

STANDARDIZED TAKE-OFF AND LANDING PROCEDURES FOR AIR TAXIS: URBAN AIR MOBILITY

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Abstract

Despite extensive research on UAM concepts of operations, vehicle design, airspace integration, and vertiport development, a key operational gap remains: standardized, implementable take-off and landing (TOL) procedures for air taxi services. This paper develops region-adaptive and standardized TOL procedures by translating and adapting established helicopter terminal procedures to air-taxi operations and evaluates their robustness across representative high-impact operating contexts, including airport approaches over densely populated areas and rail-station environments with terminal versus through-station constraints, selected to capture real-world limitations such as constrained approach sectors, runway/control-zone proximity, complex obstacles, and wind-driven directionality. The scenarios are deliberately drawn from contrasting operating conditions to derive procedure templates that can subsequently be mapped to additional UAM use cases with similar constraint patterns. For each scenario, TOL procedures are designed and assessed under three commuter-demand levels (1,000, 2,000, and 3,000 passengers/day) to quantify capacity limits and conflict sensitivity. Multi-year wind-direction statistics are used to optimize feasible take-off and landing directions for each site, ensuring alignment with prevailing wind conditions. Integrated simulation and visualization are performed using MATLAB for trajectory generation and wind-adaptive parameter studies and AnyLogic for event-driven vertiplace operations and turnaround interactions, supported by ATC-oriented expert review to assess controllability, procedural clarity, and workload implications.

Keywords: Urban Air Mobility (UAM), Air Taxi Operations, Take-Off and Landing (TOL) Procedures, Vertiport Operations

1. Motivation and Scientific Background

Urban Air Mobility (UAM) is increasingly being considered as a future transportation mode capable of complementing existing ground-based transport systems. Advances in electric vertical take-off and landing (eVTOL) aircraft, battery technology, automation, and communication systems have accelerated the transition of UAM from conceptual studies toward practical implementation [1, 2, 3].

While substantial progress has been achieved in vehicle development, airspace integration [4] and [5], communication infrastructure, navigation technologies [6, 7], and vertiport design [8], the operational procedures governing take-off and landing activities remain comparatively less mature. However, take-off and landing operations represent some of the most critical phases of flight, particularly in urban environments where aircraft operate in close proximity to buildings, transportation infrastructure, populated areas, protected zones, and other obstacles. Unlike conventional airport operations, urban air mobility requires procedures that can safely accommodate highly diverse operating environments while maintaining acceptable levels of efficiency, safety, noise exposure, and public acceptance [9].

Current research and regulatory initiatives frequently rely on concepts adapted from conventional helicopter operations [10, 11]. Although helicopter procedures provide a valuable foundation, direct transferability to future eVTOL operations is limited. Differences in vehicle characteristics, vertiplace

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configurations, expected traffic densities, and operational concepts require dedicated procedure development tailored to the requirements of urban air mobility. Furthermore, the available literature primarily focuses on specific operational concepts [12, 13], whereas standardized and transferable approaches applicable across different urban environments remain limited.

The development of such procedures presents a multidisciplinary challenge. Flight routes, obstacle environments, approach and departure sectors, wind conditions, infrastructure constraints, demand levels, and vertiplace characteristics must all be considered simultaneously. Modifications to one design parameter often influence multiple aspects of the resulting operation. Consequently, procedure development cannot be reduced to the definition of isolated flight paths but instead requires a systematic methodology capable of producing operationally feasible solutions across different urban environments. To address this challenge, our research project URTEAM (Urban/Regional Traffic, Emergency and Airspace Management) investigates the development and validation of standardized take-off and landing procedures for urban air mobility. The project aims to establish a common operational framework that can be adapted to different urban environments while maintaining consistent safety and operational principles. Representative airport, railway station, and residential scenarios were selected to capture a broad range of operational conditions and constraints encountered in future UAM operations.

Building upon previous work, this paper presents a structured methodology for the development and validation of standardized take-off and landing procedures for urban air mobility operations. The approach begins with the selection of representative urban scenarios, followed by demand modelling and the determination of required vertiport infrastructure. Based on the resulting demand characteristics, suitable vertiport locations are identified and adapted take-off and landing procedures are derived using established helicopter operational concepts as a foundation. The resulting procedures incorporate environmental constraints, obstacle assessments, operational requirements, and wind-dependent considerations. For the validation of proposed TOL procedures, the adapted TOL procedures are implemented within an AnyLogic simulation environment to evaluate their operational feasibility and applicability under realistic urban air mobility conditions. The methodology and results presented in this paper provide a systematic framework for the design and assessment of standardized UAM take-off and landing procedures across different urban environments.

