FH AACHEN
UNIVERSITY OF APPLIED SCIENCES

DLR

Master Thesis

Performance Based Navigation Concept for Vertiports

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Handed in 18.11.2022

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I want to thank everyone who helped me within the process of researching and writing this thesis. A special thanks goes to my supervisor Thomas Dautermann and my colleague from the DLR ANTS project Maria Hanna.

Thanks go as well to Prof. Bauschat for supporting this thesis.

Abstract

This thesis aims to develop an initial Performance Based Navigation concept for vertiports. Developing versatile and robust navigational concepts for UAM is key for safe and efficient operations within urban areas. A vertiport and its geofences and the airspace as well as routes through it were designed. Codes were written to make distance and timing estimations to ensure safe operations and make a capacity statement. The concept includes placing navigational points in the terminal airspace, which can be combined to offer individual and flexible route planning for the VTOL. To calculate a capacity for the airspace a safety distance calculation was performed to determine the minimum distance between two VTOLs. This was done by modelling two normal distributions and a target safety factor of $5*10^{-9}$ collisions per flight hour. One takeaway is that a VTOL needs to keep 247.15 m of distance during the approach and departure. A complete approach through the airspace takes 151 seconds with a flight path length of 1076.1 m. The calculated vertiport capacity with this configuration is 38 VTOLs per hour. The development of a PBN concept for vertiports is not only influenced by navigation accuracy and the safety distance that needs to be kept, but also by considerations like passenger comfort. VTOL manufacturers and operators, vertiport operators, and regulators need to work together to achieve a safe and optimal solution for the navigation of VTOLs during approach and departure.

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Abbreviations

CAD	Computer-aided design
DLR	Deutsches Zentrum für Luft und Raumfahrt e.V.
DME	Distance Measurement Equipment
EASA	European Union Aviation Safety Agency
FMS	Flight Management System
FTE	Flight Technical Error
GBAS	Ground Based Argumentation System
GCA	Ground-Controlled Approach
GNSS	Global Navigational Satellite System
ICAO	International Civil Aviation Organization
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IRU	Inertia Reference Unit
MLS	Microwave Landing System
NSE	Navigational Senor Error
PBN	Performance Based Navigation
PDE	Path definition error
PDF	Probability distribution function
PinS	Points in Space
RNAV	Area Navigation
RNP	Required Navigation Performance
SBAS	Satellite Based Argumentation System
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
TOLP	Take-off and Landing Pad
TSE	Total System Error
UAM	Urban Air Mobility
VTOL	Vertical Take-off and Landing Vehicle

Units

°	degrees	
ft	feet	1 ft = 0.305m
hr	Hour	60 min = 1 hr
km	kilometres	1000 m = 1 km
m	meters	
m/s	Meters per second	
NM	Nautical Mile	1 nautical mile = 1852 m
min	Minute	60 sec = 1 min
sec	second	
kt	Knots	1kt = 0.5144 m/s

1. Introduction

This thesis gives an impression of how a Performance Based Navigation (PBN) concept could look like for the upcoming vertiports for VTOLs. It is furthermore thought to be a kick-off point for vertiport related required navigation performance at DLR.

1.1 Task description

The purpose of this thesis was the development of a modern navigation concept for vertiports. This concept should be based on literature research within the fields of PBN, vertiport design, and path-following accuracy of future air taxis.

As a next step, the arrival and departure procedures of an urban vertiport will be defined, including where they come from, where they go to and how long every step of this procedure takes.

From the Total System Error (TSE) a Required Navigational Performance (RNP) is derived, for collision avoidance purposes.

As a last step, some initial ideas regarding contingency procedures should be developed. It is to be clarified what happens in abnormal and emergency situations, like go-around or low fuel or battery situation.

As a result, a 4-D flight path consisting of position definitions in all three directions and as a fourth dimension the time, that the VTOL can follow to avoid conflicts, should be developed.

1.2 Urban Air Mobility (UAM)

UAM describes a new way of urban mobility, by providing air transport for short distances, for example within cities or from and to an airport.

This raises technical challenges like how can flight guidance and navigation be handled and implemented within a UAM airspace. The UAM airspace describes a new type of airspace, which is in development, with its own rules and standards for UAM aircraft. It is fitted between the already existing airspaces for small general aviation aircraft and large transport aircraft. [1]

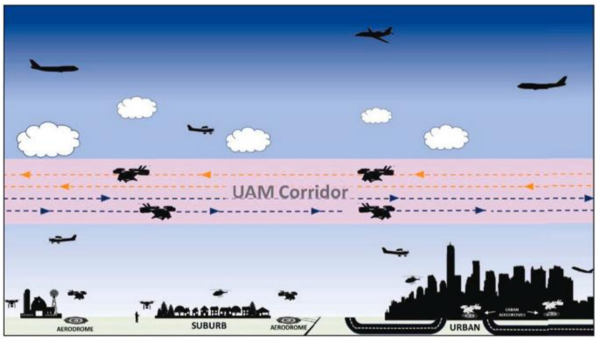

Figure 1 UAM Corridor placed between a hight of 400 ft and 2000 ft. Below the airspace of large commercial airliners, but right in the airspace of the general aviation. [20]

Those systems need to be robust and precise to ensure safe and efficient operations, especially because the flying aircraft, called VTOL, are intended to fly autonomously in the future.

1.2.1 Vertical Take-off and Landing aircraft (VTOL)

Figure 3 Volocopter, powered by 18 electric motors, it generates lift only with its rotors. ©Volocopter.com

Figure 3 Lilium Jet, it is electrically powered and generates its lift during cruise via wings and in hovering phases with thrust vectoring. ©lilium.com

VTOL is used as an umbrella term in this thesis for every UAM vehicle which will use a vertiport. Regardless of whether it is a pure rotary-based vehicle, like the Volocopter, or a vehicle which is generating lift via wings and thrust vectoring, like the Lilium Jet, but is still capable of doing vertical take-off and landing operations.

Due to the variety of solutions and designs, the fast-paced development, and due to trade secrets of the manufacturers, it is necessary to work based on assumptions and simplifications.

1.2.2 Vertiport

A vertiport is an airport for VTOLs. It provides at least the necessary Take-off and Landing Pads (TOLP) and passenger services.

They will be located within urban areas like city centres or trade fares. Placements next to already existing transport hubs like airports and train stations are also in the planning stages. [2]

1.3 Performance Based Navigation concept

Performance Based Navigation specifies the requirements for RNAV and RNP of an aircraft in terms of accuracy, integrity, continuity, and functionality [3]. This thesis focuses on the accuracy aspect of RNP. Accuracy is a measure of the position error by taking the difference between the estimated and the true position of the VTOL. [4]

RNP refers to the required level of performance, an RNP 0.3 describes the required navigational performance with an error of 0.3 NM, thus the aircraft must be capable of not deviating from the path for more than 0.3 NM for 95 % of the flight time.

RNAV stands for Area Navigation and is a method of Instrument Flight Rules (IFR) navigation where the aircraft follows set navigation points on its way to the destination.

RNAV and RNP systems are principally similar. The key difference between them is the requirement for onboard performance monitoring and alerting. A navigation specification that includes a requirement for onboard navigation performance monitoring and alerting is referred to as an RNP specification. One not having such requirements is referred to as an RNAV specification. An area navigation system capable of achieving the performance requirement of an RNP specification is referred to as an RNP system [3].

PBN has many advantages over sensor-specific navigation methods development, such as:

- Reducing the need to maintain sensor-specific routes and procedures and their associated costs
- Clarifying how RNAV and RNP systems are used
- Allowing more efficient use of airspace

[3]

Part of the RNAV and RNP are considerations regarding the Total System Error (TSE). The TSE is described by the Flight technical error (FTE) and the Navigation system error (NSE). The 3rd component is the negligible Path definition error [4]. It is given in meters.

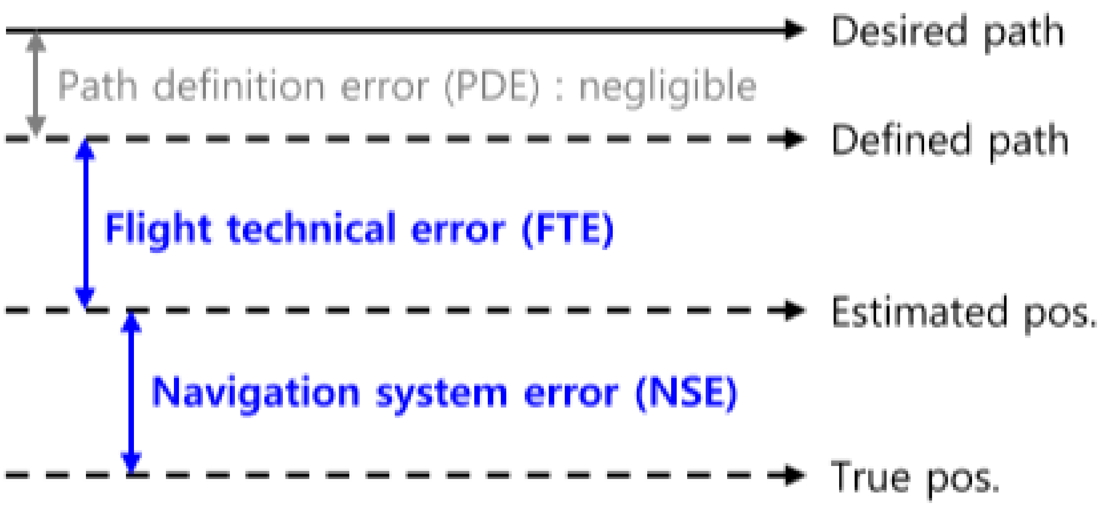

Figure 4 TSE composition overview, showing the three different parameters the TSE is composed off. [5]

The PDE is the difference between the designed flight path and the flight path the flight guidance computer calculated.

The FTE is the difference between the estimated position and the defined path. It is a measure of how well the aircraft can follow the guidance information.

The NSE is the difference between the true position and the estimated position. [4]

1.4 State of the Art

This chapter provides an overview of the findings of the literature research, to give an overview of the different available technologies and future technologies and their application.

1.4.1 Current navigation technologies

Currently, aviation mainly uses "Standard Terminal Arrival Route (STAR)" and "Standard Instrument Departure (SID)" for navigation during arrival and departure, as well as "Points in

Space (PinS)" in helicopter operations. Those procedures are using the ARINC 424 path termination concept with waypoints as navigational aids [6]. These approach and departure procedures are driven by either Global Navigation Satellite System (GNSS) or inertial guidance systems and PBN, as well as radio-based systems like Distance Measurement Equipment (DME) and DME RNAV [7] [8].

For precision approaches, aircraft and airports are using a system called "Instrument Landing System (ILS)". This technology is in service since 1946 and was selected by the ICAO as standard in 1947 [9]. The ILS is a ground-based antenna system that provides fixed lateral and horizontal guidance for approaching aircraft. The antennas are located in arrays on each end of the runway. Each runway that is equipped with an ILS system is categorized into three groups. The categories demand different equipment but provide different grades of navigational performance and safety levels. The higher the category the lower the limits and visibility requirements.

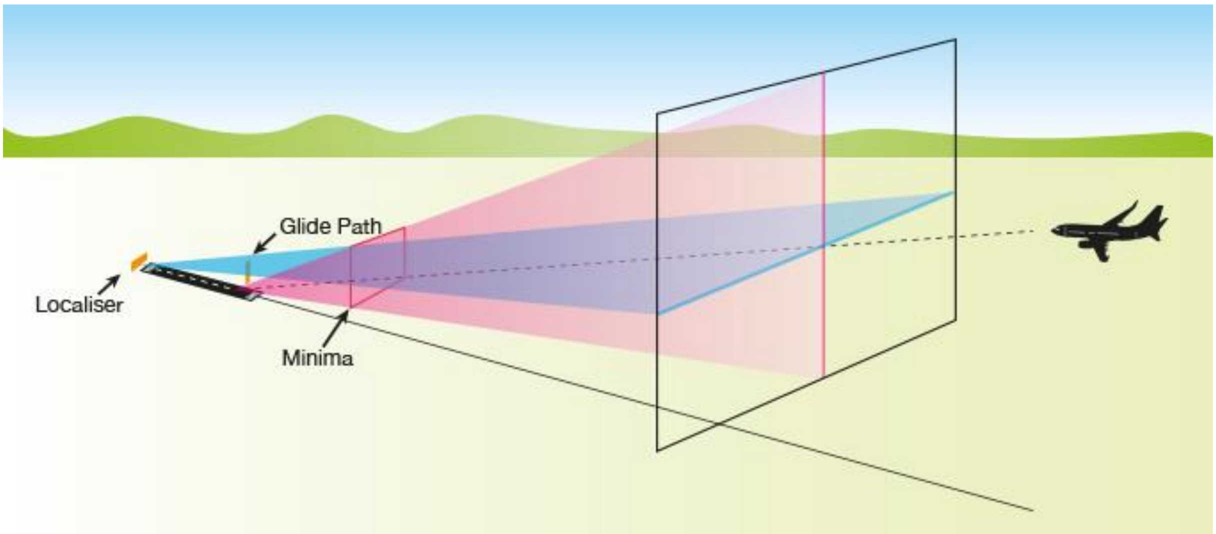

Figure 5 ILS, showing the different components the ILS is composed of and where to find them. It provides fixed lateral and vertical guidance with the localiser and the glide slope antenna. © Eamon Ryan https://www.quora.com/What-does-ILS-mean-in-aviation

ILS systems work by sending out horizontal and vertical signals from fixed antennas, thus they have the problem that the approach path is fixed, which limits the systems operation scope. The aircraft have to be queued up behind each other for the final approach.

