict detection and resolution (CD&R) individually by using the Modified Voltage Potential (MVP) algorithm. To resolve a conflict, flight parameters of each aircraft are needed. Therefore PAVs and UAVs transmit their position, heading and speed to all aircraft in their vicinity. Based on the fact that the allowed heading of each layer (except for the feeder layer) is limited to 45 degrees in this concept and PAVs can freely climb and descent through the layers, head-on conflict might occur. For conflict detection and resolution a look-ahead time is necessary. For this concept two PAVs can converge the fastest, when their headings differ by 180 degrees. Taking two AW609 going 200 kt (103 m/s) and a horizontal separation (system requirements) of 250 meters between them, it takes about 1 sec until they meet. A safe approach for the AW609 is to have a 2500 meter minimum look ahead distance (see section 4.2.3), which can be achieved by having a 30 second minimum safe look ahead time for short-term CD&R (including a 20 % safety margin). In case of UAVs a head to head conflict is possible at any time. For UAVs the minimum safe look ahead distance is 250 meters (1/10th of PAVs), so 15 seconds represents the minimum look-ahead time for short-term CD&R.

For long-term CD&R the look-ahead time will again contain a 100 % safety margin. Only in case of altitude changes long-term CD&R in combination with priority rules will be applied. In general PAVs have priority over UAVs, while inside the layer system cruising aircraft have priority over climbing aircraft. For conflict resolution the following principles will be applied for interactions between climbing and cruising aircraft:

1. Change of vertical speed,
2. Reduce of normal speed, or
3. Heading change.

Inside a Level Layer there also might occur conflicts between two cruising aircraft. In this case the following rule will be applied:
1. Heading change, or
2. change of speed.

The following table summarizes the look ahead value for CD&R.

<table>
<thead>
<tr>
<th></th>
<th>PAVs [s]</th>
<th>UAVs [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-term CD&amp;R</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Long-term CD&amp;R</td>
<td>60</td>
<td>30</td>
</tr>
</tbody>
</table>

If for some reason a failure of CD&R occurs, TCAS will take control over collision avoidance in emergency. It is independent of CD&R and doesn't allow any manual control input to not generate further conflicts.

**Flow Management (Pre Departure/Pre landing)**

The main assumption in relation to flow management will be the usage of the “First-Come, First-Served” principle. Due to a distributed control system there is the need for a pre departure planning. The easiest and most efficient way to avoid any loiter is to implement an authority taking care over pre departure and pre-landing sequencing. Therefore the preferred departure time needs to be filed. It is conceivable that besides the time of the request delivery also the adherence to departure times is decisive. If someone deviates from the before requested departure time very often a time penalty could be added to the actual takeoff time. In case of a missed departure slot an automatic creation of a new departure time should be carried out.

Besides Pre departure planning the sequencing of arrivals in a distributed control system causes much more difficulties. Therefore the PAVs have to transfer their estimated landing time to the authority at least 10 minutes before arrival. Due to individual trajectory planning the landing sequence is generated by sorting the PAVs by arrival time. Before entering the landing cone in this concept a clearance has to be given.

**Trajectories**

As mentioned before trajectories should be created in coordination with the passenger. The angle of evasive maneuvers should be restricted to allowed flight directions. Furthermore, for PAVs which are already flying a prediction for the development of the actual trajectory in comparison to the planned trajectory will be necessary (monitoring and automatic update functionality) together with an automatic conflict detection and resolution. Any change of destination during flight will not be considered in the simulation though.
Demand Capacity Balancing over Time

It can be assumed that the traffic to and from special parts of the observed city area will differ highly in density and used flight directions over time. This is caused on one hand by commuter traffic and on the other hand by recreational facilities which will attract many people after closing times and at weekends. A solution would be to allocate flight directions to layers in dependence of the expected traffic distribution over day, e.g. only one layer in low traffic times and three in case of high traffic. Using the proposed concept (see Figure 5.2, page 39) it would be possible to use one set of layers as standard layer and advise layers from the second set in dependency of traffic requirements.

Another possibility for balancing the expected traffic could be the introduction of a time dependent departure / landing fee system where the most desired or overbooked times at special take-off- and landing spots are much more expensive than the usage of a nearby spot or another time. As a modifier the number of passengers could be used so that it of interest for the people to establish ride sharings.

5.3 Take-off and Landing Procedures

Based on the distinction between the different layers (feeder, UAV and PAV level) it is necessary for PAVs to transit feeder and UAV level layers to reach MSA. To transit through these layers safely a type of tube or cone will be established. These cones meet the requirements of the different PAVs, which will not take-off and land completely vertical due to acceleration for entering and deceleration for exiting the first/last PAV level layer. To cope with the requirements given by the different PAV types every cone allows climb and descend angle range of 3 to 20 degree seems to be a realistic assumption. In Figure 5.3, the cones are shown in a simple way for take-off and landing sites that are already in line with the runway direction and an exemplary climb/descend angle of 10 degrees. Furthermore the cones offer an opening angle of +3 degrees to generate more space in the upper UAV layers and make smooth Heading changes possible for PAVs. In addition to this climb cone, a descend cone exists which works the other way around. Additionally the cones represent a restricted area for UAV operations.

Figure 5.3: Take-off and landing cones exemplary for PAVs for two different sites already in the direction of the runway
To compensate for any type of delay or waiting time several options can be introduced. During flight options cover:

- speed adjustments,
- holdings patterns,
- hovering (for VTOL only) and
- path stretching,

Speed adjustments are most valuable during low frequented periods due to less affected aircraft in the same layer. A high traffic volume is not suitable for speed adjustments since a high amount of additional conflicts are generated. Located in the upper section of the climb and descend cone it is conceivable to implement either holding patterns or hovering areas. It is also possible to enlarge the cone to create more space for holding or hovering. Separated from traffic in the level layer and the UAVs, it offers an acceptable solution. Path stretching as another option has the consequence of inserting additional climb and descend phases for the flights since the flight directions of each layer are limited, and therefore doesn’t seem to be an optimal option for the layer concept. Looking at the demand during evening rush hour for take-off and landing sites inside the simulation area gives an idea on the capacity utilization. During 15 minutes about 8731 PAVs (Scenario 4, Table 8.4) are allocated to 1600 sites (based on simulation area). Assuming an equal distribution between each site, in average every 2.8 minutes a take-off or landing will take place at all 1600 sites in the experimental area. Due to an unequal distribution, the utilization will be much higher, which in consequence will make holding, path stretching or other options to compensate waiting time, necessary. Which option will be applied in the end depends on the traffic situation and should be selected by taking the lowest effect on cruising traffic into account. On the other hand PAVs having a delay for takeoff should be held at the parking position until they get a new slot. The following takeoff separation depends on the individual performance of the PAVs and the space offered by the cone angle.

5.4 Handling of abnormal situations

Abnormal situations like different weather phenomena or even temporarily restricted areas always affect flight operations. For PAVs the driving force is the certification of the vehicle, which maximum permissible value for wind or precipitation like snow, hail or rain. Since most extreme weather conditions are local phenomena, it might be possible to just close sections of a layer and go around it. Thunderstorms provide additional risks due to lightning and extreme winds, which most likely will lead to dismissal of any PAV flight operation in the vicinity of the respective area. In all these cases and especially in high wind scenarios, it is advisable to increase the protected zones and separations of PAVs. In terms of visual conditions it can be assumed that PAVs are highly automated so in consequence no visual minima will be required.
Dynamic no-go areas (included in the validation phase) could affect several layers, but will only be of local appearances. So in consequence the layer concept will offer enough space to go around (either by climbing/descending or by horizontally avoiding) this restricted area. Also the wind implemented in the Simulations doesn’t represent a problem for the layer concept. In all layer there is enough space offered to compensate any changes in heading.

For simulation purposes only rogue aircraft and Wind will be considered in the validation phase. Rogue aircraft are comparable with dynamic no-go areas and easy to handle for the layer system. With the option of heading change or even climbing to a different level layer will at most cause a deviation of 45 degrees.
This page intentionally left blank
6 Concept 3: Zones [ENAC]

This chapter presents an overview of the Zone concept that structures the airspace into different zones based on vehicle types, speed ranges as well as global directions.

6.1 General Description

The Zone concept 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. In addition, different vehicle types have their own zones that are almost fully separated.

UAVs operate in the airspace that covers the distribution area of the associated distribution centre and is vertically separated from the airspace where other vehicles like PAVs operate. This airspace also excludes landing and take-off areas designed for other vehicles that pass through this airspace (Figure 6.1). This is the lowest vertical airspace that lies just above MSA (Minimum safe altitude). In this airspace UAVs fly at the same level and use a pre-defined airway structure. As UAVs of one distribution centre only serve customers within this area, airway topologies of different distribution centres are therefore fully separated and there are no exchange routes between them. The same airway topology for UAVs exists in the entire metropolitan area (centre, inner and outer area). Between MSA and minimum altitude for PAVs, several layers of UAV topologies may exist.
Higher levels of metropolitan airspace, above UAV airspace, are assigned to PAVs. In this airspace traffic is organized into flows following nearly the same direction and speed in a given area. Speed and the flow structures are controlled by an external authority (like current ATC) and may vary during the day. To ensure that every user is able to connect any pair of points in the METROPOLIS area in a safe and efficient manner, METROPOLIS airspace is then divided into several airspace areas each possibly consisting of several zones:

1. Collector/Distributor area – the objective of this area is to enable both inbound and outbound traffic to and from the city centre,
2. Outer ring – airways structure in the outer and inner city area that enables traffic between minor centres of activities that are out of the core city area,
3. Major flow area – serves major centres of activity within the core city area with the highest traffic volumes,
4. Traffic exchange area – connects the major flow area with a landing and take-off area, organizing climbing and descending traffic into a safe manner, and
5. Landing and take-off areas – include pre-defined routes that enable traffic from/to MSA to/from landing strips during approach/Departure procedures.