2. Selection of Representative Scenarios

The objective of the scenario selection process was to identify representative operational environments that capture the primary constraints influencing UAM take-off and landing (TOL) procedure design. While vehicle performance establishes the operational envelope, the feasibility and structure of approach and departure procedures are largely determined by local environmental and operational constraints. These include obstacle distribution, surrounding land use, availability of emergency landing opportunities, proximity to controlled airspace, airport infrastructure, and prevailing wind conditions. Consequently, the selected scenarios were intended to represent recurring constraint configurations rather than individual locations alone, allowing the resulting procedures to be generalized to comparable UAM environments.

Based on an assessment of potential UAM operating environments, three representative scenario categories were identified: airports, major railway stations, and residential areas. These categories encompass a broad range of infrastructure characteristics and operational constraints relevant to future UAM operations. The selected scenarios are illustrated in the following subsections (all figures in this section are derived from Google Earth Pro). These categories represent distinct operating environments with different infrastructure characteristics, traffic demand profiles, and procedure-design constraints. Together, they cover a broad range of conditions expected during the initial deployment of urban air taxi services.

2.1 Airport Scenarios

Airports are considered key candidates for early UAM deployment due to their established infrastructure and passenger demand. However, airport environments introduce operational constraints associated with runway operations, controlled airspace, and interactions with conventional air traf-

fic. To represent these conditions, two airport scenarios were selected, which differentiates airports according to surrounding urban density and runway-crossing requirements.

1. Düsseldorf Airport (DUS) was selected as the first representative airport scenario (Figure 1). The airport is characterized by approaches through densely populated urban areas while generally avoiding mandatory runway crossings. Consequently, procedure design is primarily influenced by obstacle clearance, urban overflight considerations, and the availability of suitable emergency landing opportunities within the surrounding urban environment.

2. Hamburg Airport (HAM) was selected as the second airport scenario (Figure 2). In contrast to Düsseldorf, operations at Hamburg Airport may require crossing active runway areas, introducing additional operational and safety constraints. Furthermore, the airport is embedded within a densely developed urban environment, limiting the number of feasible approach and departure sectors. The combination of runway-crossing requirements and urban obstacle constraints makes Hamburg Airport one of the most restrictive airport environments considered within the study and therefore a suitable case for evaluating standardized TOL procedures under demanding operational conditions.



Figure 1 – Airport – Düsseldorf



Figure 2 – Airport – Hamburg

2.2 Railway Station Scenario

Major railway stations represent attractive vertiport locations because of their central urban location, high passenger demand, and direct integration with existing public transportation networks. However, these locations are typically embedded within dense urban environments characterized by tall buildings, transportation infrastructure, limited open spaces, and complex obstacle configurations. Consequently, the available approach and departure sectors are often significantly more constrained than those at airports, making railway stations a relevant category for the development and assessment of standardized TOL procedures. To consider different urban constraint conditions, two railway station scenarios were selected: Frankfurt Main Station and Hamburg Main Station.

1. Frankfurt Main Station (Figure 3) represents a terminal-station environment located within one of Germany's most densely built urban areas. The surrounding cityscape is characterized by numerous high-rise buildings and limited open spaces, which impose significant restrictions on feasible approach and departure paths. Furthermore, the proximity of major transportation corridors and urban infrastructure requires careful route design to maintain obstacle clearance while ensuring access to suitable emergency landing opportunities. As a result, Frankfurt Main Station represents a highly constrained city-centre scenario where procedure design is strongly influenced by the surrounding built environment.

2. Hamburg Main Station (Figure 4) was selected as a representative through-station scenario. In contrast to Frankfurt, the railway tracks extend through the urban area and provide natural transportation corridors that can support approach and departure routing. Nevertheless, the

surrounding city centre remains densely developed and includes numerous buildings, roads, waterways, and other infrastructure elements that constrain operational flexibility. The scenario therefore combines the advantages of existing transportation corridors with the challenges associated with operating in a complex urban environment.



Figure 3 – Train station – Frankfurt



Figure 4 – Train station – Hamburg

2.3 Residential Scenarios

Residential areas were included to represent decentralized UAM operations beyond major transportation hubs. Compared with airports and railway stations, residential environments generally offer lower infrastructure density but introduce different challenges related to population exposure, local obstacle structures, noise-sensitive areas, and emergency landing availability. Two residential scenarios were selected within the Munich metropolitan region.