Over the years several competing landing systems have been developed, including the radar-based ground-controlled approach (GCA) and the more recent microwave landing system (MLS) [9]. Those systems are more flexible regarding the approach path because they can provide variable approach paths, but they never have been in wide use.

For helicopter approach navigation the “Point in Space” procedure is in use, it is a GNSS-based system. The system works by providing virtual navigational points in space which can be programmed into the Flight Management System (FMS). They are then followed by the aircraft via a GNSS signal. The issue with a pure satellite system is the lack of accuracy to provide vertical guidance. [1]

As a backup for GNSS-based systems, inertia navigational systems are still implemented in every larger commercial aircraft. These systems need to be fed with new position data as often as possible, but usually, this is done at the gate position where a sign tells the crew the exact position of the gate. There are systems like Airbus´s “GPS Primary” function which continuously updates the inertia guidance system with the new position data of the aircraft.
Not a single failure can cause the loss of guidance compliant with the navigation accuracy associated with the approach. Typically, the aircraft must have at least the following equipment: dual GNSS sensors, dual FMS, dual air data systems, dual autopilots, and a single IRU. [10]
But the vehicle is only one part of this system, the vertiport it departs from and goes to needs to provide all necessary equipment and procedures for a safe and efficient operation.

1.4.2 Which new technologies are available

GNSS systems become increasingly important for aviation especially, for precision approaches and departures. The goal is to achieve a low positioning error to ensure a highly precise location of an aircraft in urban areas. This is achieved by either deploying a ground station, which is sending a GNSS correction signal to the aircraft, to ensure a safe and low navigation error. This is called Ground-Based-Augmentation-System (GBAS), and it has been proven that it is more accurate than an ILS in flight tests [11]. Minimizing the position error is very important to stay clear of any obstacles, even other aircraft within its vicinity.
GBAS stations are aimed to be deployable at any desired location. The system can offer an alternative to the traditional ILS at larger airports, but they provide exactly what is needed for UAM applications because it has advantages over the traditional ILS regarding flexibility in the route choice and even can serve multiple runways at once [11]. This is mandatory to accommodate the different needs of VTOL compared to traditional fixed-wing aircraft.

Due to the increase in computational power and image processing power, camera-based systems have become an alternative to classical navigational aids, especially for the final approach segment and line-up process prior to touch down.

They work by acknowledging visual clues, like pad markings, on the ground.

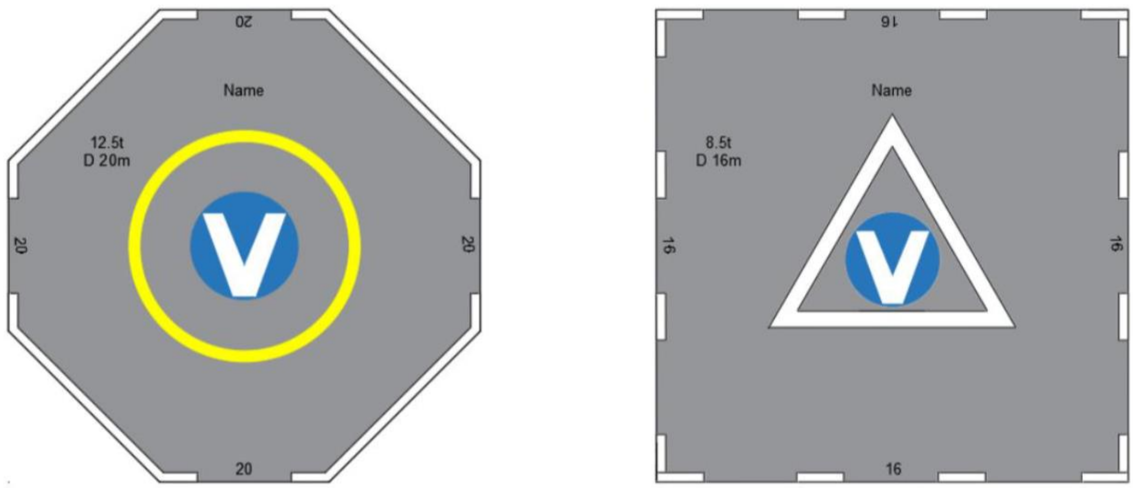

Figure 6 EASA examples for TOLP markings, the left is showing an octagonal TOLP with a diameter of 20 m. The right one has square shape with a side length of 16 m. [12]

2. Methods

Based on the conducted literature research, a vertiport was designed and an example location was chosen. For a better representation of the results, visualisations were prepared with CAD models and photo editing software.

To be able to conduct safety and capacity evaluations code was written to assess this important aspect of approach and departure procedures.

2.1 Vertiport Design

Current design proposals vary in a lot of aspects. Variations range from a single pad and single VTOL handling to multiple pads and multiple clearances. Every variation is in development. Those designs widely differ in their operations and their required procedures.

A single pad, single handling port is smaller and only can house one VTOL at a time like the Volocopter Skyport.

Figure 7 Volocopter Skyport, vertiport with only one TOLP, it can only handle one single VTOL at a time. ©Brandlab

Larger designs have more Take-off and Landing pads (TOLP) and gates. Some even have storage or parking spaces to buffer VTOLs for the system. The larger the vertiport gets and the more TOLP it has the more complex the operation becomes. With the size of the vertiport, the capacity increases as well. [13] suggested a turnaround time, from the entrance to the final approach over the landing, deboarding and boarding, takeoff, and leaving the terminal airspace, of 741 sec for a two TOLP design and no delays in the clearing process. The major portion with 600 sec, is taken up by the deboarding and boarding process. The approach takes up about 75 sec while the departure is a bit quicker at 66 sec [13].

The design of the vertiport itself has a significant impact on the approach and departure procedure design. This thesis discusses a vertiport with two TOLPs. Both TOLPs are spaced diagonally on the flight deck, to get the maximum distance between them.

The size of a TOPL is chosen with a size margin to be able to account for larger VTOL with a span of up to 20 m.

The passengers are exiting the VTOL on a floor below the flight deck so that the flight deck is always clear of no authorized persons to ensure the safety. The VTOLs are ascending and descending the flight deck with 2 elevators.

2.1.1 Vertiport Design Example

In the following subsection, the developed concept will be visualized and explained further based on the example of Frankfurt am Main Trade Fair Hall No. 4. This example was chosen among other things due to the intention of the Fraport AG, together with Volocopter, to provide a VTOL service between the airport and the Trade Fair [14] [2]. The direct distance between the trade fair and the airport is around 9 km.

It provides some open space for flight path development, but also it has obstacles, like high rise buildings in its proximity to show up some difficulties which need to be overcome. Also, the roof of Hall No.4 is large enough to accommodate a vertiport with two enough-spaced TOLPs. It is currently used as a parking lot and has a side length of about 130 m by 140 m. It has an area of roughly 18200 m². Hall No.4 is in the centre of the trade fair and a local train stop is located nearby. The provided CAD model of the vertiport flight deck is based on a design that was developed during a studies project and was adapted to fit the chosen example. The trade fair itself is located near the city centre (2,5 km) and the Main Station of Frankfurt (1,5 km).

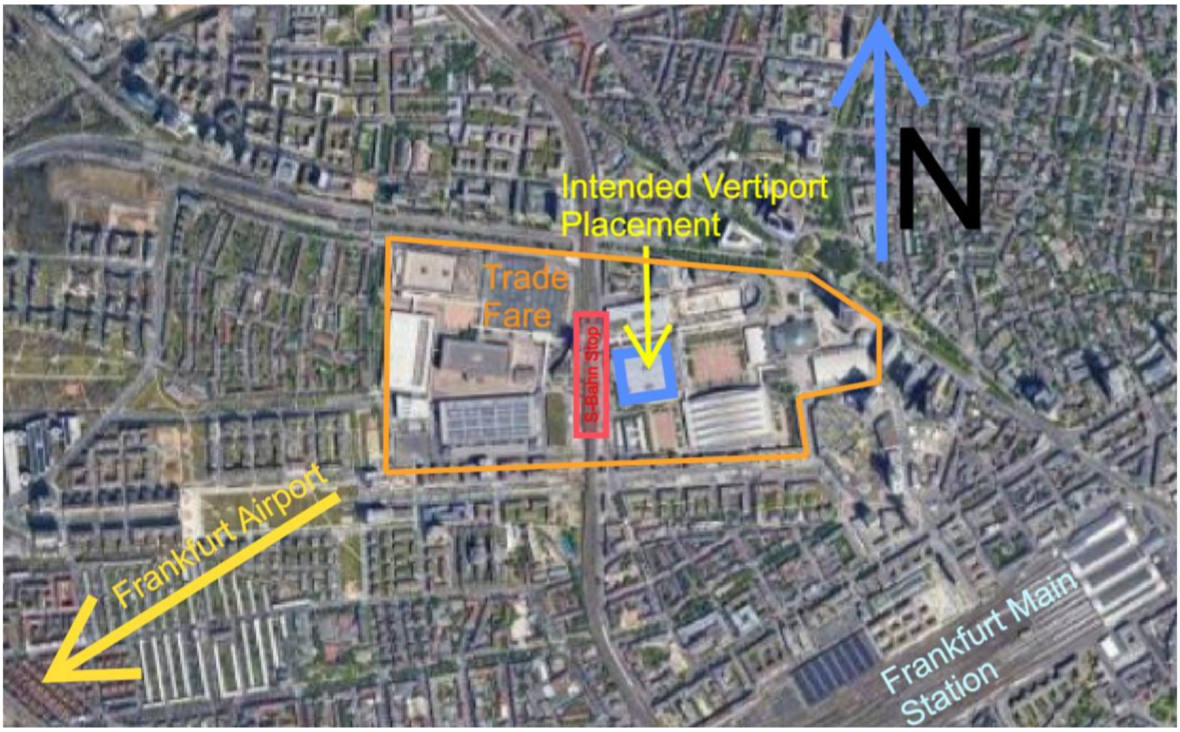

Figure 8 Overview Frankfurt Trade Fare, the orange line encloses the site of the trade fare. The blue box marks the intended vertiport placement at the trade fare and the red box the train stop. ©Google Maps for the satellite picture

2.2 Required minimum separation calculation

To operate a vertiport it is important to know the timings but also distances that need to be kept between two or more VTOLs during approach and departure. The calculated required minimum separation value is a TSE value which is directly converted into the RNP value.

Based on the RNP value flight routes can be developed.

This calculation is aimed to establish a minimum distance between at least two VTOLs in a 1-D plane, as a first step to determine the required minimum separation.

The vehicle behaviour cannot be anticipated accurately as well, due to a lack of real-world data. The calculation was done by using MatLab[1] and self-developed code[2].

The script calculates a lateral TSE value for a VTOL based on parameters, that were developed as part of this thesis. Each VTOL is modulated with a probability distribution function (PDF) for its flight path deviation, based on its TSE. The PDF represents the probability of stay within this TSE. The second standard deviation away from the mean of the PDF describes the required border for the calculation. Within this border, the VTOL should be for 95% of its flight time.

[1] Version MatLab 2021a

[2] The full code is attached in the Appendix

The two modulated PDFs are then used to determine the required minimum separation between both VTOL.

The main variables for this calculation are the span and a disturbance behavior parameter. The EASAs definition of span for VTOL was taken over. 'Span' means the diameter of the smallest circle enclosing the VTOL aircraft projection on a horizontal plane, while the aircraft is in the take-off or landing configuration, with the rotor(s) turning [12].

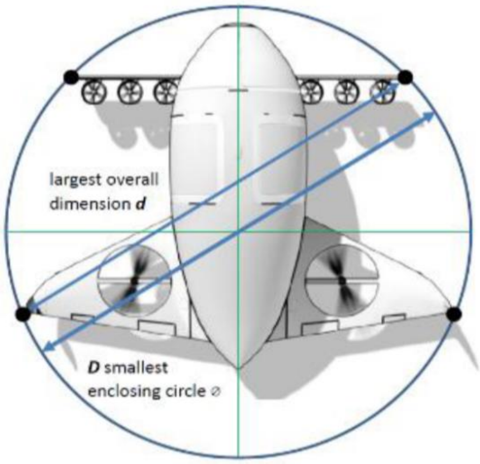

Figure 9 EASA span definition, shown on an example VTOL design. The span is defined by the diameter of the smallest enclosing circle. [11]

The issue is that the calculation is only valid for a 1-D lateral application may be overcome by using the Reich Model for example. The Reich Model considers all three positions two flying objects can have to one another, laterally, vertically, and longitudinally. Then each position is assigned a collision risk probability with respect to the flight time and position. All three are then combined to derive an overall collision risk assessment [15].