### 6.2 Zone topology

The topology of the zone concept is based on the assumption that the shortest route (Euclidian distance) is always preferable in METROPOLIS airspace, taking into account moderate travel distances and a low ceiling that prevents exploiting vertical flight efficiency. As a consequence all users will use the lowest available level to perform their flights.

Based on the general concept definition, UAV and PAV topologies are fully separated in space with possible interaction during departure/arrival procedures of PAVs (explained in 6.2.2.5 on page 57).

#### 6.2.1 UAV airspace topology

UAVs operate in the airspace that covers the distribution area of the associated distribution centre and therefore the entire Metropolitan airspace is divided into smaller airspaces each having a separate topology. Airway structures that connect a distribution centre with all drop-off points, are defined in the horizontal dimension with the same altitude for all UAVs flying on the same airways structure. Pre-defined departure and approach routes are used to connect landing/take-off spots with these structures.

In the horizontal dimension, the UAV topology has a grid-like structure that follows the street pattern and building layout of the city as shown in Figure 6.3. The streets of the city with a width of 30 m (light grey) and the size of the building blocks with a side length of 470 m (dark grey) result in a total width of 500 m per block as defined in the scenario definition report [1]. The green colour represents UAV airways that are centred on the city’s streets. Having drop-off points located on the top of every city block and an airway structure that is on the top of city streets, laterally displaced from them, a direct vertical connection between landing/take-off spots and airways is not possible. Therefore pre-defined
departure and approach routes for UAVs consist of two parts: first, a horizontal part that connects an airway with a connection point (point that is located above landing/take-off spot at the same horizontal plane as the airway structure) and second, a vertical part from the connection point to the landing/take-off spot. In Figure 6.3, the orange points represent connection points, while the horizontal parts of the approach and departure routes are marked with orange lines.

PAV approach/departure routes use the same airspace as UAVs. To reduce interaction with UAV traffic, airway structure is established on top of every second city street block. This results in almost 1 km of space between two consecutive UAV airways. Although every distribution point (one distribution point per city block) would be reachable from the distribution centre, having a one-way airway structure would additionally increase flight distance\(^2\). To keep flight distance moderate, a bi-directional airway structure is designed as shown in Figure 6.3. Each pair consists of two airways with opposing flight directions that are separated by 50 m allowing independent operation on both airways simultaneously. This increases traffic complexity at intersections that are therefore designed in a roundabout-like pattern.

\(^2\) grid-like structures requires longer routes compared to direct routes – Manhattan distance vs. Euclidian distance
Figure 6.4 shows an octagonal airway intersection structure that allows distributed traffic management on-board of each UAV. Each side of the octagon is 50 meters in length; consequently UAVs may enter the intersection only if there is no other traffic on preceding and succeeding octagon arcs.

The first layer of the airway structure is situated at MSA, 30 meter above the highest building in each distribution area. With 400 ft between MSA for UAVs and MSA for PAVs, several layers of airway structure can be designed on top of each other. Separation between two successive layers is restricted by the minimum vertical separation requirement between two UAVs. Between a distribution centre and a drop-off point or between two drop-off points UAVs fly at a given airway layer (altitude) and change of the layer during this flight leg is prohibited. Higher layers would only be used when required by traffic demand and only to increase capacity.
6.2.2 PAV airspace topology

Unlike the UAV topology that is divided into small zones covering one distribution area, the PAV topology spans the entire Metropolitan area and links all possible origin-destination pairs. The initial idea of the zone concept is that mixing all traffic types (all origin-destination pairs, all aircraft types, and all flight phases) would reduce system capacity. Therefore, to ensure sustainable capacity regardless of the traffic mix as well as safe and efficient operations, METROPOLIS airspace is divided into several parts of airspace each having PAV traffic organized into flows following nearly the same direction and speed.

6.2.2.1 Collector/Distributor area

The main objective of this area is to drive both inbound and outbound traffic flows to and from the city. The Collector/Distributor area connects the outer area (ring) and part of the inner area of the METROPOLIS city. Having vehicles coming and going mainly from and to the city, this area has been designed as a disk shape in the horizontal dimension with sector-like zones on which traffic is going in one direction (Figure 6.6). Each zone gathers together two segregated flows moving in opposite directions (inbound and outbound). The capacity of each flow is defined by the size of the associated angular sector. Such capacity is controlled by ATC by adjusting the virtual separation line (dashed lines in Figure 6.6). In the morning, having more inbound traffic, the associated sectors are larger than the one dedicated to the outbound flows. In the evening the situation evolves in the opposite direction.

![Figure 6.6: Top View of the Collector/Distributor Area](image)

In the vertical dimension the Collector/Distributor area includes the whole Metropolitan airspace from MSA up to the ceiling. For easier management of traffic that commutes within the entire METROPOLIS area, a single MSA is used for all city areas. Common MSA has a value of 450 meters as required by the highest buildings in the core city area. As a result each zone has a pie-shape in 3D space.

Designing flight routes for circular paths would require a large number of waypoints; instead a polygonal shape structure is used in the simulation environment of METROPOLIS (Figure 6.7). The metropolitan
area is then divided into eight zones (N, NE, E, SE, S, SW, W, and NW). Inbound traffic, going to the core city area, is merged into flows at the end of the collector area (red merging point in Figure 6.7). On the other hand, outbound traffic from the core city area is merged in a single flow at the beginning of the distributor area (green point on Figure 6.7).

### 6.2.2.2 Outer ring

Even though most of the traffic runs from a suburb of the metropolitan area to the central area of the city or in the opposite direction, there are commuters within the core city area as well as in the suburbs. Following the previously defined structure of the Collector/Distributor zones, flights having both origin and destination out of the city centre will have to fly to the city centre, change direction and then fly out of the city centre in the direction of their desired destination. This would unnecessarily increase flown distances and also increase congestion in the core city area. For this purpose, a peripheral airway structure in the outer and inner city area is designed that drives traffic between minor centres of activities that are out of the core city area (orange octagonal shape in Figure 6.8).
To minimize interaction with local traffic in the collector/distributor areas, outer rings are implemented in the horizontal dimension. Several layers of outer rings are designed, one every 1000 m, the first being at MSA (450 m). A protection zone around the outer ring represents a no-fly zone for crossing inbound and outbound traffic (Figure 6.9).

The outer rings are also used in emergency situations. In order to manage emergency situation in which the centre of the METROPOLIS area is fully congested, inbound traffic is rerouted into an outbound direction in a safe manner using the outer rings. When the inbound flow has to be rerouted outbound, it is first routed toward the closest outer ring and then merge with the regular outbound flow (see Figure 6.10).
6.2.2.3 Major flow area

When vehicles arrive above the city or when they want to depart from this area, they must be able to reach their destination points in a safe manner. In order to reach this objective, a major flow area is built as shown in Figure 6.11. Due to the high density in the core city area, traffic is structured ensuring a full separation of traffic in the 3D airspace.

![Figure 6.11: Major Flow Area – Horizontal View](image)

All flows are located in the horizontal dimension. However, inbound and outbound flows are located 100 m above the inner flow enabling independent simultaneous operations. Horizontal separation between inbound and outbound flow is 500 meters. Every intersection between inbound/outbound and inner flow features an interconnecting 3D structure that is used to merge traffic between the different flows (Figure 6.11 – left). The interconnecting structure has a width of 250 meters and a length of 500 meters to enable safe merging of the flows. Although each inner flow ring gathers one flow of traffic with the same direction, this direction is changed on every successive layer between anti-clockwise and clockwise direction. This structure results in more efficient (shorter) routes, because otherwise it might be necessary to travel around the full circle before reaching the required destination point.

When a user wants to reach a destination (purple point in Figure 6.11), he/she first selects the nearest inner flow ring close to his destination with the associated direction and then directly connects on this ring as shown on the figure.

---

3 During the merging, traffic at the interconnecting structure and inner flow is separated in the vertical dimension. With decreasing vertical separation, additional horizontal separation is provided by lateral displacement of the interconnecting structure.

4 500 m horizontal distance corresponds to 100 m vertical distance (that is how much inbound/outbound and inner flows are separated) with 10 degrees climb/descent gradient.
Considering the minimum vertical separation requirement between PAVs, there is an additional buffer between the layers. In total one layer of flows requires at least 200 meters of vertical airspace. However, a buffer could be increased due to safety reasons. The first layer is designed at an altitude of 450 meters (MSA). The vertical view of the major flow area is shown in Figure 6.12. NOTE: Inbound/outbound flows of the same layer are located in the same horizontal plane. The Inbound flow and outbound flow (red and green lines in the figure) are only separated horizontally; no vertical separation exists between them.

Figure 6.12: Major Flow Area – Vertical View

6.2.2.4 Traffic exchange area
The traffic exchange area is designed with the objective to connect the major flow area with landing and take-off areas. It represents the area where traffic can move in the third dimension, organizing climbing and descending traffic into a safe manner.