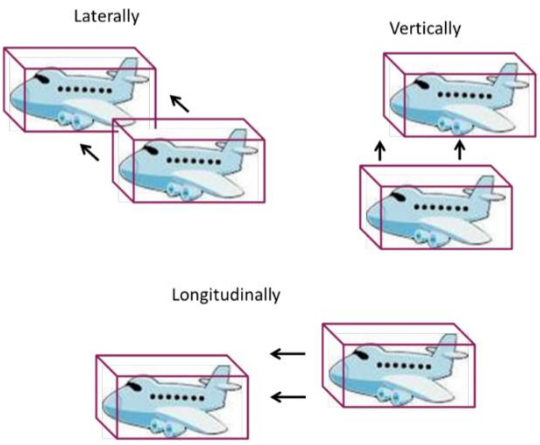

Figure 10 Three types of collisions according to the Reich Model, laterally, longitudinally, and vertically [15]

Also, the same gust disturbance behaviour was assumed for every VTOL, regardless of its size. The assumed value is only an approximation due to the lack of real-world data. It could be further improved through a higher fidelity wind model and more intensive vehicle modelling for example.

2.2.1 Calculation

The script is using the following values as inputs:

- Span of the VTOL,
  - Most VTOLs in development have a span width between 8m (Airbus CityBus) and 14 m (Lilium Jet). To have some overhead, the distance calculation was done with spans width between 5m and 20m.
- A desired safety factor,
  - The chosen safety factor is conservative with $5*10^{-9}$ collisions per flight hour [3]. It can be argued to use the value for simultaneous approach operation to an airport for large airliners with $5*10^{-7}$ collisions per flight hour, but it was not chosen to have a more conservative approach.
- Gust speed (gs), the speed of the encountered gust
  - For the gust encounter, a 15 m/s or roughly 30 kt gust was assumed.
- Maximum tolerated gust speed (mgs), the speed which can be tolerated at max by the vehicle
  - The maximum tolerated gust speed was as well 15 m/s
- Maximum reaction time (mrt), describes the time the flight control computer should need at maximum to acknowledge the gust and counteract it to the point where the VTOL has stopped relative to the gust furthest point away from the desired path
  - The maximum reaction time was assumed to be 3 sec.

As s first step the script calculates a gust encounter disturbance behavior for the VTOL.
The VTOL reacts to a gust disturbance with an exponential equation. To assume the gust behavior the maximum tolerated gust speed and the maximum reaction are taken into account and calculated over time with the following equation:

$$reaction\ time = \sqrt{\frac{gs * mrt^2}{mgs}} \quad (1)$$

The result can be seen plotted over 3 sec in Figure 11.

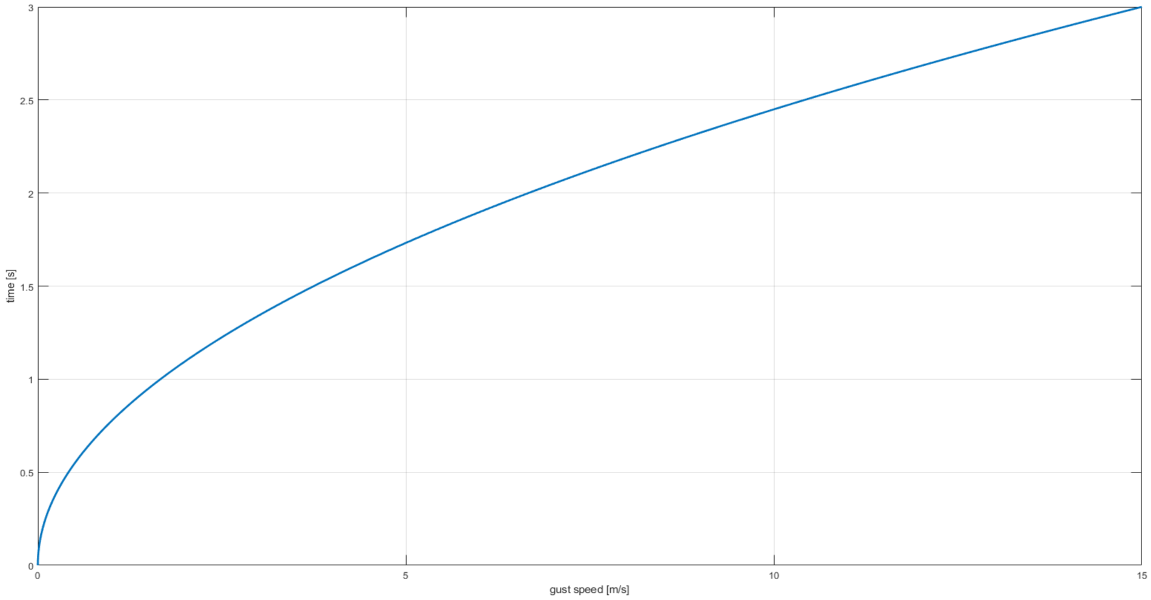

Figure 11 Gust encounter disturbance behavior of a VTOL, the graph reads the different times the VTOL needs to acknowledge and decelerate the gust to the point with the largest path deviation before it is returning to its desired path.

The function was chosen because the VTOL will not react with a linear behavior.

Smaller gusts will be smoothed out by slower reactions to ensure passenger comfort. High gust speeds will lead to a faster, more aggressive reaction to ensure a minimal path deviation. The reaction time is defined as the time the VTOL needs to process and decelerate the disturbance which hit the vehicle perpendicular to its flight path. This then marks the maximum path deviation. The maximum deviation is needed for the TSE-value calculation to account for a worst-case scenario.

The calculated reaction time is then multiplied by the gust speed to get a path deviation in meters. To modulate a safety zone around the VTOL the span is multiplied by 2 and the path deviation coming from the disturbance behavior is added to it. The safety zone is used to modulate a PDF to represent the probability of stay of the VTOL and represents the position of the VTOL in 95% of the flight time.

To be able to make a distance calculation between two VTOLs a second one is modulated the same way. The mean of the second PDF is placed away from the mean of the first PDF with a distance of seven times the span value of the first VTOL. The closer this initial distance guess is, the faster the distance iteration is. It usually needs between 30 and 75 iterations steps with this factor.

To derive the collision probability both PDFs are integrated within the same integration borders, from the mean to the 2nd standard deviation(2-sigma) of the PDF of the first VTOL, marked in red in Figure 12.

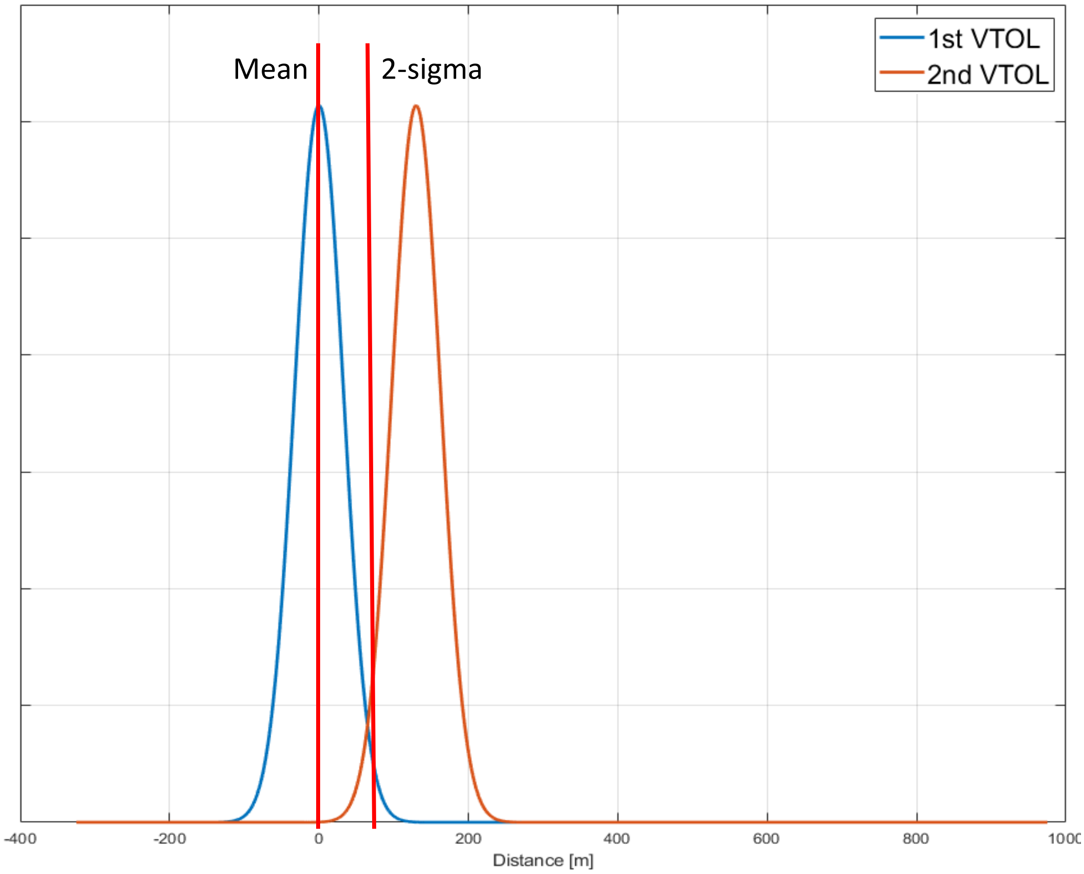

Figure 12 PDFs with both needed integration borders (marked in red) for the calculation

The two derived probability values are then multiplied to get the collision probability. If it is larger than the desired safety factor, i.e. > $5*10^{-9}$, the distance between both VTOLs is increased and the integration is done again until the probability is smaller than the desired safety factor. If the initial distance was too far, the script will reduce the distance to receive the same result of a minimum safety distance.

The derived distance results in the distance between both VTOLs which need to be kept to ensure the desired safety factor. As shown in Figure 13, the orange PDF is moved to the right side until the desired safety distance is reached. The thin yellow PDF marks the starting point of the calculation.

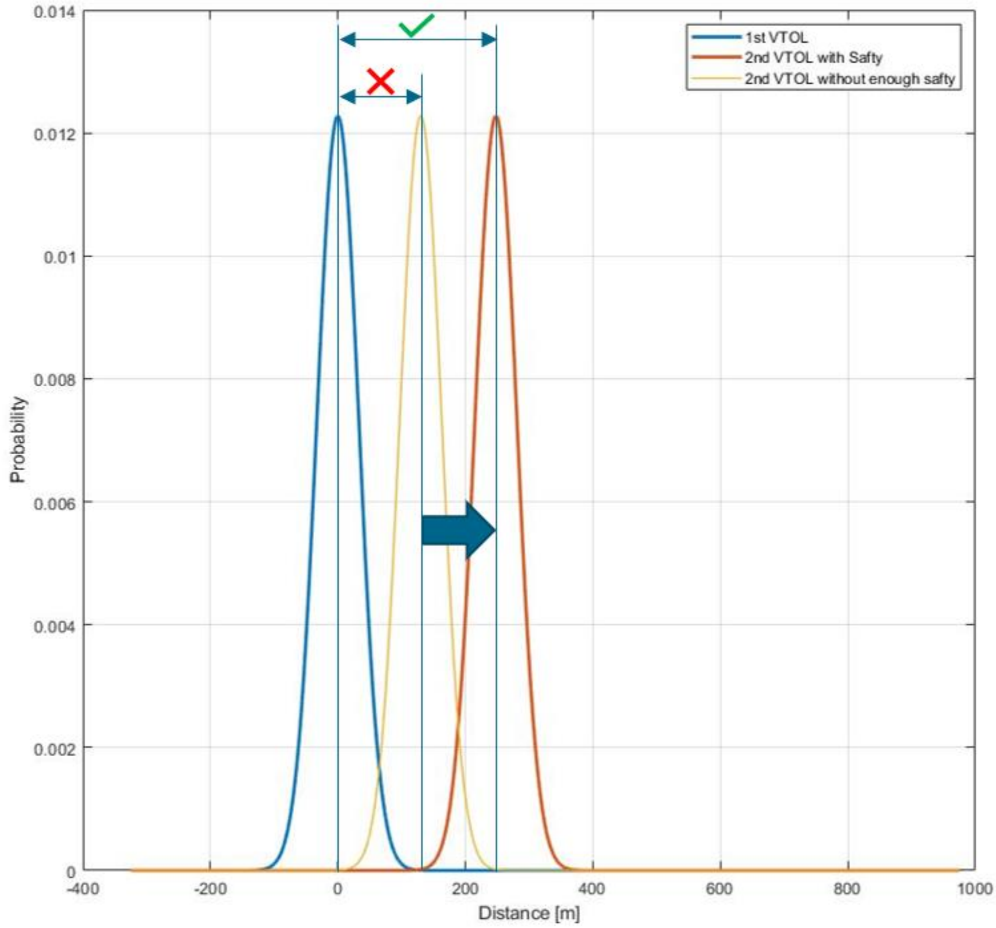

Figure 13 Example of the calculation result, it shows how the iteration has moved the yellow PDF to the right to increase the distance between both means.

Figure 13 is showing only one combination of VTOLs next to each other. To be able to calculate multiple combinations the basic script was modified to calculate all VTOL span combinations between 5 m and 20 m. It saves the output results in an external matrix file.

2.2.2 Timing/scheduling

The safety distance alone is not enough for a procedure design, so a timing estimation was done for the individual approach phases. For this purpose, the approach is divided into four phases. The first part is from entering the terminal airspace at cruise speed of 20 m/s to a final approach fix with a speed of 8.3 m/s. The second is from the final approach fix to a point 30.5 m above the TOLP. The 3rd part is solo a vertical part with a descending speed of 2.5 m/s. The last one is from landing to clearing the pad for the next landing.