To avoid any interaction between climbing and descending traffic as well as between climbing/descending vehiles and cruising vehicles in the inner flows, the traffic exchange area and the major flow area are separated horizontally. To enable smooth transitions between climb/descend and the cruise phase of the flight, both left and right slope exchange tracks are needed. In Figure 6.13, red lines represent left slope exchange tracks and green lines represent right slope exchange tracks. Depending on the flow direction in inner flow tracks (rings), left and right slope exchange tracks are used for climbing and descending traffic as indicated in the figure. Every inner flow ring needs to have access to both exchange tracks. One full track in the core city area, consisting of inner flow and exchange tracks including buffers requires 2000 meters of horizontal airspace (Figure 6.13 – left). Multiple track structures cover the entire core area of the city (and more if required).
Independent of the inner flow direction, the “right-hand rule” always applies. This means that vehicles with the intention to descend should turn right from the inner flow ring, and vehicles should merge right into the inner flow ring after reaching the required altitude. For this purpose, an interconnecting structure in the horizontal plane is established. If one wants to change the current flow layer, this rule will no longer apply\(^6\). However, this is not a regular situation and vehicles will be advised to change the flow layer only in case of an emergency.

Horizontal separation of the major flow area and the traffic exchange area is not sufficient to prevent intersections between inbound/outbound flows and climbing/descending tracks in the exchange area. Therefore climbing/descending tracks have to be carefully designed (spread) allowing insertion of inbound/outbound flows between them.

\[^6\text{Anyhow this represents no problem to the operations.}\]
Figure 6.14 shows that two exchange area tracks have to be separated at least 1500 meters in order to meet the separation requirements with inbound and outbound flows between them. With a 10 degree climb/descent rate, these tracks reach a vertical separation of 100 meters between inbound/outbound flows when no horizontal separation exists. When no inbound/outbound flows need to be inserted, 1000 meters is enough separation between two exchange tracks. Climbing and descending tracks are established on both left and right slope exchange tracks.

Figure 6.15 shows a 3D view of a traffic exchange area. Left and right slope exchange tracks that are used to allow movement in the third dimension, are represented with red and green lines respectively. Climbing tracks are distinguished from descending tracks with solid lines compared to dashed lines. Red and green circles represent intersections of inbound and outbound flows with an imaginary octagonal prism in which all shown left slope (red) exchange tracks belong.

6.2.2.5 Take-Off and Landing Areas

When descending vehicles reach MSA (using spiral routes in the traffic exchange area) they can connect to their final destination using pre-defined landing routes (blue routes in Figure 6.16). The same principle is used for take-off, where vehicles use departure routes before reaching MSA (green route on Figure 6.16). Landing and take-off areas are designed to ensure safety of the flight in an area with possible high obstacles (buildings). For this reason the metropolitan street structure is used and landing/take-off routes follow the heading of the landing strip (that is aligned with street) using 10 degree climb/descent trajectories until MSA is reached.
Another issue is that PAV approach/departure routes use the same airspace as UAV operations. UAV airway structure (section 6.2.1 on page 48) is designed in such way as to reduce interaction between UAVs and PAVs. Having UAV airways on top of every second city street (block), PAV landing strips are located in the centre of this airway structure, as shown in Figure 6.17 (black circles). The density of PAV strips is one per 4 square kilometres.

Taking into account a 10 degree climb/descent rate and the MSA where the first layer of UAV airway structure is located, one may calculate that PAV landing/take-off routes reach MSA in the core metropolitan area (330 m vertically) after a horizontal flight distance of 1800 meters. Therefore, PAV
landing/take-off routes cross through the centre of an UAV airway block (green block in Figure 6.17) that is located two blocks away in the heading of the landing strip. As a result, three UAV airway blocks (equal to 12 city blocks, each airway block containing 4 city blocks) are closed for UAV drop-off (red exclusion zone in Figure 6.17). However UAVs may still operate on the airways structure\(^7\). In the inner and outer metropolitan areas, active PAV landing/take-off routes require closure of UAV drop-off in the orange exclusion zone in Figure 6.17. Finally, PAVs with VTOL capabilities might fly through the same airway block from which it departs/ where it lands, no matter of the city area (yellow exclusion zone in Figure 6.17).

Every landing strip is located at a street intersection, allowing for four landing/take-off routes that are used depending on wind direction. Theoretically, two adjoining PAV strips might have routes with different headings that will lead to intersecting routes and dependent operations. In that case, ATC would have to regulate lading/take-off directions, therefore it is concluded that PAV landing/take-off routes are independent of each other.

It is expected that the structure of the zone concept will self-sequence traffic before reaching a landing point. However, this structure enables to absorb some additional delay when the destination point is congested. Figure 6.18 presents an example in which a vehicle wants to land at point \(D\) and can select several position between \(P_{\text{init}}\) and \(P_{\text{final}}\) in order to postpone its landing at the destination. This process is the same as the one used in Air Traffic Control based on the point merge in a terminal manoeuvring area.

\[\text{Figure 6.18: Landing Buffer}\]

\(^7\) Simultaneous operations of UAVs and PAVs in the UAV airway block that is traversed by PAV landing/take-off route needs to be further studied. Horizontal separation between UAVs and PAVs, at the point when no vertical separation exists, is approximately 500 m.
6.3 Flow Management, Separation and Conflict avoidance

6.3.1 UAV operations and management

UAVs operate in the structured airspace that covers the distribution area of the associated distribution centre. This airspace is almost fully separated from PAV airspace allowing few management actions to control UAV traffic. Due to low operating speed of UAVs and their and hover capability, an automatic collision avoidance algorithm is easy to implement and should be very reliable.

Every UAV makes several deliveries before returning back to the distribution centre. The sequence of deliveries is optimized (common element) at pre-departure level, i.e. before the first flight leg. UAVs fly their optimal flight route following the airway structure between origin-destination points (one flight leg) avoiding other UAVs. The optimal route is issued by ATC. Based on congestion level, ATC always provides clearance for the lowest layer possible. Clearance is given for each leg separately and during one leg UAVs are not allowed to change the airway layer (altitude).

The sequence of UAVs is always respected (there is no overtaking of UAVs), and therefore speed on one airway segment is restricted by the slowest flying UAV on that segment. Following UAVs need to adapt their speed so that minimum safety separation is respected at all times. Due to similar performance (speed) of UAVs this raises no issue. At intersections of the airways, an octagonal airway structure is implemented (explained in section 6.2.1) such that it allows distributed traffic management on-board of each UAV. UAVs may safely enter the intersection only if there is no other traffic on preceding and succeeding octagon arcs. If a UAV is not able to enter the intersection between two UAVs that are already in the octagonal roundabout without violating minimum separation, than merging of the traffic is done by speed adjustment of involved UAVs through the negotiation process respecting the First Come – First Serve (FCFS) principle.

Due to interactions with PAVs in landing/take-off phase, UAVs need clearance for delivery or departure that is issued by ATC. Departing UAVs will simply be delayed on the ground; however the possibility that UAVs should wait for drop-off until a PAV departs/lands requires the design of a holding airspace. Thanks to hover capabilities of UAVs, UAVs simply need to be displaced laterally from the airway so they do not interrupt traffic on the airway. After conflicts are cleared, UAV operations (drop-off and departures) will be performed in FCFS order.

6.3.2 PAV operations and management

In the part of the airspace designed for PAVs, ATC is responsible for airspace organization and management. Airspace organization will establish an airspace structure in order to better accommodate associated demand (based on historical or forecasted data) while with airspace management, traffic is dynamically managed by imposing speed and other temporary restrictions. One rule is for example to reduce speed on high density areas in order to increase the overall safety. Demand and capacity balancing is done dynamically and capacity of the collector/distributor area is controlled by adjusting virtual separation lines between them.
Outside of the city’s core area, traffic is less (if at all) structured. To be able to fit such traffic into a structured network, several procedures are designed. In the collector/distributor area, angular sectors start organizing traffic into flow before entering the central area. Once traffic reaches the centre, it has to be merged into inner flow rings using an interconnecting structure (entrance ramp). Both procedures are done through local automatic collaborative decision making (negotiation process) and require gaps in the traffic flows. Although flow merging is done automatically, ATC has to ensure that merging is possible by controlling flow density. When flow density on an inner flow ring reaches a certain limit, ATC will not give clearance for routes that use this ring.

PAV operators are obliged to use designated parts of the airspace structure and to follow the route and restrictions set by ATC when operating such vehicles. Separation assurance is the user’s responsibility aided by advanced CNS systems that each vehicle is equipped with. In the flows (inbound, outbound, inner flow, and traffic exchange route) the sequence of PAVs is always respected and speed in one flow is restricted by the slowest PAV (if minimum separation is established). Contrary to UAV operations, there are different PAV types with different performance characteristics\(^8\) and such speed restriction could be very inefficient or even unfeasible (if minimum and maximum speeds of different vehicle types do not overlap). For this reason, several zones in the major flow area could be defined with regulated minimum speeds in each zone (different layers with different minimum speed limits). Another solution could be to design overtaking lanes for each inner flow ring that will allow traffic sequencing in the flows.