The final approach fix needs to be defined for every possible approach angle and therefore can vary in the height above the pad, one suggestion is to have it fixed at 1000 ft or 305 m horizontally away from the pad. [13]

2.3 Contingency procedures

Contingency procedures are part of the planning process for abnormal situations. They define what to do in each case to streamline the behaviour of every emergency situation. For example, they describe what needs to be done and how it should be done during a go-around situation. They get into effect when a prior clearance cannot be obtained. [16]

The procedures are difficult to develop since VTOLs have vastly different behaviour during flight, arrival, and departure compared to smaller and larger aircraft. They are more comparable to helicopters but even helicopters have a different mission profile. Nevertheless, some shared characteristics can be identified, like downwash or the proneness to encounter turbulent air during low-ground operations, which are generated by the interaction of the surrounding buildings with different wind directions.

The contingency procedures for VTOLs must consider some more aspects regarding the operations in an urban environment. The airspace around the vertiports will not always be clear in any direction, there might be obstacles that are high enough to puncture a safety zone and therefore need to be avoided, like high buildings, trees, or industrial chimneys. The further away an obstacle is from the vertiport the higher it can be without interfering with the safety zone.

2.3.1 Backup systems

Contingency procedures also require the need for backup systems to the main GNSS-based navigational systems [17], especially if the VTOL flies autonomously and there is no pilot as a backup. There are a variety of technologies available which is required today for a resilient navigation infrastructure, like Distance Measurement Equipment (DME) and ILS [18]. These systems could be adapted to the use within the UAM.

2.4 Flight Path development

To develop a 4-D flight path it is necessary to not only specify a course in all three dimensions but also the timings. With the introduction of time, vehicle performance parameters need to be considered. This adds a lot of complexity and again assumptions because there is no flight test data from VTOL aircraft available to the public.

The development is done with values from different papers and behaviour assumptions regarding de- and acceleration. Some key velocities are the speed any vehicle enters the terminal airspace of $v_{entrence}$ = 20 m/s as well the final approach velocity $v_{max\ hor\ appr.}$ = 8.3 m/s. The highest vertical speed is set to be $v_{max\ ver.}$ = 2.5 m/s [13]. The terminal airspace is defined by borders which incorporate a lot of security aspects like obstacle clearance as well as downwash considerations.

The flight path for VTOL is determined by GNSS waypoints which the vehicle can navigate to by using RNP systems. Which points are used for the navigation is decided either by the VTOL or by the approach/departure control of the vertiport. The focus was on providing a smooth and safe transition between cruise flight and landing/take off.

To ensure a safe operation with GNSS, safety boundaries and approach surfaces are needed, they are called geofences. A geofence is a virtual border that should not be crossed by any means.

Each port needs a dedicated assessment of possible hazardous objects within its vicinity, like high buildings, windmills, or powerlines. Objects like this must not be passed too close, they need a geofence [1]. Not only do obstacles need a geofence, but noise and privacy of residents must also be considered especially during low flight phases. Another aspect of interest is the wind which flows around buildings and is creating disturbances that could influence the safety of VTOL operations. Those single geofences then need to be combined in a meaningful way to create a geofence or a no-fly zone. [1]

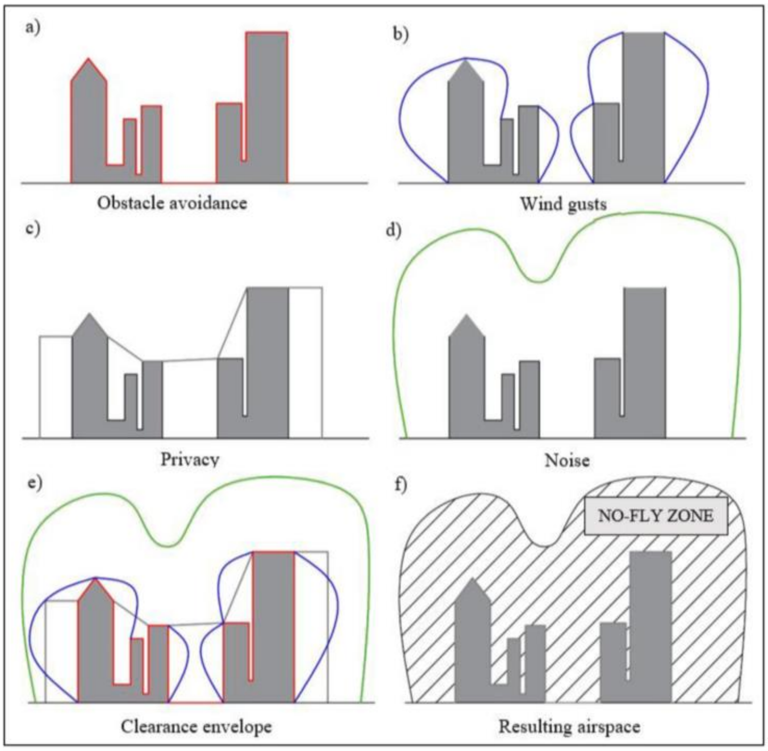

Figure 14 Geofence variables to consider, the figure shows 4 individual parameters which are added up to derive the No-fly zone around buildings. [1]

3. Results and Discussion

In this chapter, the results of the calculations will be discussed.

3.1 Vertiport and Geofence Design

The vertiport has been designed to specifically fit the Frankfurt Trade Fare Hall No. 4. It is a two TOLP configuration on an area of around 18000 m², with a side length of 130 m by 140 m. The TOLPs are spaced diagonally on the flight deck to get the maximum distance between both. Each pad is designed for a maximum size of VTOL with a span of 20 m, to account for larger VTOL. With the needed safety margin of 1.5 times the span of the VTOL [12] each pad has a diameter of 30 m.

The vertiport is thought to have at least two floors, a flight deck, and a terminal area. They are connected via two large elevators.

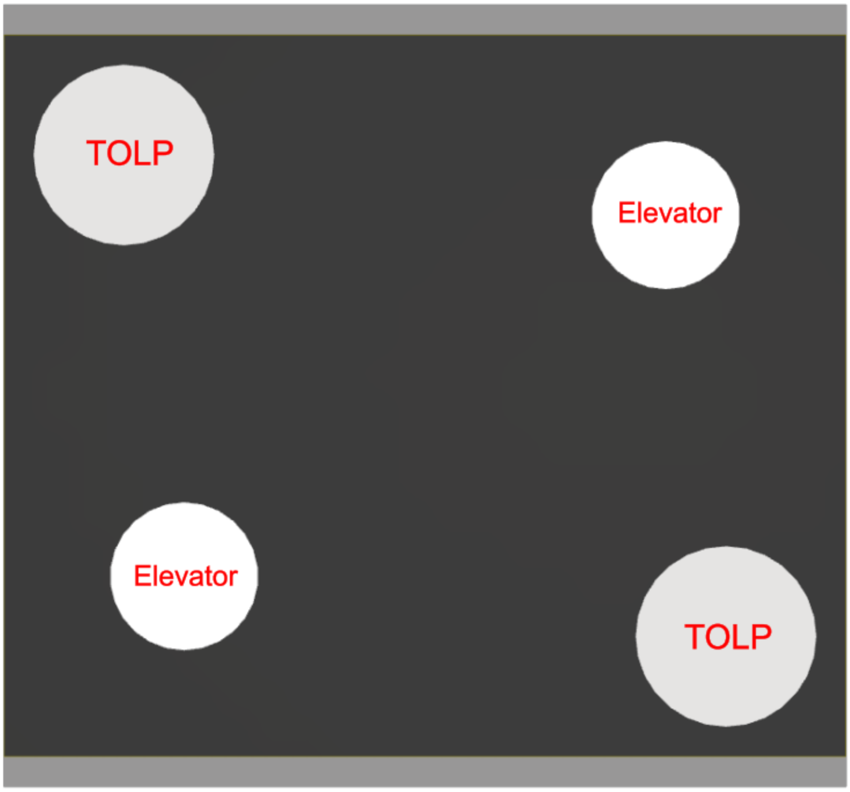

Figure 15 Vertiport flight deck layout, it shows the 130 m x140 m large flight deck with its two TOLPs and elevators which symmetrically distributed on it.

The geofence is created with the help of the EASA guidelines for manned VFR vehicle operations[3].

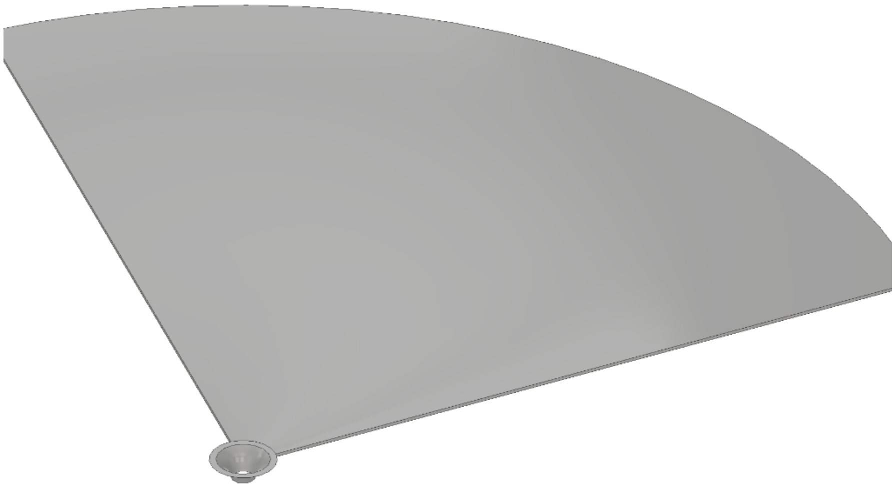

Figure 16 Developed geofence for on TOLP of a vertiport with an opening of 95°

It consists of two main parts. The first one is the cone, shaped like a chalice, right above the TOLP. The cone is hollow and starts with the flight deck and ends at a height of 30.5 m above the flight deck. The chalice opens to the top, on the flight deck level it has the same inner diameter as the TOLP in size, in the case of this vertiport it is 30 m in diameter. At the top, it has an inner diameter of 80 m.

The second main part has the shape of a dented washer. The pitch of the part is suggested to be between 4.5 % to 12.5 % [12], which translates to 2.55° to 7.1°. The part shown and used here has a pitch of 7.1°. It ends at a height of 500 ft or 152 m above the flight deck, in this case here the outer diameter of the part is 1025 m. This also marks the entrance and exit of the terminal airspace, where the control/guidance is intended to be done by the vertiport. The airspace is enclosed by a cylindrical dome which has its peak height over the TOLP of 1300 ft or 400 m. This height is subject to change depending on the altitude at which VTOL in this region will fly.

The geofence has a „thickness" to represent the provided safety margin. It is different for each portion of the geofence to take care of the different security margins needed at different stages of the landing or approach. A VTOL that is flying above or within the geofence can continue on its route even if it is flying in an offset to it. The volume above the geofence is guaranteed to be free of obstacles. But if it breaks through a certain threshold the approach

[3] Prototype Technical Specifications for the Design of VFR Vertiports for Operation with
Manned VTOL-Capable Aircraft
Certified in the Enhanced Category

or departure needs to be terminated and the VTOL has to perform a contingency procedure before it penetrates the no-fly zone or safety zone.

Ideally, the vertiport has 360° of free airspace around it so that just a vertical or height-based geofence is needed, but in a real-world application, it will need some adjustment to the surrounding area. For example, if there is a high rise the flying zone needs a cutout, to ensure obstacle-free flight paths. Obstacles, like high buildings or transmission towers, are not the only thing to consider. A multiport design will have several areas where large-angle flight areas will overlap each other when they have a 360° opening. This will be an issue because then flight paths might overlap as well, so these areas need to be trimmed down like it is shown in Figures 16 and 17.

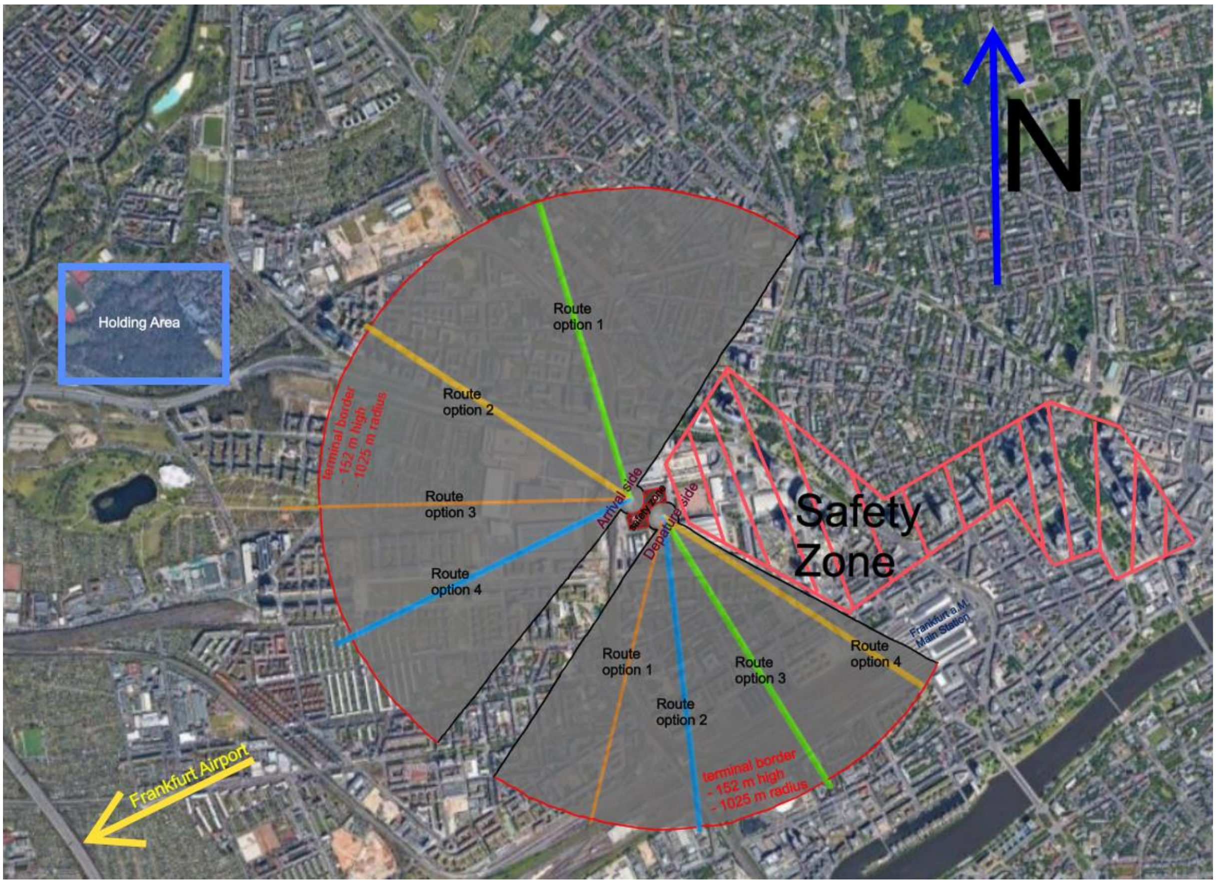

Figure 17 Application to Frankfurt a.M. Trade Fare Hall No.4, it shows the vertiport with its geofences. The red-marked safety zone encloses high buildings and obstacles which can hinder approach and departure operations ©Google Maps for the satellite picture

Figure 17 shows the application to the Frankfurt Trade Fair. Since this example has two TOLPs, there are two geofences visible from the top (grey areas with red terminal borders). The northwest pad has a rather large opening angle, due to very few obstacles. The southeast one has a meaningful smaller opening angle because there are more obstacles to the east, in form

of high buildings which are high enough to interfere with possible flight paths and thus need to be avoided (marked with red surroundings and red crossed lines).
The blue box which can be seen in the northwest of the terminal airspace is the holding area. The position is subject to change to different configurations of the vertiport operations e.g., the approach and departure directions, or the wind directions or noise obtainment procedures.

3.1.1 Discussion

The design of a vertiport is highly dependent on the location and on the layout of the flight deck. The more TOLPs it has the more complex the operations will become and the more complex the geofencing becomes.
Another important factor in the process of designing the geofences for the vertiport is the surrounding of the vertiport. The surroundings will influence the design and layout of a vertiport and its geofences. Because there might be large buildings that would interfere with possible flight routes. The reduction of the available airspace influences the requirements for PBN equipment for a certain VTOL that will need to approach and depart from that vertiport.

The essence is that each vertiport will need an individual assessment of its surroundings and with that an individual arrival and departure concept regarding the geofence. But one thing should not be neglected, it might be possible that certain VTOLs are capable of overflying the safety zone earlier than others because their performance is high enough to do so. Out of this comes the requirement to assess these scenarios as well and develop routing options that make this possible.
In the end, the shape of the geofence depends on the placement of the vertiport and its intended routing. The here chosen round, cylindrical shape is only one option. The EASA proposes for example rectangular designs in its concepts [12].
The development and design of geofences is of great importance because it influences nearly every parameter. It also influences the needed RNP value, the larger the safety zone the higher the RNP will be allowed to be. If a VTOL cannot meet a required value, it may not be allowed to fly every possible route during an approach or departure within that terminal airspace.

3.2 Required minimum separation calculation

Finding the right separation value is a challenge because many factors must be considered and then an optimisation needs to take place. Safety is the number one priority, still, factors like the throughput and with that the economics of a vertiport should not be neglected.

3.2.1 Calculations results

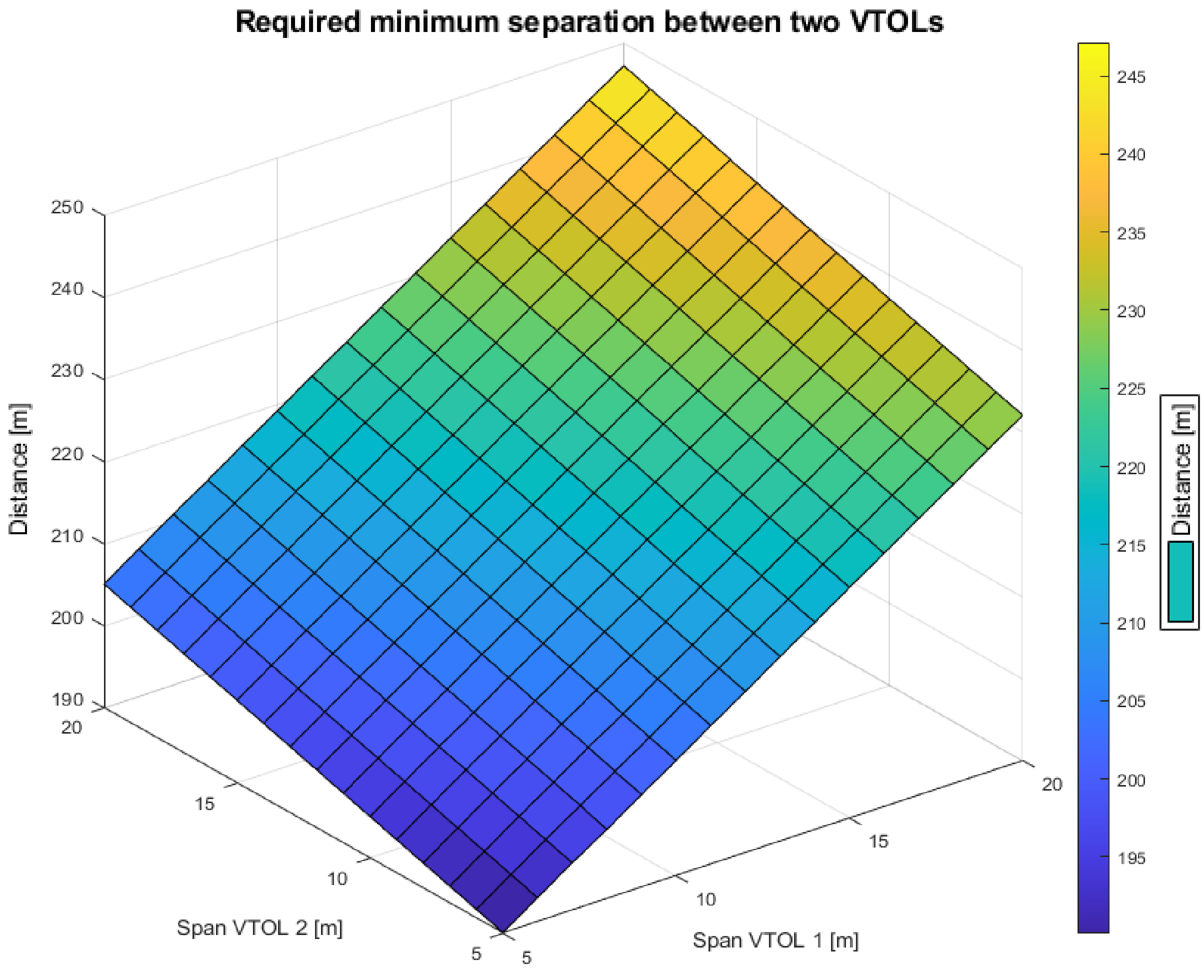

Figure 18 Separation results diagram, it shows the required minimum separation between two VTOLs with regard to there span in a 3-D mesh plot.

The 3-D mesh-plot shows on X- and Y-axis the span of the VTOL. The Z-axis shows the necessary distance between both VTOLs with the desired safety of $5*10^{-9}$ collisions per flight hour.

The smallest assumed VTOL has a span of 5 m which leads to a TSE of 50 m and translates as an assumption to an RNP value of 0.027 NM. The required minimum separation is 190 m. The largest assumed VTOL with a span of 20 m and a TSE of 65 m and with that it has an RNP value of 0.035 NM and needs to keep a safety distance of 249 m.

But the distance between two or more VTOLs may also be influenced by the time, especially by the time a VTOL is blocking the final approach sector.

3.2.2 Timing

To cover the along-track separation a timing calculation was conducted as well. The time is measured from the entrance into the terminal airspace to clearing the pad for the next landing and for the departure from entering the pad to leaving the terminal airspace. For the calculation, the approach is split into four parts.

This first part is defined as from entering the terminal airspace down to the final approach fix. The final approach fix is defined by the lateral distance to TOLP. In this thesis, the point was chosen to be at a radius of 250 m and not like previously discussed of 305 m [13], around and above the TOLP. The 250 m is the required safety distance between the two largest assumed VTOLs within the previous calculation. The comfort of the passengers needs to be thought of as well, at the distance of around 250 m to the TOLP gives the VTOL sufficient time to decelerate from 8.3 m/s with moderate accelerations.

The second part is from the final approach fix on to the point directly above the TOLP at a height of 30.5 m. The third part includes the pure vertical descent onto the TOPL. The last part is for the ground operation, so the time required to leave the pad is set to a flat assumption of 10 sec.

For the departure, the measuring is started from entering the TOLP and ends with leaving the terminal airspace.

Figure 19 [4] combines two corresponding values, the flight time for a certain flight path segment, shown as bars. The second value is the flight distance within a certain segment, represented by the dots. Those two parameters are plotted over the approach angle. The time and the respective flight path length have the same colour. The complete approach length is marked with red dots.

[4] Table with all values can be found in the Appendix in table no. 2

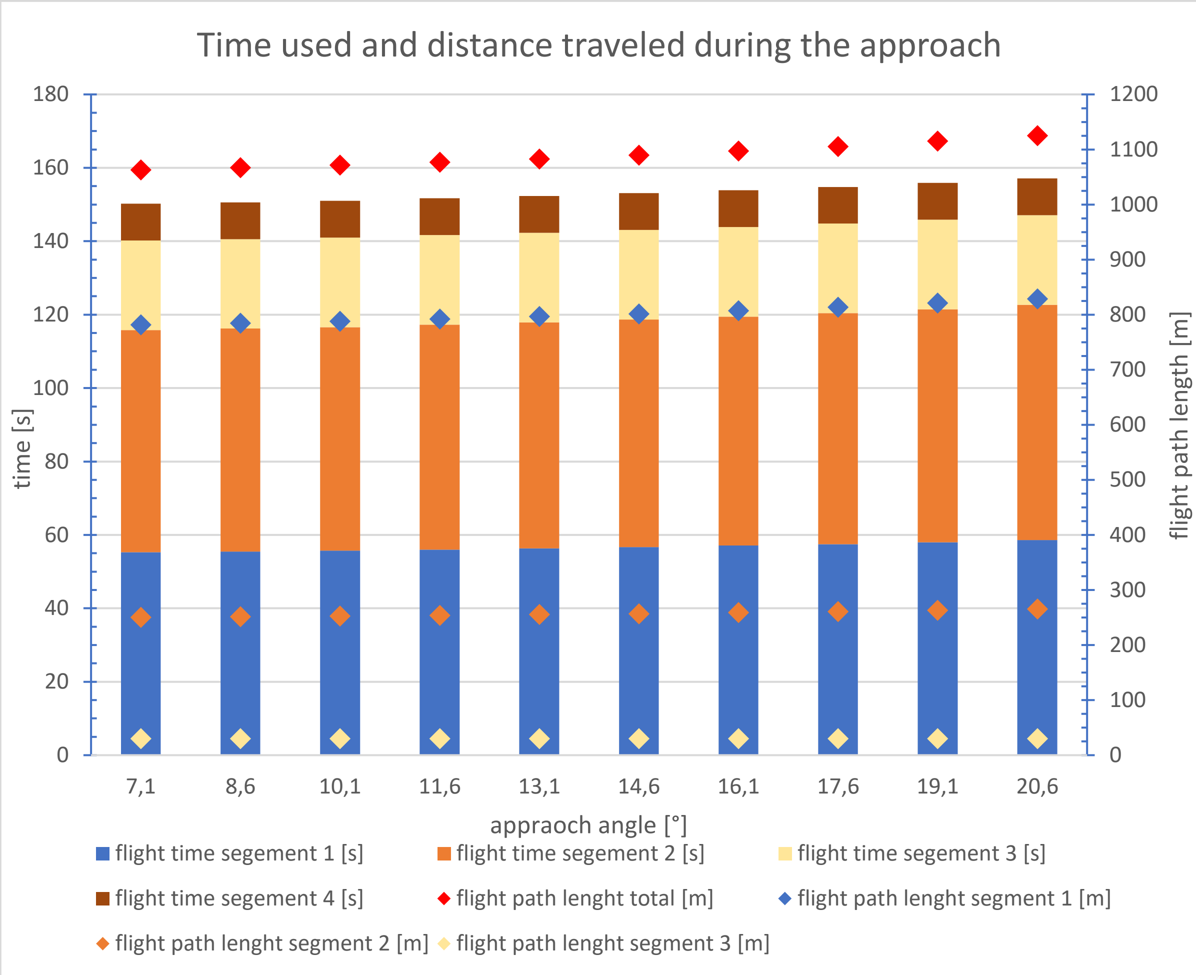

Figure 19 Flight time and distance plotted over the approach angle, it shows teen different approach angles and which time is needed for that angle and how much distance the VTOL needs to travel for approach and/or departure.