CD&R principles for PAVs will follow predefined rules, which are similar to the Layer concept and are summarized in the following table. CD&R between two cruising aircraft will first be solved with heading changes followed by speed changes if needed. Conflict resolution between two climbing or descending aircraft will be conducted by following the principles of:

1. Vertical speed changes,
2. Heading changes, or
3. Speed changes.

<table>
<thead>
<tr>
<th>Table 6.1: CD&amp;R principles for PAV and UAV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climb/Descent</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Level</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

\(^8\) Cruise speed of TF-X, AW609 and PAL-V One in kts is 174, 275 and approximately 90 respectively [1].
6.3.3 Flight planning

Flight plans, as the input for the simulations in METROPOLIS, are not known in advance. Therefore, routes can only be planned at the moment they are requested and can only take into account other flights that are already in the air (FCFS principle). When a user wants to fly, he/she makes a request for the flight plan at ATC. Input for the flight plan are the origin and destination point (strip), and the desired departure time (usually a few minutes after the request is sent). Shortest path algorithm is used to find a shortest available route. Route availability depends on traffic volume at the merging points that is measured by flow density at these points. In the example shown in Figure 6.19, a flight requests going from A to B (purple points in the figure). The nominal route represented by the purple line contains three merging points marked by black-red circles. The first merging point (from A to B) at the end of the collector area merges all inbound flights from East (E) zone coming to the city centre. A second merge point merges inbound traffic from E zone to the selected inner flow circle. Finally, at the last merging point, all traffic (there is also traffic coming from upper flow layers) destined to point B is sequenced into a landing flow. With an approximate speed of the vehicle, it is possible to calculate estimated time of arrival at these merging points and calculate flow density. In the case when flow densities of all merging points are lower than a given limit (allowing additional vehicle to be merged) this nominal route is available and clearance will be issued.

Figure 6.19: PAV Flight Planning Example

However when a nominal route is not available, alternative routes are examined and sorted in ascending order by delay they incur at the destination compared to the nominal route. In Figure 6.20, three alternative routes, all in the same horizontal dimension, are shown. The same availability check procedure is applied, calculating flow density at merging points. In the case when a merging point at the end of the collector area is congested, horizontal rerouting inside the major flow area will not solve the problem. Therefore, rerouting is necessary in vertical or time dimension. Another alternative is to delay a flight by postponing its departure time so that the nominal route becomes available. The nominal

---

9 Speed is not known in advance as it might change during merging of the flows and in the flow.
horizontal route could also be used if a different major flow layer is selected. This will require an additional altitude change, climbing after departure and descending, using traffic exchange routes, before landing. To simplify the alternative evaluation process only delay at the destination is calculated, since additional fuel burn by altitude changes will be relatively small.

Figure 6.20: Alternative Route Selection – PAVs

Similar flight planning is done by ATC for UAV traffic. The grid-like structure of the airways makes the route planning process easier due to the similarity. Therefore, if route between two points always heading in the direction of the destination (doesn’t leave minimal square that contains the origin and destination point), all such alternatives will have the same length\textsuperscript{10} and the same number of merging points. Merging points exist at every inbound route of airway intersections (octagonal roundabout). Although merging is done automatically, ATC has to ensure that merging is possible by controlling flow density. When flow density reaches the limit at one airway layer, ATC has to give clearance for another airway layer. An example of several alternative routes in the horizontal dimension is shown in Figure 6.21.

\textsuperscript{10} Not taking into account distance flown in the octagonal roundabout.
6.4 Handling of abnormal situations

In the case of both static and dynamic no-go areas, that block part of metropolitan airspace for a certain time interval, additional management action needs to be taken to reroute vehicles that were already in the air and prevent others entering the no-go zones.

In the case of such disruptions some inner flow rings could become restricted and traffic will be routed to the neighbouring ring accordingly. An emergency situation for which the centre of METROPOLIS area is fully congested would require more drastic measures restricting all inbound traffic. In that case, inbound traffic will be rerouted outbound, while new requests for departure from or heading to the city’s core area will be rejected (restricted).
7 Concept 4: Tubes [NLR]

This chapter presents an overview of the tubes concept.

7.1 General Description

7.1.1 Introduction

In the tubes concept, 3-dimensional tubes are defined to provide a fixed route structure in the air. This concept therefore represents a maximally structured airspace. Air vehicles all have to follow the tubes and all travel at equal speed in the tubes, thus ensuring safe separation and prohibiting conflicts. UAVs and PAVs each have their own tube topology. Tubes offer the advantage of channeling traffic going in the same direction in a safely separated manner. By introducing multiple layers of tubes the concept also takes advantage of the abundant availability of space in the air as opposed to 2D road traffic.

7.1.2 Preliminary assumptions

All air vehicles are divided into two main categories: UAVs and PAVs. Both categories will use their own tube topology: a tube structure dedicated to a specific air vehicle type (i.e., UAVs or PAVs). For UAVs, the tubes are located in lower airspace regions: above the minimum safe altitude (see section 3.1.1), but below – first estimate – 1500 ft. PAVs will use tubes located in the higher airspace regions: above 1500 ft but below the maximum safe altitude for flying vehicles (6500 ft). The only interaction between the two categories therefore occurs when entering or leaving the tube structure during take-off and landing by means of so-called connecting tubes (see section 7.1.8 for a glossary of tube concepts).

Tubes do not intersect and contain at most one air vehicle in the vertical and lateral plane: see Figure 7.2.

Figure 7.1: Tube Airspace Concept Design

Figure 7.2: Cross section of a tube containing only one air vehicle in the vertical and lateral plane
In the longitudinal plane (see Figure 7.3), air vehicles within a tube all fly at equal speed. As a result, a tube can only contain one air vehicle within a timeslot and time-based separation will be used.

![Figure 7.3: Side view of a tube with three air vehicles, separated in the longitudinal plane](image)

In order to take advantage of the 3D airspace (as opposed to 2D road infrastructure), a number of different layers\(^\text{11}\) of UAV or PAV tubes are foreseen (from bottom to top). These layers represent the current road structure in 3D. At the lower layers there are many short connections (these represent the small streets in a city). At higher layers less but longer connections exist between districts. At the highest layer there are very long connections, these represent the highways\(^\text{12}\). Each layer consists of two horizontal levels with opposite directions. Cruise speeds in higher tubes will generally be higher as only faster PAVs will use the higher tubes.

All layers taken together form a topology; UAVs and PAVs each have their own, unique tube topology. Between and within the layers of a topology three different types of tubes are defined:

- **Connecting tubes**, connecting the ground (i.e., the UAV distribution centre and landing spots or the PAV landing strips) to the first layer
- **Horizontal tubes**, connecting different nodes within a layer in one direction. Each layer has two levels: one level for one direction, another for the opposite direction.
- **Transitional tubes**, allowing air vehicles to transition between layers and directions. During a transition, vehicles may only climb or descend one level or layer at a time.

To illustrate, Figure 7.4 shows an example topology with three layers. The black arrows indicate the connecting tubes between ground and Layer 1\(^\text{13}\); the red (climb) and green (descent) arrows mark the transitional tubes between layers. To simplify, finally, the horizontal tubes are depicted as bi-directional arrows between nodes within a layer (blue for Layer 1, green for Layer 2, orange for layer 3). Note that the topology supports diagonal transfers between layers, allowing air vehicles to arrive at and depart from nodes with a proper forward speed.

\(^{11}\) Each layer connects nodes in the same, horizontal plane.

\(^{12}\) The introduction of highway tubes allows air vehicles to travel more direct routes, but also facilitates de-conflicting flights since an alternative route between different nodes is introduced.

\(^{13}\) As will be subsequently explained: here the UAV and PAV topologies differ since UAVs will connect vertically, PAVs diagonally (i.e., a combination of vertical and horizontal movement).
Tubes at the same horizontal level are located such that they *never intersect* except at the nodes. The partial layer on the left in Figure 7.5, for instance, is not allowed since the two red edges intersect with one another; instead, it could be replaced by the partial layer on the right by introducing an extra connection point in the middle.

A tube topology constitutes of a (directed) graph with *vertices* and *edges*. The vertices are the *nodes* that are connection points for one or more routes. The edges are the tubes connecting two nodes. Since tubes only connect nodes in one direction, two tubes are required to connect nodes in two directions. To prevent intersection, these tubes are located above each other. To simplify, it is assumed that all nodes are always connected in two directions; hence, between all connected nodes within a layer two levels are required: one per direction. Tubes are always created in pairs, one for both directions. In the remainder of this section, when referred to a tube, a dual level tube is meant enabling traffic in two directions.
Regarding the connection tubes, all UAVs are assumed to transfer vertically from landing spots to the connection points (and vice versa) of the tube topology; hence, all connection points in the UAV topology are located above the landing spots. In contrast, PAVs will not connect vertically from landing spots to connection points but will instead climb through a diagonal tube towards these connection points. As the PAV topology is above the UAV topology, the PAVs will need to climb through the UAV topology.

Below a side view of the interaction between the two tube topologies: for UAVs and PAVs. The UAV takes off from the UAV Distribution Center (DC) and makes three deliveries after which it returns to the DC (blue arrows). In addition, two PAVs take-off and merge in the tube that takes them to their landing spot, e.g. an office (green arrows). Tubes going in opposite directions are located above each other. Note that only one UAV and only one PAV layer is depicted for simplification purposes.

Figure 7.6: Side view of the two tube topologies (1 layer shown): for UAVs and PAVs

7.1.3 Input
The following static input (topology) is assumed:

- The set of all PAV VTOL take-off and landing locations\(^{14}\) (3D coordinates) relevant to the area of simulation (i.e., including locations a bit outside the pie-chart area to allow for traffic simulation flying into/outside the area of simulation)
- The set of all PAV non-VTOL take-off and landing locations in 3D relevant to the area of simulation

\(^{14}\) It is assumed here that each take-off location may also serve to accommodate landings
• The set of all UAV distribution centres in 3D (i.e., distribution centers) relevant to the area of simulation
• The set of all UAV drop-off locations (i.e., residential/office block drop-off points) relevant to the area of simulation
• A minimum safe altitude for UAVs of a given distribution area, based on the highest buildings in this area plus a minimum safe separation.
• Static no-go areas relevant to the area of simulation (if any).