As shown in Figure 19 the time needed for the approach increases with the approach angle as well as the needed travel distance. This comes from the increasing distance in the flight path segments 1 and 2, due to the cylindrical shape of the airspace around the vertiport. The angle increases up to the highest outer point of this cylinder which is in this case here 400 m above and 1025 m away from the TOLP. Segments 3 and 4 always have the same travel distance and time consumption, due to them having the same travel distance at the same speeds.

The approach usually takes longer than the departure process, so this is of main concern for the throughput of the vertiport. This is due to the intermediate steps needed in the deceleration process and the varying accelerations during the deceleration. During the departure procedure, the VTOL is capable of a constant acceleration up to its cruising or desired climb speed.

The time spent on the pad depends on the vertiport and the VTOL capabilities in ground operations. If the VTOL can roll itself off the pad it will take less time than if it needs a carriage of some sort because it only has sleds. If the vertiport has a system which works for every type of VTOL, like a conveyer belt or similar, there is no time difference, this was assumed here.

3.2.3 Discussion

The results provide a starting point to develop initial PBN requirements and they need to be understood as such.

The obtained distance values are not the limiting factor in flight segment 1 rather they become one in segments 2 and 3. The 1st segment of the airspace provides enough space to not limit the operations, but the segment cannot be entered by a VTOL until the previous VTOL has cleared the airspace and the TOLP. A landing VTOL would block the airspace for 95 sec, which means that only 38 VTOLs can land within one hour per TOLP. The time between two departures is shorter if the VTOL has enough performance and is allowed to accelerate to cruise speed as fast as possible. If it has to stick to “speed limits” and/or does not have enough performance the departure capacity is similar to the arrival capacity.

The smaller the RNP is the smaller the required safety distance becomes. Leading to a closer approach fix to vertiport, which would then lead to a higher capacity.

Depending on the type of VTOL this may be achievable with improvements in the flight guidance technologies or already is possible, but the acceleration might not be bearable for the passengers.

Another factor is the processing speed of the vertiport. The faster the TOLP is cleared and the landed VTOL is safe the faster the next VTOL can proceed with its landing. The ground processing speed of the vertiport itself depends on the used technology and its layout. Depending on the VTOL type it might need to be picked up because it has no wheels, which takes more time than the processing of a VTOL which has proper landing gear.

The slope of the distance graph, Figure 18, is linear because for every VTOL the same gust encounter was assumed. Thus, this section of code needs improvement or modifications to better suit the real behaviour. Also, it was always planned for every possible scenario, including the worst case.

Another part in the VTOL operations which might need to be considered is the downwash and vortices created by the VTOL, so it might be that it is not possible to fly back-to-back even with the calculated safety distance. Because it only considers the collision risk between two VTOLs.

3.3 Contingency procedures

Contingency procedures are very important to be capable of handling abnormal or emergency situations. To handle special case situations, you have to take measures beforehand. This chapter focuses on approach issues that are encountered when planning go-arounds and have to be taken into account. It will show the example of Frankfurt a.M. possibilities and unfeasible ways for go-arounds.

The first step in developing contingency procedures is to determine decision points, where certain criteria need to be fulfilled. If they are fulfilled the VTOL can have a normal landing, if not a contingency procedure is needed.

Problems that contingency procedures need to be designed for are for example medical emergencies, damaged aircraft, or priority landings from emergency services. As well as "low on fuel" scenarios, which include low battery status from e.g., an eVTOL[5]. Giving way for a low-battery VTOL is most likely one of the more common scenarios which will be encountered, but this is snowballing problem because if one VTOL gets a priority landing others may have to wait which makes it possible that they become an emergency as well and so forth.

For this reason, there need to be alternate landing sides where a VTOL can divert, to avoid such situations.

There can be several reasons for an aircraft to fly a go-around, like obstacles on the flight path or the runway. If a large commercial airliner is going-around, it can fly on the runway heading even at the latest possible point and it will have an obstacle-free departure. However, VTOL operations take place in urban areas and approach vertiports from various angles within cities, thus often not all directions are clear. This leads to a limitation in routing options. Depending on the area around there might be zones that cannot be penetrated. In the example of the Frankfurt a.M. Trade Fair, there are high buildings on the east side of the intended placement (marked in red). Another point to consider for multi-TOLP vertiport is if and when and at which height it is feasible and safe to overfly the flight deck to allow for safe ground operations. But even if it is safe to overfly it, it is not given that the VTOL can continue straight ahead because

[5] An eVTOL is a fully electrical-driven VTOL.

of other obstacles. The chances of the need for evasive manoeuvres of some sort in low altitude increase with each obstacle within the vicinity of the vertiport.

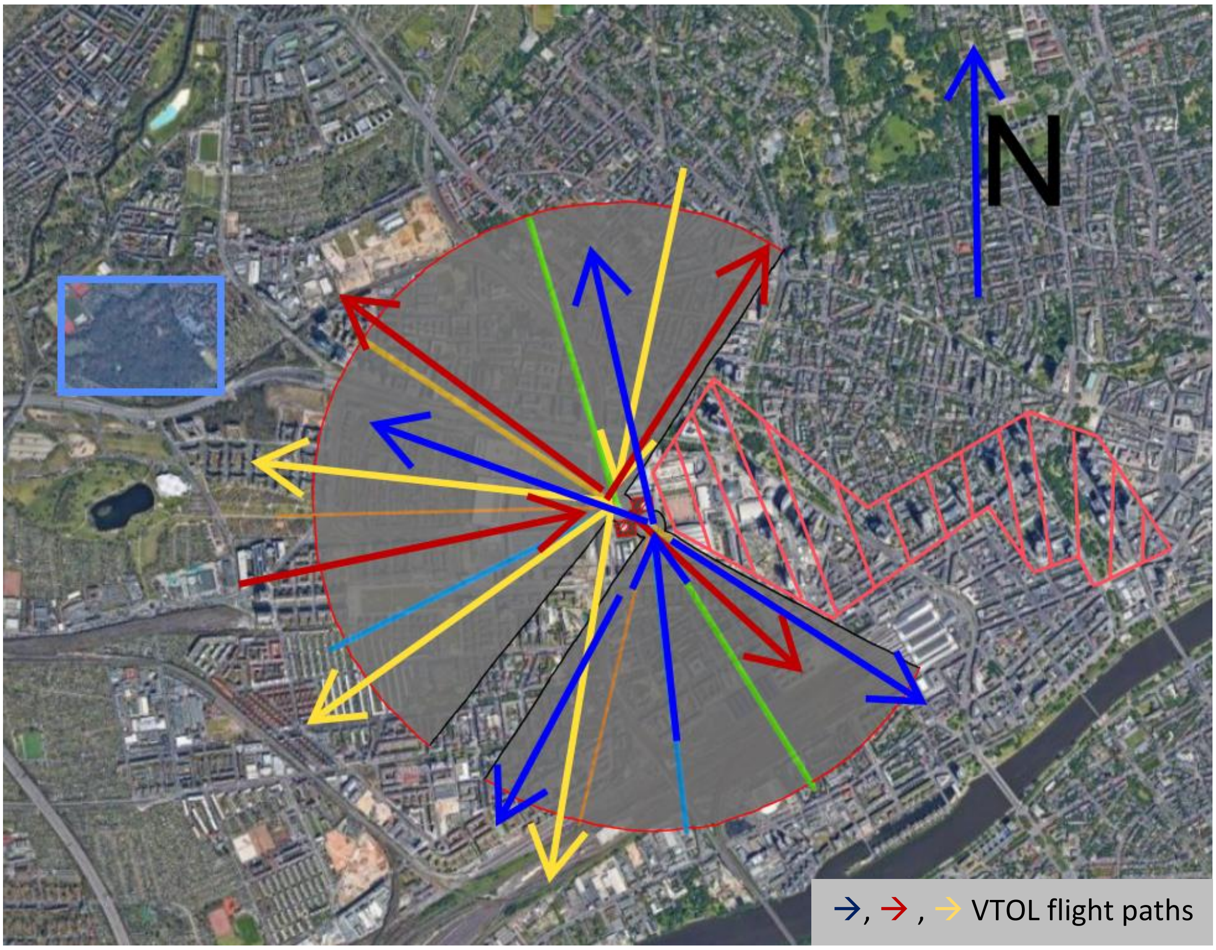

Figure 20 Contingency flight path possibilities, it shows three different approach angles and possible contingency flight path options. Each VTOL is marked with its colour. ©Google Maps for the satellite picture

Figure 20 shows different possibilities for the Trade Fare. Each colour represents one VTOL approaching the vertiport and then a selection of possibilities for the go-around and contingency flight paths. One arrow of each colour shows the approach direction and the others the options, to make some encountered problems visible.

The blue VTOL enters the airspace of the south TOLP flying to the north and aborts its landing at the latest possible point, right over the TOLP. Now it has serval options, some are shown here. Two possible routes, where it stays within the geofences of this TOLP, forcing the VTOL to make either sharp left or right turn or flying backword. The two other options allow the VTOL to only make slight turns, but it has to overfly the flight deck of the vertiport.

The red and yellow VTOLs are similar, both are approaching the north TOLP one towards the south, the other one to the east. The yellow one could, in case of a late landing abort, fly straight ahead without overflying the flight deck to large extent but it would leave the geofence. As an alternative, it could fly a slight turn to the right and be fine. The red VTOL cannot fly straight head because it would then penetrate the No-fly-zone where high buildings are physically blocking its flight path. It can either make a left turn and be fine or do a sharp right turn and overfly the flight deck.

The blue box in the northwest of the vertiport represents a possible holding area for one or more VTOLs which have to wait for their approach into the terminal airspace. The VTOLs are waiting there in hovering mode.

3.3.1 Backup systems

For VTOL operations in the proximity of a vertiport two operators have to be considered, the VTOL and the vertiport. Each one is the need of different infrastructure to achieve redundancy, but both operators need to ensure that they are compatible and communicate with each other.

The vertiport operator needs to provide a different navigational aid besides the GNSS/GBAS for the approach and departure procedures. This can be for example visual clues for cameras that the VTOL has on board and can be used for navigational purposes even in noncritical operations status to increase the navigational accuracy and support the GNSS. Another alternative could be a laser-based guidance system.

Older systems like ILS or radar-based systems could be used as a backup as well.

Another part of backups are alternate landing sides, this can be either other vertiports or pre-defined landing sites near the vertiport.

3.3.2 Discussion

There is a need to define contingency procedures in a general matter. They are then adapted to the design of a vertiport. The adapted contingency procedures then determine the standards a VTOL needs to fulfil to be allowed to approach the vertiport.

If a vertiport has more than one TOLP it might make sense to alcoate different use cases to each TOLP. Meaning it might be feasible to use one TOLP solo for arrivals and one for departure operations, to streamline the traffic flow and be able to avoid head-to-head traffic and with that even more evasive maneuvers. If a vertiport has three or more TOLPs available, it as well might be feasible to dedicate one TOLP solo for emergency landings.

In the case of the chosen example, it is so that it might be feasible to use the northwest TOLP solo for arriving traffic, because it opens more contingency options to the VTOL, with turning angles smaller than 90 degrees. The southeast TOLP then would be solo used for departure operations, to avoid steep and sharp turns near the ground, because the VTOL could be too low to fly straight over the flight deck and make a sharp turn or fly backword.

If a delay happens due to any reason other VTOLs need to have an area where they can wait for their slot in the approach sequence. Placing a holding next to a vertiport is essential to buffer delays. But it is not feasible to be placed within the terminal airspace of the vertiport, because it would block required routing flexibility, therefore it needs to be placed outside but not too far to avoid more delays, because of a too large distance between the holding area and vertiport.

Another point to discuss within the frame of contingency procedures are backup systems and their benefit to increase navigational performance. Systems like a camera-based augmentation system are implemented into VTOL for the means of navigational purposes, some are processing the raw images and using computer vision to identify obstacles and some are using it to identify specific visual markers. This improves the RNP of a VTOL in different ways, but it also provides a certain level of redundancy and thus provides backup for the GNSS/GBAS-based systems.

3.4 4-D Flight Path development

The flight path development takes all previously made results and combines them.

From entering to landing, from take-off to leaving the terminal airspace the VTOLs are guided by GNSS with the addition of GBAS.

They receive a routing through the terminal airspace from the vertiport in the form of GNSS navigational points. Those points are defined in height and position within the terminal airspace. They are distributed over the terminal airspace in a way that the density of points increases towards the centre of the TOLP. In areas where the density is too low, filling points are used, to be able to accommodate a large variety of different approaches and departure needs of different VTOLs. Each point can be reached from any other point, so there are no fixed routes within the airspace for the best possible flexibility.

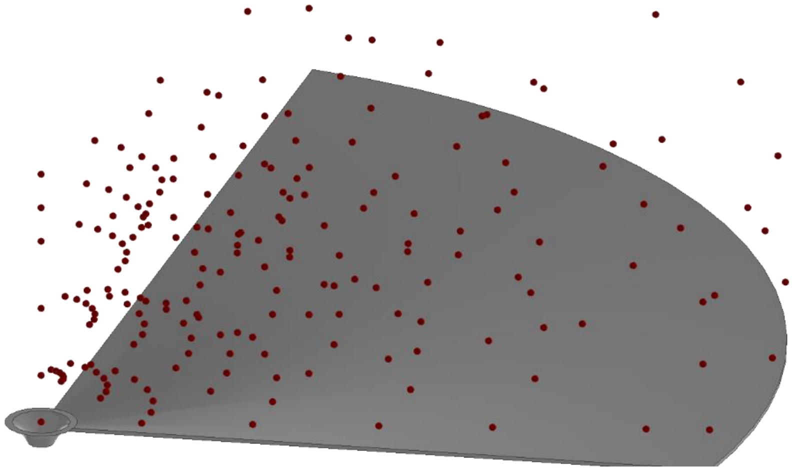

Figure 21 GNSS waypoint placement example, it shows possible waypoint distribution for the designed geofence.

Before entering the terminal airspace, a VTOL receives its set of navigational points which it should use for a safe approach. If a VTOL is departing from the vertiport it receives the set before its take-off. The sets are customized for each VTOL. With the flight path, the VTOL receives a timing schedule for each point, so it can be ensured that operations are going as smoothly as possible. The time management of vertiports is of great importance because it will limit its capacity if the timings are calculated inaccurately. The timing is influenced by factors, like the profile of the flight path, the accelerations of the VTOL, and the weather conditions.

The largest contributor to the time is the needed distance between two VTOLs, it is driven by safety considerations like RNP value but also by the generated wake turbulence or downwash.

3.4.1 Example

Applied to the vertiport example this could look like this:

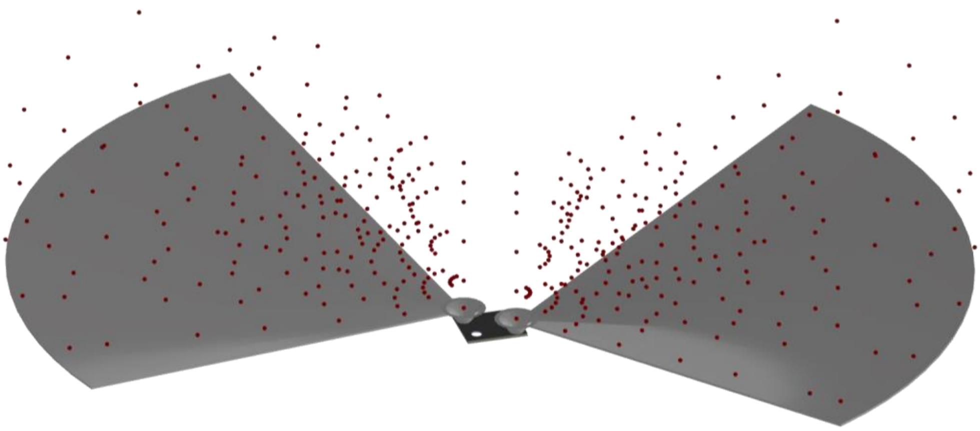

Figure 22 GNSS waypoint application to a vertiport, it shows the application to vertiport with two TOLPs and two similar geofences.

Figure 23 shows a potential approach or departure route marked in blue. The VTOL enters the terminal airspace on a navigational point which is 400 m high and 1025 m lateral away from the TOLP. It follows a descending path for 4 more waypoints, then it steepens its approach a bit and skips a row of points before its starts heading for the last GNSS point over the TOLP. The shown arrival has a length of 1070 m, measured from the beginning of the dome, which would take 150 sec.
For the departure, it works the other way around.

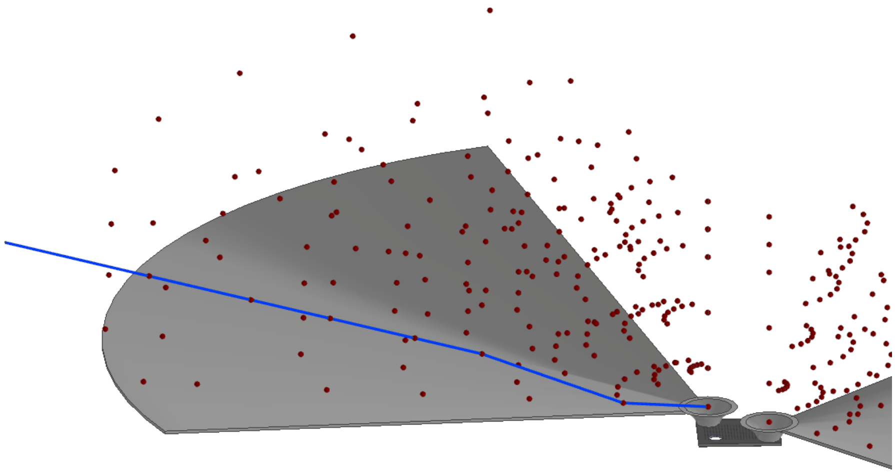

Figure 23 GNSS waypoints application with flight route example, the blue line shows a possible flight path that could be used by a VTOL during its approach. It combines different approach angles and waypoints of different inclinations.

3.4.2 Discussion

The development of flight paths must take a lot of aspects into account and is influenced by a lot of variables, from vehicle performance over the vertiport capacity and the weather. Each vertiport will have its approach and departure design due to the different surroundings, but they will have similar navigational requirements as minimum standards. VTOLs will need to fulfill minimum navigational standards as well to be able to operate from a set vertiport.
The lower the RNP value of a VTOL, the tighter they can be scheduled and, the capacity increases. It should be in the interest of the VTOL manufacturers to improve the navigational performance to reduce the RNP value, but also the vertiport operators must ensure the navigational aids are sufficient to keep up with the possibilities.
The density of navigational points within the vertiport airspace should be as high as possible because it ensures the highest flexibility, but it increases the complexity and with that the

computational effort for each approach and departure, but this should not be of concern anymore with modern computer systems. With the increased complexity of a system comes reduced robustness and a susceptibility to errors. This can be problematic if more than one VTOL is near another one and navigational systems fail both can get too close to each other because their navigational points and timings overlap.

PBN approach- and departure-based route planning offer new ways of designing them to every participant´s needs. It not only allows for curved routes it also allows variable vertical profiles, this is a huge advancement over the nowadays common ILS, which allows only for a set approach route. The required hardware already exists, in the form of GBAS, which can easily be deployed to increase GNSS accuracy at a set location. This is of importance because GNSS signals can be inaccurate especially in urban areas where the signals can be negatively influenced by e.g., reflections of buildings (multipath).

4. Conclusions

Developing a Performance Based Navigation concept for vertiports showed that different considerations, like how much space is available, need to be made. They interact with each other which leads to a development iteration loop to derive the best possible option.

The design of the vertiport depends on its placement within a certain area and its surroundings which then influences the design of the airspace and geofences.

The geofence will look different for each deployed vertiport, it can also have a rectangular shape instead of the round shape used in this thesis. The EASA made suggestions for both options. Another aspect is the angle of the lowest possible approach path, it can be reduced from the chosen 7.1° or it could be made steeper depending on the needs. A lower angle will lead to an even larger geofence and airspace of the vertiport itself, but it could increase passenger comfort, due to the decrease in the descent rate.

The GNSS navigational waypoint placement and the corresponding waypoint density are dependent on the available airspace and the surroundings of the vertiport. For the placement and the density of waypoints, standards need to be derived which then can be applied. The standard should reflect the developments in PBN and within the industry.

The designed vertiport could operate both TOLPs simultaneously, if the pads are used in an alternating operating mode, with the calculated RNP values in this thesis. If the TOLPs could be spread further out, or the RNP values are improved, accuracy-wise, it could be possible to simultaneously take off and land on both. The parallel operation could be hindered by other factors as well, like vortices and the downwash of the VTOLs.

Compared to the required minimum distance between the centre lines of two for parallel approach ILS-equipped runways of 1035 m [16] the distance between both TOLP centre points of the assumed vertiport is relatively small at 130 m.

The derived RNP values between 0.027 NM and 0.035 NM are compared to the lowest implemented RNP values of 0.1 NM [4] very small. But those low RNP values are needed to ensure the safety of close proximity VTOL operations. To operate a vertiport with RNP 0.1 or even RNP 0.3 would reduce the capacity by a factor of at least 3 with the assumptions done in this thesis. This is due to the increase in the required minimum separation and with that the approach fix moves further out as well.

To achieve a higher capacity from a navigation accuracy standpoint, it is necessary to improve and reduce the RNP value. This will reduce the required minimum separation and with that required safety distance between two VTOLs. If the required safety distance is reduced, the final approach fix can be moved closer to the vertiport, this will lead to a further reduction in airspace blockage time. The closer the approach fix is placed to the vertiport, the shorter the timings become and the capacity is increasing.

The determined RNP values might as well change if the minimum separation calculation is done in 2 or 3 dimensions, for example with the Reich model.

If not only navigation accuracy is of interest, there can be problems with wake turbulence and the downwash of the VTOL. This might lead to a necessary increase in the time between two landing VTOLs. Another topic that needs to be addressed is the time it takes for the ground handling (i.e. clearance for landing, passengers boarding, maintenance, and other checkpoints, etc.) of the vertiport itself. The faster the vertiport is the smaller the time added to the approach sequence. This comes into account if the safety distance is not of concern anymore because of navigational performance improvements and the resulting reduction of the RNP.

The issue with improving flight performance is usually not found within internal parameters like the engine power or flight controller speeds, but rather in external parameters like the G-load tolerance of passengers. Since flight planning is essential to avoid inconveniences for the passengers, the flight path needs to be as flexible as possible, which is served by the concept of GNSS waypoints. The more flexible the flight paths are, the more flexible the vertiport itself is in handling approach and departing VTOLs. Especially step approaches, flown with high velocities can be a problem for passenger operation, because of high negative G-loads. These kinds of approaches can probably cause motion sickness. It might be better to fly flatter approaches, which again can limit the throughput of the terminal airspace. For autonomous cargo operations, step and fast approaches might not be a problem.

The deployment of such a system will account for most VTOL types because each VTOL can be assigned to the best flight path for its approach or departure. This will improve passenger comfort as well as the safety of everyone involved.

To be able to deploy such a system in a real-world environment will take time and must be tested extensively. Especially because of the shortcomings of the concept described in this thesis due to the lack of real-world data.

Further studies are needed on the computational effort on both sides. A vertiport might have sufficient processing power available but a VTOL might not necessarily. Therefore, it might be feasible that the vertiport does the approach and departure route planning and then sends it to the VTOL. On the other hand, this can be an error source, so the VTOL needs to check the data for validity. This could result in the problem that VTOL is calculating a differing route by itself and thus raises the question of who decides which is the valid option. All this must be considered besides all the technical considerations and developments.

The VTOL manufacturer and operators, as well as the vertiport operators, play an important role in the process of streamlining and implementing the necessary procedures. The regulators need to take everything into account as they determine the RNP standard for vertiport operations.

Within this highly iterative process, everyone is learning from each other and technologies are being improved quickly. Every new technology or change in the procedure design is changing requirements and demands for every party involved.

All these processes need to be moderated to be able to derive PBN specifications. This is essential to write the rules, laws, and requirements to ensure a safe and efficient UAM operation.