The following dynamic input (flights) is assumed:
• At the moment a PAV wishes to departure:
  o its take-off location (landing strip);
  o the take-off direction (determined by e.g. the wind conditions)
  o its destination (landing strip);
  o its vehicle type (i.e., the TF-X or AW609, implying VTOL, or the PAL-V).
• At the moment an UAV wishes to departure:
  o its take-off location (which is a DC);
  o its list of destinations (consisting of max 4 drop-off points which can be visited in any order).
• Dynamic no-go areas relevant to the area of simulation (if any).

7.1.4 The tube topology
The topology of the tubes needs to accommodate several different types of flights. The most significant difference is the distance between current position and destination. Short flights profit from a fine grid at the lowest layer of the topology, supporting short, direct connections. This ensures that a direct flight path exists that brings the aircraft to its nearby destination. Longer flights however profit from longer straight tubes in the higher layers of the topology, allowing them to travel longer distances in efficient straight and direct paths.

The initial topology will be based on a diagonal grid layout consisting of edges (tubes) and vertices (nodes), see Figure 7.7a. This structure ensures efficient (i.e. short) routes to many destinations in all directions. The different uses of the topology are represented by the granularity of the topology (Figure 7.7b–c). Different diagonal grid layers are placed above each with decreasing granularity (Figure 7.8).
The grids are placed such that they allow for a smooth transition between layers taking the climb and descend paths into account. For this, connections are created between nodes at different lateral positions to enable a smooth transfer between different layers. Figure 7.9 depicts how an air vehicle may take-off towards the topology and climb through three consecutive layers to reach its final altitude; conversely, Figure 7.10 depicts how the same air vehicle may descend through three layers to reach its final landing strip/spot.
Figure 7.9: An air vehicle (1) climbing to the topology, (2) moving horizontally in the first layer, (3) climbing to the next layer, (4) moving horizontally in the second layer, and (5) climbing to the highest layer.

Figure 7.10: The air vehicle now (6) descending to the second layer, (7) moving horizontally in the second layer, (8) descending to the first layer, (9) moving horizontally in the first layer, and (10) descending to its landing spot/strip.

An aircraft traveling a short local distance, will typically only use the lower layers of the topology. An aircraft traveling a long cross-country distance will typically start at the lower layer, then continue its climb to join the higher layers with longer connections (see Section 7.2.2 for details). Close to its destination, it will first descent to the lower layers after which it will be able to reach its destination.
The grids represent the tubes and nodes. A grid contains many sharp angles, in reality these are rate one turns. Altitude transfers (represented by vertical edges) are continuous climb paths in reality.

7.1.5 UAV and PAV tube topologies

UAVs and PAVs will each employ a separate tube topology. This topology is designed in a similar manner. However, except for different parameter settings, stemming from the different air vehicle characteristics and different densities of landing spots/strips, two principle differences should be noted.

First of all, the PAV topology covers the entire metropolitan area (simulation area), whereas the UAV topology is divided into a number of separate, local topologies centred around a distribution centre. Each local UAV topology is a system connecting a UAV distribution centre to all nearby drop-off points (all office/domestic blocks) within approximately 6 NM. This local topology will be employed by each UAV taking off from the DC and making deliveries to max. five drop-off points before returning to the DC. As a UAV only serves drop-off points at a maximal distance of 6 NM, there is no need to make longer connections. On a city-view level, this leads – in contrast to the PAV topology, spanning the entire city – to the following separate DC tube topologies, each serving a specific part of the city. The resulting topology is shown in Figure 7.11.

Second, as indicated before, UAVs are assumed to take-off, land, and transition between layers vertically. In contrast, PAVs are all assumed to require climb- and descend paths with a horizontal speed. As a result, in the PAV topology the nodes between consecutive layers, and between levels within a layer, are not placed above each other but instead at a horizontal distance as well. This allows for a smooth transfer between levels, and layers, taking the climb- and descend paths of PAVs into account. More detail about this will follow in section 7.2.2.
7.1.6 Minimum safe altitude

As indicated, both the UAV- and PAV topologies will be located above the city infrastructure (buildings, etc.). The UAV topology of each distribution center will be located at a safe separation above the highest infrastructure within that distribution area. Therefore, each UAV topology may be located at a different altitude depending on the altitude of the highest infrastructure. The PAV topology is located above the highest layer of the highest UAV topology.

7.1.7 Optimizing the tube topology

Some ideas for optimizing the topology, these will need to be tested in simulation:

- The topology could be further optimized by allowing aircraft that travel in the same direction to share a topology. This will decrease the number of crossing aircraft (and nodes) within a single topology and hence increase capacity. Some initial ideas exist to let a diagonal grid alternate with a square grid. Experiments will be necessary to further pursue this idea.
- The traffic is not evenly distributed over the area. Given a rough indication of “hot spots” (places with a lot of traffic) and their main direction may open opportunities to improve the topologies.
- The number of layers of the tube topology may be increased to accommodate more traffic.

7.1.8 Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer</td>
<td>a horizontal tube structure located at a specific altitude (part of a topology). In the tube concept, each layer has a diagonal grid layout and consists of two levels: one in one direction, the other in the opposite direction.</td>
</tr>
<tr>
<td>Grid</td>
<td>a potential layout of a layer</td>
</tr>
<tr>
<td>Topology</td>
<td>a complete tube structure, typically composed of multiple layers, for a certain air vehicle type (UAVs or PAVs)</td>
</tr>
<tr>
<td>(Altitude) transfer</td>
<td>a transfer from one layer to another at a different altitude</td>
</tr>
<tr>
<td>Tube</td>
<td>a uni-directional connection between two nodes</td>
</tr>
<tr>
<td>Connecting tube</td>
<td>a tube connecting a departure/arrival node at ground level (a UAV landing spot/DC or PAV landing strip) to a node at the first layer of the topology</td>
</tr>
<tr>
<td>Horizontal tube</td>
<td>a tube connecting two nodes within a layer</td>
</tr>
<tr>
<td>Transitional tube</td>
<td>a tube that either (1) connects a node in one layer to a node located in a higher, or lower layer, or (2) connects a node in one level of a layer to a node at the other level of that same layer</td>
</tr>
<tr>
<td>Level</td>
<td>a horizontal tube structure in a specific direction, part of a layer</td>
</tr>
<tr>
<td>Node</td>
<td>an start or endpoint for a tube. A node can be used as start or endpoint for multiple tubes</td>
</tr>
<tr>
<td>Edge</td>
<td>a tube representation in a graph</td>
</tr>
<tr>
<td>Vertex</td>
<td>a node representation in a graph</td>
</tr>
<tr>
<td>Graph</td>
<td>representation of the topology by edges and vertices</td>
</tr>
</tbody>
</table>
7.2 Flow Management, Separation and Conflict avoidance

7.2.1 Ensuring separation
By definition, in a scenario, aircraft will request a flight plan at irregular intervals (i.e. when spawned), not known in advance. This makes the planning problem similar to an “online” planning problem in which the input set is not known in advance. A path for an aircraft can therefore only be planned at the moment it requests a flight plan, which is at the same moment as its preferred departure time.

Many aircraft will share the same topology at the same time. This also implies that there will be many aircraft at the same layer (i.e. flight altitude) at the same time. To ensure separation some rules will apply. First, the speed of all aircraft in a tube will be similar. This will ensure that aircraft will not overtake within a tube. Hence, having the same speed will ensure that when two aircraft are separated at one end of a tube (i.e. in a node), they will still be separated at the other end.

Within the topology, minimum separation will be ensured based on time. This minimum separation dictates that, when an aircraft passes a node, it will “occupy” this node for some interval. If the minimum separation of two flights is 10 seconds, then if an aircraft passes a node, the corresponding interval is 20 seconds wide (10s before and 10s behind the aircraft). Within this occupancy interval no other aircraft is allowed to pass this node. As all tubes emerge from a node, the occupancy intervals ensure that no two aircraft exit a single node at the same time. Therefore the occupancy intervals ensure that within the tubes no conflicts occur.

For each node an interval list is maintained that states at which times a node is occupied. New flights may only pass the node when its necessary interval is completely free.

![Diagram](image.png)

**Figure 7.12:** Example of occupancy intervals at a single node. The aircraft that needs the dashed interval at the node is not allowed to pass the node because its necessary interval overlaps with existing intervals.

7.2.2 Transfers between layers
The diagonal grid structure with different granularity ensures that the nodes of the layer with the most coarse granularity (the “highways”) are located above nodes of layers with finer granularity, such that these nodes can be reached taking the climb- and descend paths required into account. These nodes are therefore not only connection points of tubes at the same altitude, but also serve as transfer points for aircraft that want to change altitude. The occupancy intervals ensure that there is at most one aircraft at a node. For a conflict free altitude transfer an interval needs to be available at both nodes on both layers.
Air vehicles will have a forward speed when arriving at the nodes. Efficient transfers should therefore take place with a proper forward speed. Figure 7.9 and Figure 7.10 depicted a 3D view of an example air vehicle using a topology to transfer through three different layers to reach its destination. Figure 7.4 depicted a side view of this example topology, allowing diagonal transfers for air vehicles between layers (red = climb, green = descent).

An aircraft is only allowed to climb or descent one layer at a time. When taking the two levels per layer into account, both UAV and PAV topologies will be slightly more complicated than depicted in Figure 7.4. As indicated, a layer consists of two levels: one for one direction, the other for the opposite direction. As a result, transitions will be required not only between layers, but also between levels, and finally also between landing strips/spots and the first layer. Figure 7.13 depicts an example 3-layer UAV topology. Note that UAVs are assumed to connect to the first layer vertically from the ground.