5. Appendix

5.1 Calculated Safety Distances Including RNP values

5.1.1 MatLab Code

```
% Input Values

clear;

% spannwidth of vtol
span1a = 9:1:10;
span2a = 9:1:10;


% desired safty
safe = 5 * 10^-9;

% Windstuff
%macl = 0.2;     %max accelration of an vtol [m/s²]
%mgust = 0.8;   %max gust acceleration
windspeed = 15;   %windspeed = max expected winds [m/s]
windspeedmax = 15; %max tolertable windspeed of VTOL
reacctmax = 3;      %maxreaction time



% counter
it1 = 1;
it2 = 1;
sc = 0;     %Speichercounter
l1 = length(span1a);
l2 = length(span2a);
maxvalue1 = max(span1a);
maxvalue2 = max(span2a);

% memory allocation
values = zeros(5,l1*l2);

% react time calculation

windi = 1;

windx1 = 0:0.01:reacctmax;

divider = reacctmax^2/windspeedmax;

windy1 = (windx1.^2)/divider;
```

```
if windspeed > 15
    fprintf("max Windspeed exceeded!")
    reactt = 5;
else
    while windy1(windi)<windspeed
    windi = windi+1;
    end
    reactt = windx1(windi);
end

reactt1 = reactt;
reactt2 = reactt;

p = plot(windx1,windy1);
grid on;
p(1).LineWidth = 2;
xlabel('time');
ylabel('windspeed');
% Iteratrionsschleifen

while span1a(it1)<=maxvalue1
    span1 = span1a(it1)
    span2 = span2a(it2)
    fprintf('Next round');

% Border calculations

%no fly span/area around vtol

noa1 = 2*span1 + windspeed*reactt1;
noa2 = 2*span2 + windspeed*reactt2;

% calc borders
dx = 0.01;  % step size
ug = -noa1*5;   % lower border
og = noa2*15;    % upper border



% standart deviation
% course deviation half of 95%mile
sigma1 = noa1/2;
sigma2 = noa2/2;

%calc of integration boraders
ui = 0;               % lower integration border
oi = sigma1*2;        % upper border --> sigma1*2 = the 95%-mile border

% initial distance between both vtol
mean1 = 0;  % course of 1st vtol
```

```
mean2 = sigma2*7; % course 2nd vtol

%Calculation

% calculaions %
x  = ug:dx:og;
x1 = ug:dx:og;
y1 = normpdf(x, mean1, sigma1);
y2 = normpdf(x, mean2, sigma2);

% definerte Flächen aus dem integral
syms x
yfi1 = int(exp(-0.5 * ((x - mean1)./sigma1).^2) ./ (sqrt(2*pi) .* sigma1), ui
, oi);
f1 = vpa(yfi1);
yfi2 = int(exp(-0.5 * ((x - mean2)./sigma2).^2) ./ (sqrt(2*pi) .* sigma2), ui
, oi);
f2 = vpa(yfi2);

% probability at the beginning
intProp = f1*f2;

% iteration
 dist = mean2;
 prop = intProp;
 it = 0;

 % decreasing distance
 if prop<=safe
    fprintf("Distance is enough ...reducing...");
    while prop<=safe
    %fprintf("iterating pls wait\n");
    dist = dist-0.1 ;
    yfi2i = int(exp(-0.5 * ((x - dist)./sigma2).^2) ./ (sqrt(2*pi) .*
sigma2), ui , oi);
    f2i = vpa(yfi2i);
    prop = f2i*f1;
    it = it + 1;
    end

fprintf("iteration steps needed: %d \n", it);
fprintf("distance reduced to at least: %.3f from %.3f\n",dist,mean2);
fprintf("propability of a collosion was: %1.3e \n", intProp);
fprintf("propability of a collosion now is: %1.3e \n", prop);

% calculation of new plot
%y3 = normpdf(x1, dist, sigma2);


 else
```

```
% increasing distance

while prop>safe
    %fprintf("iterating pls wait\n");
    dist = dist+0.1 ;
    yfi2i = int(exp(-0.5 * ((x - dist)./sigma2).^2) ./ (sqrt(2*pi) .*
sigma2), ui , oi);
    f2i = vpa(yfi2i);
    prop = f2i*f1;
    it = it + 1;
end
 end

fprintf("Distance has been increased!")
fprintf("iteration steps needed: %d \n", it);
fprintf("distance needed at least: %.3f m \n", dist);
fprintf("propability of a collosion was: %1.3e \n", intProp);
fprintf("propability of a collosion now is: %1.3e \n", prop);

% calculation of new plot
%y3 = normpdf(x1, dist, sigma2);

values(1,it1+sc) = span1;
values(2,it1+sc) = span2;
values(3,it1+sc) = noa1;
values(4,it1+sc) = noa2;
values(5,it1+sc) = dist;


if it1==l1
   if it2 == l2
       return
   end
    it2 = it2+1;
   it1 = 1;
   sc = sc + l1;
else
    it1 = it1+1
end %end from this if/else

end %end of the complet while term
```

5.1.2 Results table

Span VTOL 1 [m]	Span VTOL 2 [m]	RNP VTOL 1 [m]	RNP VTOL 2 [m]	Safety Dist. [m]
5	5	50	50	190,1
6	5	51	50	191,1
7	5	52	50	192,1
8	5	53	50	193,1
9	5	54	50	194,1
10	5	55	50	195,1
11	5	56	50	196,1
12	5	57	50	197,1
13	5	58	50	198,1
14	5	59	50	199,1
15	5	60	50	200,1
16	5	61	50	201,1
17	5	62	50	202,1
18	5	63	50	203,1
19	5	64	50	204,1
20	5	65	50	205,1
5	6	50	51	192,95
6	6	51	51	193,95
7	6	52	51	194,95
8	6	53	51	195,95
9	6	54	51	196,95
10	6	55	51	197,95
11	6	56	51	198,95
12	6	57	51	199,95
13	6	58	51	200,95
14	6	59	51	201,95
15	6	60	51	202,95
16	6	61	51	203,95
17	6	62	51	204,95
18	6	63	51	205,95
19	6	64	51	206,95
20	6	65	51	207,95
5	7	50	52	195,8
6	7	51	52	196,8
7	7	52	52	197,8
8	7	53	52	198,8
9	7	54	52	199,8
10	7	55	52	200,8
11	7	56	52	201,8
12	7	57	52	202,8
13	7	58	52	203,8
14	7	59	52	204,8
15	7	60	52	205,8

16	7	61	52	206,8
17	7	62	52	207,8
18	7	63	52	208,8
19	7	64	52	209,8
20	7	65	52	210,8
5	8	50	53	198,45
6	8	51	53	199,55
7	8	52	53	200,55
8	8	53	53	201,55
9	8	54	53	202,55
10	8	55	53	203,55
11	8	56	53	204,55
12	8	57	53	205,55
13	8	58	53	206,55
14	8	59	53	207,55
15	8	60	53	208,55
16	8	61	53	209,55
17	8	62	53	210,55
18	8	63	53	211,55
19	8	64	53	212,55
20	8	65	53	213,55
5	9	50	54	201,3
6	9	51	54	202,3
7	9	52	54	203,4
8	9	53	54	204,4
9	9	54	54	205,4
10	9	55	54	206,4
11	9	56	54	207,4
12	9	57	54	208,4
13	9	58	54	209,4
14	9	59	54	210,4
15	9	60	54	211,4
16	9	61	54	212,4
17	9	62	54	213,4
18	9	63	54	214,4
19	9	64	54	215,4
20	9	65	54	216,4
5	10	50	55	204,05
6	10	51	55	205,05
7	10	52	55	206,05
8	10	53	55	207,15
9	10	54	55	208,15
10	10	55	55	209,15
11	10	56	55	210,15
12	10	57	55	211,15

13	10	58	55	212,15
14	10	59	55	213,15
15	10	60	55	214,15
16	10	61	55	215,15
17	10	62	55	216,15
18	10	63	55	217,15
19	10	64	55	218,15
20	10	65	55	219,15
5	11	50	56	206,9
6	11	51	56	207,9
7	11	52	56	208,9
8	11	53	56	209,9
9	11	54	56	211
10	11	55	56	212
11	11	56	56	213
12	11	57	56	214
13	11	58	56	215
14	11	59	56	216
15	11	60	56	217
16	11	61	56	218
17	11	62	56	219
18	11	63	56	220
19	11	64	56	221
20	11	65	56	222
5	12	50	57	209,65
6	12	51	57	210,65
7	12	52	57	211,65
8	12	53	57	212,65
9	12	54	57	213,65
10	12	55	57	214,75
11	12	56	57	215,75
12	12	57	57	216,75
13	12	58	57	217,75
14	12	59	57	218,75
15	12	60	57	219,75
16	12	61	57	220,75
17	12	62	57	221,75
18	12	63	57	222,75
19	12	64	57	223,75
20	12	65	57	224,75
5	13	50	58	212,5
6	13	51	58	213,5
7	13	52	58	214,5
8	13	53	58	215,5
9	13	54	58	216,5

10	13	55	58	217,6
11	13	56	58	218,6
12	13	57	58	219,6
13	13	58	58	220,6
14	13	59	58	221,6
15	13	60	58	222,6
16	13	61	58	223,6
17	13	62	58	224,6
18	13	63	58	225,6
19	13	64	58	226,6
20	13	65	58	227,6
5	14	50	59	215,25
6	14	51	59	216,25
7	14	52	59	217,25
8	14	53	59	218,25
9	14	54	59	219,25
10	14	55	59	220,25
11	14	56	59	221,35
12	14	57	59	222,35
13	14	58	59	223,35
14	14	59	59	224,35
15	14	60	59	225,35
16	14	61	59	226,35
17	14	62	59	227,35
18	14	63	59	228,35
19	14	64	59	229,35
20	14	65	59	230,35
5	15	50	60	218,1
6	15	51	60	219,1
7	15	52	60	220,1
8	15	53	60	221,1
9	15	54	60	222,1
10	15	55	60	223,1
11	15	56	60	224,1
12	15	57	60	225,2
13	15	58	60	226,2
14	15	59	60	227,2
15	15	60	60	228,2
16	15	61	60	229,2
17	15	62	60	230,2
18	15	63	60	231,2
19	15	64	60	232,2
20	15	65	60	233,2
5	16	50	61	220,85
6	16	51	61	221,85

7	16	52	61	222,85
8	16	53	61	223,85
9	16	54	61	224,85
10	16	55	61	225,85
11	16	56	61	226,85
12	16	57	61	227,85
13	16	58	61	228,95
14	16	59	61	229,95
15	16	60	61	230,95
16	16	61	61	231,95
17	16	62	61	232,95
18	16	63	61	233,95
19	16	64	61	234,95
20	16	65	61	235,95
5	17	50	62	223,7
6	17	51	62	224,7
7	17	52	62	225,7
8	17	53	62	226,7
9	17	54	62	227,7
10	17	55	62	228,7
11	17	56	62	229,7
12	17	57	62	230,7
13	17	58	62	231,7
14	17	59	62	232,8
15	17	60	62	233,8
16	17	61	62	234,8
17	17	62	62	235,8
18	17	63	62	236,8
19	17	64	62	237,8
20	17	65	62	238,8
5	18	50	63	226,45
6	18	51	63	227,45
7	18	52	63	228,45
8	18	53	63	229,45
9	18	54	63	230,45
10	18	55	63	231,45
11	18	56	63	232,45
12	18	57	63	233,45
13	18	58	63	234,45
14	18	59	63	235,45
15	18	60	63	236,55
16	18	61	63	237,55
17	18	62	63	238,55
18	18	63	63	239,55
19	18	64	63	240,55

20	18	65	63	241,55
5	19	50	64	229,3
6	19	51	64	230,3
7	19	52	64	231,3
8	19	53	64	232,3
9	19	54	64	233,3
10	19	55	64	234,3
11	19	56	64	235,3
12	19	57	64	236,3
13	19	58	64	237,3
14	19	59	64	238,3
15	19	60	64	239,3
16	19	61	64	240,4
17	19	62	64	241,4
18	19	63	64	242,4
19	19	64	64	243,4
20	19	65	64	244,4
5	20	50	65	232,05
6	20	51	65	233,05
7	20	52	65	234,05
8	20	53	65	235,05
9	20	54	65	236,05
10	20	55	65	237,05
11	20	56	65	238,05
12	20	57	65	239,05
13	20	58	65	240,05
14	20	59	65	241,05
15	20	60	65	242,05
16	20	61	65	243,05
17	20	62	65	244,15
18	20	63	65	245,15
19	20	64	65	246,15
20	20	65	65	247,15

Table 1 Safety Distance and RNP value calculation results

5.2 Timing calculations

5.2.1 MatLab Code

```
% Variables

clear;

%speeds
vcruise = 20 ;   % [m/s] speed at terminal entrance
vappfix = 8.3 ;  % [m/s] speed at apptoach fix
vend = 0      ;  % [m/s] speed at TOLP (needed to have a 0)
vvertical = 2.5 ;

%distances
rcom = 1000 ;   % [m] horizontal distance from TOLP
hpad = 30.5 ;   % [m] hight of cone end
rappfix = 249;  % [m] horizontal distance between TOLP and final aprroach fix

% flight path angle
alphadeg = 7.1:1.5:20.6 ;  % [°] angle of flight path

result = zeros(8,length(alphadeg));

% Calculations

% flight path length
i = 1;
while i<=length(alphadeg)

alpharad = deg2rad(alphadeg(i));   % needed convertion from deg to rad
```

```
fplcomplet = rcom/cos(alpharad);   % flight path length w/o appraoch cone
fpl2 = rappfix/cos(alpharad);      % flight path length from approach fix to cone
fpl1 = fplcomplet-fpl2;            % flight path length bettwen terminal                entrance and appraoch fix

%time calculation
tpl1 = (2*fpl1)/(vappfix+vcruise);  %time needed for flight path section 1
tpl2 = (2*fpl2)/(vend+vappfix);     %time needed for flight path section 2
tvpl = (2*hpad)/(vvertical);        %time needed for flight path section vertical flight

tcom = tpl1+tpl2+tvpl;              %time needed for complet flight path

%result matrix
result(1,i) = alphadeg(i);
result(2,i) = fplcomplet;
result(3,i) = fpl1;
result(4,i) = fpl2;
result(5,i) = tpl1;
result(6,i) = tpl2;
result(7,i) = tvpl;
result(8,i) = tcom;

i = i+1;
end
```

5.2.2 Results table

angle [°]	7,1	8,6	10,1	11,6	13,1	14,6	16,1	17,6	19,1	20,6
flight path length total [m]	1063,4	1067,2	1071,6	1076,9	1082,9	1089,7	1097,3	1105,8	1115,2	1125,5
flight path length segment 1 [m]	782,0	784,8	788,2	792,2	796,7	801,9	807,7	814,1	821,2	829,0
flight path length segment 2 [m]	250,9	251,8	252,9	254,2	255,7	257,3	259,2	261,2	263,5	266,0
flight path length segment 3 [m]	30,50	30,50	30,50	30,50	30,50	30,50	30,50	30,50	30,50	30,50
flight time segment 1 [s]	55,3	55,5	55,7	56,0	56,3	56,7	57,1	57,5	58,0	58,6
flight time segment 2 [s]	60,5	60,7	60,9	61,3	61,6	62,0	62,4	62,9	63,5	64,1
flight time segment 3 [s]	24,4	24,4	24,4	24,4	24,4	24,4	24,4	24,4	24,4	24,4
time segment 4 [s]	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00	10,00
flight time total [s]	150,1	150,5	151,0	151,6	152,3	153,1	153,9	154,9	155,9	157,1

Table 2 Timing calculation results

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