![Figure 7.13: Side view of a complete UAV topology with three layers.](image)

Subsequently, in Figure 7.14 a corresponding 3-layer PAV topology supporting also diagonal transfers between ground and the first layer. Each layer consists of two levels; all horizontal tubes within a level connect between nodes in only one direction.
7.2.3 Joining the topology
An aircraft always joins the topology at the lowest layer (the one with the finest granularity). When it needs to travel a large distance, it will then quickly transfer to a higher topology level with coarser granularity. An aircraft always joins the topology at a node. To join, it simply requests a specific interval at a node.

A conflict free transfer from departure to topology and vice versa needs to be guaranteed. For the UAVs this is straightforward since their topologies are below the PAV topology. For each potential departure location a transfer can be easily defined to reach the closest (set) of nodes. For the PAVs to reach their tube topology, they need to climb through the different UAV topologies. To prevent conflicts between PAVs and UAVs the UAV topology may need to have some “holes” that guarantee a safe PAV departure and arrival route. More details about the departure and landing procedures are given in Section 7.3.

A straightforward construction method for the topologies is to first create the PAV topology. Then the PAV transfers are created. Next the UAV topologies are created ensuring that they do not interfere with PAV departures and arrivals. Finally the UAV transfers can be created.

7.2.4 Flight planning
Once the topologies are created the concept is ready to be used for planning requests. When a flight requests a flight plan, a shortest path algorithm is used to plan a path from departure to destination. For a shortest path algorithm to function properly, a cost needs to be associated with each edge (tube). Initially, for the tubes the lateral distance serves as a cost value. To ensure the higher topologies (the “highways”) are preferred over the lower ones, a small penalty could be added to the lower topologies.
The cost of the transfer between topologies is represented in the connections between the nodes of the different topologies located at the same lateral positions. This cost could be associated to e.g. necessary energy to execute the transfer.

At each node on the path, it needs to be verified that there is a free interval available at that node. A depth-first search algorithm can be used for planning. At each step of the algorithm (when a new node is explored) it is verified that the node has a proper available interval. If not, the node is discarded for this search. The algorithm then backtracks to find another available solution.

Transfers to a different layer will be automatically handled by the above strategy. Such transfers will only be accommodated when at both nodes involved an appropriate interval is available taking the time required to perform the transfer into account.

A slightly modified A* algorithm (which is a variant of a depth-first-search algorithm) will be used to implement the above strategy. The only change necessary is to check for interval availability when an edge (tube) is considered.

If no departure route is available for an aircraft to join the topology, a pre-departure delay can be useful. In addition, while the A* algorithm quickly generates alternative routes when an edge is not available it may be beneficial to delay the departure of an aircraft (e.g. in very demanding scenarios). Therefore a pre-departure delay in multiples of 10 s (or whatever minimum separation is used) is used to further optimize capacity.

7.3 Take-off and Landing Procedures

As indicated before, UAVs are assumed to all connect vertically from landing spots to the connection points (and vice versa) of the tube topology; hence, all connection points in the UAV topology are located above the landing spots. In contrast, PAVs will not connect vertically from landing spots to connection points but will instead use a continuous climb towards these connection points.

Each PAV landing strip is assumed to be on a crossing of roads. It can therefore be used from 4 sides, depending on the wind. For each potential runway, separate (continuous climb) transfer tubes are created to connect to the PAV topology. As each runway needs both a landing and a departure tube, a total of 8 tubes are associated to a landing point. As only 2 of those are active at the same time (depending on the wind) they are allowed to intersect. Depending on the wind, transfer tubes are activated or de-activated before a flight is planned.

As the PAV topology will be located entirely above the UAV topology, PAVs joining the topology will have to climb “through” the UAV structure. To ensure efficient joining procedures, specific “holes” will be created in the UAV topology for the PAVs to climb through. This is in order to prevent climbing and descending PAVs to intersect with the UAV tubes. To exemplify, Figure 7.15 shows a top view with on
the left a PAV tube layer and on the right a UAV tube layer beneath it. Specific “holes” have been created in the UAV topology to ensure a conflict-free climb for PAVs to the PAV topology at all times. The same can be done to ensure a conflict-free PAV descent.

Figure 7.15 a–b: a) Example PAV layer (green: nodes and tubes, red: landing strips, blue: climb path towards nearby node) with b) a simplified UAV layer below (blue: nodes, black: tubes) with certain tubes omitted to allow for a conflict-free climb path of the PAVs.

In this architecture, the UAV tubes and nodes are located such that they never intersect with the green PAV climb and descend paths: the areas in which PAVs climb or descend to reach their tube topology. Note that Figure 7.15 is based on a ratio of 1 PAV landing strip per 4 UAV landing spots for illustration purposes only, following document D1.3 the METROPOLIS scenarios are based on 1 PAV landing strip per 16 UAV landing spots. Note further that the UAV topology needs to be modified depending on the runways open at each PAV landing strip (which in turn depends on e.g. the wind conditions). To simplify, the unidirectional tubes are depicted here by means of bi-directional arrows.
7.4 Handling of abnormal situations

In real-life, a great variety of abnormal situations may occur impacting the planning of air vehicles using the tube concept. The tube concept should be able to cater for these non-nominal situations, which shall be described for dynamic no-go areas.

Dynamic no-go areas might be imposed for security reasons (e.g. to cater for rogue aircraft\textsuperscript{15}, or other moving threats), to avoid dynamic weather systems impacting aviation (thunderstorms, lightning, turbulence, wind shear etc.) or to avoid areas of natural disaster (earth quakes, volcanic ashes, large fires etc.). The reason for imposing the dynamic no-go area is irrelevant for the application of the tube concept. What is relevant, however, is the shape and its position changing in time. Based on the assumptions made in section 3.1.5, the following procedure can be employed to handle dynamic no-go areas under the tube concept:

1. First assume a dynamic no-go area, composed of a limited number of 3D rectangles (with a safety margin around them), will become visible to the tube concept flight planner (i.e., it will be spawned by the Traffic Manager and communicated to the tube concept flight planner).
2. Subsequently, the tube concept flight planner will calculate (in this order):
   a. Which tubes need to be temporarily closed as a result of the dynamic no-go area. These tubes will be marked ‘no-go’.
   b. Which flights will be affected (i.e., which flights have route segments still to be flown that contain no-go tubes)
3. If any flights are indeed affected, these PAVs will be re-planned one-by-one by the tube flight planner taking the no-go tubes into account. Note that for all airborne PAVs no pre-departure delay can be assigned.
4. All alternative paths are given back to the TMX.
5. Go back to step 1.

\textsuperscript{15} A rogue aircraft is an aircraft that either doesn’t have, or doesn’t obey its route. It can therefore cross any tubes and may cause conflicts/harm other air vehicles.
This page intentionally left blank
8 Origin-Destination Algorithm for PAVs [TU Delft]

This chapter describes the stochastic origin-destination algorithm for Personal Aerial Vehicles (PAVs) to be used in the METROPOLIS project. The algorithm loops through all PAV runways during each simulation time step. For each runway, the following four ‘characteristics’ are computed (in order):

1. Runway spawn rate
2. Traffic type
3. Vehicle type
4. Destination runway

The runway spawn rate can be computed at the start of the simulation. The other three steps will need to be computed during each simulation time step. The following sections describe the computation procedure for each ‘characteristic’.

8.1 Runway Spawn Rate Determination

The spawn rate for a particular runway determines the rate with which aircraft are generated at that runway. From the spawn rate, the spawn interval can be computed. For example, if the spawn rate for a particular runway is one aircraft every 2 seconds, and if the simulation time step is 0.5 seconds, then this particular runway generates a new aircraft every fourth simulation time step.

The spawn rate differs between runways and is dependent on:

- The time of day: morning or lunch or evening
- Office ratio of runway, \( R_{rwy} \)
- Average traffic volume in the air for the city area\(^{16} \) where the runway is located, \( T_{area} \)
- Number of runways in the city area where the runway is located, \( n_{rwyarea} \)
- Distribution of traffic types in the city area where the runway is located, \( C_{XXarea} \). Four traffic types were defined for METROPOLIS: Residential–Residential (RR), Residential–Commercial (RC), Commercial–Residential (CR) and Commercial–Commercial (CC). For example, \( C_{RCcenter} \) stands for the distribution of Residential–Commercial traffic at the city center.
- Average trip time ‘per runway’, \( \bar{t}_{trip} \).

All these values are defined in METROPOLIS deliverable D1.3. In this document, an initial guess for \( \bar{t}_{trip} \) was 15 minutes or 900 seconds. This value is used as a starting point. If the resulting traffic volume for each simulation ‘hour’ does not match the desired values, then \( \bar{t}_{trip} \) can be iterated. More details about this is described in section 8.5.

Using these values, the spawn rate for a particular runway, \( \bar{t}_{rwy} \), can be computed using equation 8.1:

\[ \bar{t}_{rwy} = \frac{T_{area} \times n_{rwyarea}}{C_{XXarea} \times \bar{t}_{trip}} \]

\(^{16} \)Here city area refers to the three zones of Metropolis: city center, inner ring and outer ring
The spawn rate equations vary slightly for VTOL and non-VTOL runways. This is necessary because only VTOL aircraft can take-off and land at VTOL runways, but all aircraft can operate from non-VTOL runways. In equations (8.1a) and (8.1b), the part inside the curly brackets determines the ‘unadjusted’ spawn rate per city area. The part in the square brackets adjusts the spawn rate to take into account the office ratio of each individual runway and the distribution of traffic types (of the city area where the runway is located). The time of day is implicitly taken into account as $R_{rwy}$ varies with simulation time. $(1 - R_{rwy})$ is used to compute the ‘home ratio’ of a given runway. Both home ratios and office ratios need to be considered as ‘completely’ home or office runway.

The spawn interval (in seconds) can be computed by simply inverting the spawn rate.

**8.2 Traffic Type Selection**

If a runway is to spawn an aircraft for a particular simulation time step, the next step is to determine the traffic type of the spawned aircraft. The traffic type can be selected given traffic type distribution defined in D1.3, see section 8.6 (Table 8.2). This distribution depends on the city area location of the runway, as well as the time of day of the simulation. The following four step procedure is used to determine the traffic type that needs to be spawned:

1. Determine probability of each traffic type from the probability density function (PDF) for traffic types.
2. Determine cumulative (probability) distribution function (CDF) for traffic types.
3. Generate random number using an uniform distribution random number generator.
4. Use the generated random number and the CDF to determine traffic type for the runway under consideration.

The PDF for the four traffic types, for a particular city area and time, is given below in equation (8.2):

$$f(x)_{area} = \frac{C_{XX,area}}{C_{RR,area} + C_{RC,area} + C_{CR,area} + C_{CC,area}}$$  \hspace{1cm} (8.2)
To illustrate this procedure, the four steps are worked out below for runways in the city center for the morning rush hour.

**Step 1: Determine probability of each traffic type from the traffic type PDF**

For these conditions, Table 8.2 defines $C_{RR} = 2 \%$, $C_{RC} = 5 \%$, $C_{CR} = 2 \%$ and $C_{CC} = 5 \%$. Given the PDF for traffic types in equation (8.2), the probability for each traffic type can be computed as follows:

$$p(RR)_{center} = \frac{C_{RR_{center}}}{\sum_{1}^{4} C_{XX_{center}}} = \frac{2}{14}$$

$$p(RC)_{center} = \frac{C_{RR_{center}}}{\sum_{1}^{4} C_{XX_{center}}} = \frac{5}{14}$$

$$p(CR)_{center} = \frac{C_{CR_{center}}}{\sum_{1}^{4} C_{XX_{center}}} = \frac{2}{14}$$

$$p(CC)_{center} = \frac{C_{CC_{center}}}{\sum_{1}^{4} C_{XX_{center}}} = \frac{5}{14}$$

It should be noted that the traffic type probability is the same for all runways in a particular city area.

**Step 2: Determine the CDF for traffic types**

From the probabilities for each traffic type, the CDF can be easily determined. Figure 1 below shows the CDF for the probabilities computed in step 1:
Figure 8.1: CDF of traffic types for runways at the city center during morning rush hour. The random number generated in step 3 can be used to determine the final traffic type to be spawned. For instance, a random number between 0.14 and 0.5 results in the spawning of a Residential–Commercial aircraft.

**Step 3: Generation of random number**

A uniform distribution random number generator is used to produce a random number. This random number is used in step 4. This random number generation results in the stochastic nature of the origin-destination algorithm described in this document.

**Step 4: Determine the final traffic type to be spawned using the CDF and the generated random number**

As can be seen in Figure 8.1, the CDF defines probability intervals for each traffic type. The final traffic type to be spawned corresponds to the interval within which the generated random number lies. For example, random numbers between 0.14 and 0.5 results in the spawning of a Residential–Commercial aircraft.

### 8.3 Vehicle Type Selection

The next step in the O-D algorithm is to select the vehicle type of the aircraft to be spawned. Three PAVs have defined in D1.3 for the METROPOLIS project: TF-X, PAL-V One and AW609.

Vehicle type selection follows a similar four step procedure to traffic type selection, see section 8.2. Here, the PDF is defined based on the traffic volume ratio for the three PAVs. These ratios can be computed from the traffic volume data given in section 8.6.
\[ f(x)_{\text{rwy}_{\text{VTOL-area}}} = \frac{0.5 \cdot T_{\text{vehicle area}}}{0.5 \cdot T_{\text{TF-X area}} + 0.5 \cdot T_{\text{AW609 area}}} \] (8.3a)

\[ f(x)_{\text{rwy}_{\text{non VTOL-area}}} = \frac{k \cdot T_{\text{vehicle area}}}{0.5 \cdot T_{\text{TF-X area}} + 0.5 \cdot T_{\text{AW609 area}} + T_{\text{PALV area}}} \] (8.3b)

Note: in equation (3), \( T \) stands for traffic volume. Once again, the PDF is defined separately for VTOL and non-VTOL runways. Since VTOL aircraft can spawn on both types of runways, the PDF is adjusted by multiplying the traffic volumes for VTOL aircraft by 0.5. In this way, VTOL aircraft will be divided evenly between VTOL and non-VTOL runways. In the non-VTOL equation, \( k = 0.5 \) when computing the probabilities of VTOL aircraft (TF-X and AW609) and \( k = 1 \) for non-VTOL aircraft (PAL-V).

### 8.4 Destination Runway Selection

The final step is to determine the destination runway. Once again, the four step procedure described in section 8.2 is used. However, the PDF for destination runway selection is slightly more complicated:

\[ f'(x)_{\text{dest rwy}} = R_{\text{rwy}} \cdot (1 - R_{\text{rwy}}) \cdot \left[ 1 - \frac{(d_{\text{origin,dest}} - t_{\text{trip}} \bar{V})^2}{(t_{\text{trip}} \bar{V})^2} \right] f'(x)_{\text{dest rwy}} = R_{\text{rwy}} \cdot (1 - R_{\text{rwy}}) \cdot \left[ 1 - \frac{(d_{\text{origin,dest}} - t_{\text{trip}} \bar{V})^2}{(t_{\text{trip}} \bar{V})^2} \right] \]

\[ f(x)_{\text{dest rwy}} = \frac{f'(x)_{\text{dest rwy}}}{\sum f'(x)_{\text{dest rwy}}} \]

(8.4)

Here \( R_{\text{rwy}} \) is the office ratio of a runway, \( d_{\text{origin,dest}} \) is distance between the origin and the (potential) destination runway and \( t_{\text{trip}} \cdot \bar{V} \) is 50,000 meters according to D1.3. In equation (8.4), the part in the square bracket is used to bias the runway probabilities such that runways that are approximately 50,000 meters from the origin have preference.

A few additional points have to be taken into consideration for correct destination selection:

1. If a PAL-V is to be spawned, then the PDF should be computed by considering only the non-VTOL runways. This can be done by manually setting the probabilities of non-VTOL runways to zero (only if a PAL-V is spawned).
2. \((1 - R_{\text{rwy}})\), or ‘home ratio’ is included in equation (8.4) because no runway is purely commercial, nor residential.

In the implementation of the O-D algorithm it is recommended to compute the CDFs for all possible combinations of runways outside the loop used to select the destination runway. This will speed up the implementation of the algorithm considerably.
8.5 Ensuring Appropriate Traffic Volume Each Simulation ‘Hour’

Through trial and error, the values for $\bar{t}_{\text{Trip}}$ have been determined for all scenarios, see Table 8.1 below. This was done by running the O-D multiple times until (approximately) the required (instantaneous) traffic volumes for each scenario was obtained, see section 8.6. $\bar{t}_{\text{Trip}}$ should be interpreted as the average trip time for a runway, and not for an aircraft. NOTE: The average trip time for aircraft is not equal to $\bar{t}_{\text{Trip}}$, and varies per scenario (in fact it is influenced slightly by $\bar{t}_{\text{Trip}}$).

Table 8.1: $\bar{t}_{\text{Trip}}$ for all simulation scenarios, obtained through trial and error

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Morning [s]</th>
<th>Evening [s]</th>
<th>Lunch [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>420</td>
<td>328</td>
<td>356</td>
</tr>
<tr>
<td>2</td>
<td>420</td>
<td>341</td>
<td>357</td>
</tr>
<tr>
<td>3</td>
<td>421</td>
<td>310</td>
<td>361</td>
</tr>
<tr>
<td>4</td>
<td>421</td>
<td>287</td>
<td>360</td>
</tr>
</tbody>
</table>

8.6 Raw Data Needed for O-D Algorithm Implementation

Table 2 gives the traffic type distribution for the three simulation times. These values are needed to compute the spawn rate for each runway, as well as for traffic type selection. In the equations traffic type distribution is represented as $C_{XX\text{area}}$, where the subscript XX stand for the particular traffic type under consideration, e.g. RR is the subscript for the residential–residential traffic type.

Tables 8.3–8.5 display the instantaneous traffic volume categorized according to vehicle type (assuming an average flight time of 15 minutes, or 900 seconds, as in D1.3). This information is needed for spawn rate computation and for vehicle type selection. In the equations, $T_{\text{area}}$ is used to represent traffic volume of each area. Note TFX and AW609 are VTOL aircraft, while PAL-V is a non-VTOL aircraft.

NOTE: Traffic volumes used are those for the entire simulation area (experiment + background). This is because aircraft are also to be spawned (and simulated) outside the experiment area\(^\text{17}\). For this reason, the numbers in Tables 8.3–8.5 are higher than those given in D1.3 (in D1.3 data for only the experiment area was given).

In all of the tables below, the numbers in bold are those that need to be programmed! The red numbers indicate the values for which $\bar{t}_{\text{Trip}}$ has been tuned for.

\(^{17}\) An experiment area has been explicitly defined as data will only be logged in this area to speed up the simulation.
Table 8.2: Distribution of traffic types for the three time spans of the simulation categorized according to location within the city.

<table>
<thead>
<tr>
<th></th>
<th>Morning Rush Hour (08:00-09:00)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residential-Commercial</td>
<td>Residential-Commercial</td>
<td>Commercial-Residential</td>
<td>Commercial-Commercial</td>
</tr>
<tr>
<td>City Center</td>
<td>2 %</td>
<td>5 %</td>
<td>2 %</td>
<td>5 %</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>8 %</td>
<td>15 %</td>
<td>8 %</td>
<td>3 %</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>15 %</td>
<td>30 %</td>
<td>5 %</td>
<td>2 %</td>
</tr>
<tr>
<td>Total</td>
<td>25 %</td>
<td>50 %</td>
<td>15 %</td>
<td>10 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Evening Rush Hour (17:00-18:00)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residential-Commercial</td>
<td>Residential-Commercial</td>
<td>Commercial-Residential</td>
<td>Commercial-Commercial</td>
</tr>
<tr>
<td>City Center</td>
<td>1 %</td>
<td>2 %</td>
<td>30 %</td>
<td>9 %</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>3 %</td>
<td>7 %</td>
<td>15 %</td>
<td>7 %</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>6 %</td>
<td>6 %</td>
<td>10 %</td>
<td>4 %</td>
</tr>
<tr>
<td>Total</td>
<td>10 %</td>
<td>15 %</td>
<td>55 %</td>
<td>20 %</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Lunch Time (12:00-13:00)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residential-Commercial</td>
<td>Residential-Commercial</td>
<td>Commercial-Residential</td>
<td>Commercial-Commercial</td>
</tr>
<tr>
<td>City Center</td>
<td>2 %</td>
<td>1 %</td>
<td>8 %</td>
<td>15 %</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>10 %</td>
<td>6 %</td>
<td>7 %</td>
<td>10 %</td>
</tr>
<tr>
<td>Outer Ring</td>
<td>18 %</td>
<td>8 %</td>
<td>5 %</td>
<td>10 %</td>
</tr>
<tr>
<td>Total</td>
<td>30 %</td>
<td>5 %</td>
<td>20 %</td>
<td>35 %</td>
</tr>
</tbody>
</table>
Table 8.3: Instantaneous number of aerial vehicles during morning rush hour (08:00-09:00) in the simulation area (experiment + background)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TF-X</th>
<th>AW609</th>
<th>PAL-V</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>City Center</td>
<td>608</td>
<td>41</td>
<td>95</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Inner Ring</td>
<td>1,174</td>
<td>80</td>
<td>183</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Outer Ring</td>
<td>1,381</td>
<td>94</td>
<td>216</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Total</td>
<td>81.67 %</td>
<td>5.58 %</td>
<td>12.75 %</td>
</tr>
</tbody>
</table>

| Scenario 2 | City Center | 781 | 53 | 122 |
| Scenario 2 | Inner Ring | 1,509 | 103 | 236 |
| Scenario 2 | Outer Ring | 1,775 | 121 | 277 |
| Scenario 2 | Total | 81.67 % | 5.58 % | 12.75 % | 4,977 |

| Scenario 3 | City Center | 955 | 65 | 149 |
| Scenario 3 | Inner Ring | 1,844 | 126 | 288 |
| Scenario 3 | Outer Ring | 2,170 | 148 | 339 |
| Scenario 3 | Total | 81.67 % | 5.58 % | 12.75 % | 6,083 |

| Scenario 4 | City Center | 1,128 | 77 | 176 |
| Scenario 4 | Inner Ring | 2,179 | 149 | 340 |
| Scenario 4 | Outer Ring | 2,564 | 175 | 400 |
| Scenario 4 | Total | 81.67 % | 5.58 % | 12.75 % | 7,189 |

Table 8.4: Instantaneous number of aerial vehicles during evening rush hour (17:00-18:00) in the simulation area (experiment + background)

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>TF-X</th>
<th>AW609</th>
<th>PAL-V</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>City Center</td>
<td>642</td>
<td>44</td>
<td>100</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Inner Ring</td>
<td>1,240</td>
<td>85</td>
<td>194</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Outer Ring</td>
<td>1,458</td>
<td>100</td>
<td>228</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>Total</td>
<td>81.67 %</td>
<td>5.58 %</td>
<td>12.75 %</td>
</tr>
</tbody>
</table>

| Scenario 2 | City Center | 825 | 56 | 129 |
| Scenario 2 | Inner Ring | 1,594 | 109 | 249 |
| Scenario 2 | Outer Ring | 1,875 | 128 | 293 |
| Scenario 2 | Total | 81.67 % | 5.58 % | 12.75 % | 5,258 |

| Scenario 3 | City Center | 1,009 | 69 | 157 |
| Scenario 3 | Inner Ring | 1,948 | 133 | 304 |
| Scenario 3 | Outer Ring | 2,292 | 157 | 358 |
| Scenario 3 | Total | 81.67 % | 5.58 % | 12.75 % | 6,426 |

| Scenario 4 | City Center | 1,192 | 81 | 186 |
| Scenario 4 | Inner Ring | 2,302 | 157 | 359 |
| Scenario 4 | Outer Ring | 2,709 | 185 | 423 |
| Scenario 4 | Total | 81.67 % | 5.58 % | 12.75 % | 7,595 |
Table 8.5: Instantaneous number of aerial vehicles during lunch time (12:00-13:00) in the simulation area (experiment + background)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TF-X</th>
<th>AW609</th>
<th>PAL-V</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>City Center</td>
<td>467</td>
<td>32</td>
<td>73</td>
<td></td>
</tr>
<tr>
<td>Inner Ring</td>
<td>903</td>
<td>62</td>
<td>141</td>
<td></td>
</tr>
<tr>
<td>Outer Ring</td>
<td>1,062</td>
<td>73</td>
<td>166</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>81.67 %</td>
<td>5.58 %</td>
<td>12.75 %</td>
<td>2,978</td>
</tr>
<tr>
<td>Inner Ring</td>
<td>1,161</td>
<td>79</td>
<td>181</td>
<td></td>
</tr>
<tr>
<td>Outer Ring</td>
<td>1,365</td>
<td>93</td>
<td>213</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>81.67 %</td>
<td>5.58 %</td>
<td>12.75 %</td>
<td>3,829</td>
</tr>
<tr>
<td>City Center</td>
<td>734</td>
<td>50</td>
<td>115</td>
<td></td>
</tr>
<tr>
<td>Inner Ring</td>
<td>1,419</td>
<td>97</td>
<td>221</td>
<td></td>
</tr>
<tr>
<td>Outer Ring</td>
<td>1,669</td>
<td>114</td>
<td>261</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>81.67 %</td>
<td>5.58 %</td>
<td>12.75 %</td>
<td>4,679</td>
</tr>
<tr>
<td>City Center</td>
<td>868</td>
<td>59</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td>Inner Ring</td>
<td>1,677</td>
<td>114</td>
<td>262</td>
<td></td>
</tr>
<tr>
<td>Outer Ring</td>
<td>1,972</td>
<td>135</td>
<td>308</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>81.67 %</td>
<td>5.58 %</td>
<td>12.75 %</td>
<td>5,530</td>
</tr>
</tbody>
</table>

The last data set needed are the runway definitions. The runway definition is needed to compute the distance between runways, $d_{\text{origin,dest}}$, in equation (8.4) and for the office ratios of runways, $R_{\text{Rwy}}$. Due to the large size of this table, it is not included in this document.
## 9 List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADS-B</td>
<td>Automatic Dependent Surveillance-Broadcast</td>
</tr>
<tr>
<td>ASA</td>
<td>Airborne Separation Assurance</td>
</tr>
<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
</tr>
<tr>
<td>ATFM</td>
<td>Air Traffic Flow Management</td>
</tr>
<tr>
<td>ATM</td>
<td>Air Traffic Management</td>
</tr>
<tr>
<td>ATS</td>
<td>Air Traffic Service</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative (probability) Distribution Function</td>
</tr>
<tr>
<td>CD&amp;R</td>
<td>Collision Detection and Resolution</td>
</tr>
<tr>
<td>CNS</td>
<td>Communications, Navigation, Surveillance</td>
</tr>
<tr>
<td>CPA</td>
<td>Closest Point of Approach</td>
</tr>
<tr>
<td>DC</td>
<td>Distribution Center</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)</td>
</tr>
<tr>
<td>ENAC</td>
<td>École Nationale de l’Aviation Civile</td>
</tr>
<tr>
<td>FCFS</td>
<td>First Come – First Served</td>
</tr>
<tr>
<td>GA</td>
<td>General Aviation</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>MSA</td>
<td>Minimum Safe Altitude</td>
</tr>
<tr>
<td>MVP</td>
<td>Modified Voltage Potential</td>
</tr>
<tr>
<td>NLR</td>
<td>Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory)</td>
</tr>
<tr>
<td>O-D</td>
<td>Origin–Destination</td>
</tr>
<tr>
<td>PAV</td>
<td>Personal Aerial Vehicle</td>
</tr>
<tr>
<td>PDF</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>RBF</td>
<td>Radial Basis Function</td>
</tr>
<tr>
<td>TCAS</td>
<td>Traffic Collision Avoidance System</td>
</tr>
<tr>
<td>TMX</td>
<td>Traffic Manager</td>
</tr>
<tr>
<td>TUD</td>
<td>TU Delft (Delft University of Technology)</td>
</tr>
<tr>
<td>UAV</td>
<td>Unmanned Aerial Vehicle</td>
</tr>
<tr>
<td>VTOL</td>
<td>Vertical Takeoff and Landing</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
</tr>
</tbody>
</table>
This page intentionally left blank
10 Bibliography