1. Pullach im Isartal (Figure 5) represents a suburban environment with comparatively open surroundings and a larger number of feasible approach and departure options. The scenario serves as an example of a less constrained residential operating environment where procedure design is primarily governed by local land use and community considerations.
2. In contrast, Golfclub Olching (Figure 6) represents a more constrained residential scenario. Although located outside the dense urban core, available maneuvering space is reduced by local land-use restrictions and the requirement to avoid sensitive areas such as recreational and sports facilities. As a result, the scenario provides a useful comparison to Pullach by illustrating how local constraints can influence route selection and procedure geometry even in relatively open environments.



Figure 5 – Residential area – Pullach im Isartal, Munich



Figure 6 – Residential area – Golfclub Olching, Munich

The selected airport, railway station, and residential scenarios reflect substantially different operational environments, allowing the applicability of the proposed procedures to be examined across a broad range of constraints and operating conditions.

After selecting the representative scenarios, the corresponding operational demand was estimated. The resulting demand levels form the basis for determining vertiport infrastructure requirements, operational capacity, and the subsequent development of TOL procedures.

3. Demand Modelling and Allocation to Vertiports

Demand is represented as commuter-driven daily air-taxi demand at city scale and is propagated to a capacity-relevant peak-hour movement intensity per vertiport. Following the adopted approach, daily commuter demand is specified as

$$n_{\text{commuter}} \in [1000, 3000] \text{ passengers/day}. \tag{1}$$

To determine the corresponding flight activity, passenger demand is converted into daily flight movements using the passenger capacity of the reference air taxi. Assuming an average payload of n_{PAX} passengers per flight (here $n_{\text{PAX}} = 2$), the required number of daily flight movements becomes

$$n_{\text{mov,day}} = \frac{n_{\text{commuter}}}{n_{\text{PAX}}}. \tag{2}$$

Since commuter demand is expected to be concentrated during morning and evening rush-hour periods, daily movements are converted into a peak-hour movement intensity. Assuming that demand is distributed among n_{VP} vertiports and concentrated within a peak period of duration t_{peak}, the resulting movement intensity per vertiport is

$$n_{\text{mov,h}} = \frac{n_{\text{mov,day}}}{n_{\text{VP}}\, t_{\text{peak}}} = \frac{n_{\text{commuter}}}{n_{\text{PAX}}\, n_{\text{VP}}\, t_{\text{peak}}}. \tag{3}$$

Using the reference assumptions for Hamburg, adopted from our project (URTEAM), namely $n_{\text{VP}} = 20$ vertiports, $t_{\text{peak}} = 3\,\text{h}$, and the demand range defined in Eq. (1), the resulting peak-hour movement intensity is

$$n_{\text{mov,h}} \in \left[\frac{500}{20 \cdot 3}, \frac{1500}{20 \cdot 3}\right] = [9, 25] \text{ movements/h/vertiport}. \tag{4}$$

This range defines the target operational demand used for the subsequent vertiport capacity and throughput assessment. Furthermore, to transfer the Hamburg reference case to other cities, a population-based scaling approach was adopted. Both the commuter demand and the number of vertiports were assumed to scale proportionally with the city population while maintaining a constant peak-hour movement intensity per vertiport. The scaling was performed according to

$$n_{\text{VP}}(c) = n_{\text{VP}}^{\text{HH}} \frac{P(c)}{P(\text{HH})} \tag{5}$$

$$n_{\text{commuter}}(c) = n_{\text{commuter}}^{\text{HH}} \frac{P(c)}{P(\text{HH})} \tag{6}$$

where (P(c)) denotes the population of city (c) and (HH) refers to the Hamburg reference case. By scaling both demand and vertiport count using the same population factor, the resulting peak-hour movement intensity defined in Eq. (3) remains unchanged. The resulting scaled demand and vertiport values are summarized in Table 1.

Table 1 – Scaling of vertiplaces and daily flight demand from Hamburg to Munich and Frankfurt using population as the basis.

City	Population	Vertiplaces	$n_{\text{flights,min}}$	$n_{\text{flights,max}}$
Hamburg	1,900,000	20	1000	3000
Munich	1,500,000	16	790	2370
Frankfurt	800,000	8	420	1260

Table 1 summarizes the resulting vertiplace requirements and daily flight demand for the selected cities.This demand analysis provided the basis for determining the required vertiplace infrastructure and operational capacity within each scenario. Based on these infrastructure requirements, standardized take-off and landing procedures were subsequently developed for the selected operating environments.

4. Development of Standardized TOL Procedures

Following the determination of demand and infrastructure requirements, standardized take-off and landing (TOL) procedures were developed. Existing helicopter procedures were used as the initial basis for the procedure design due to the comparable low-altitude operating characteristics of both vehicle classes. Candidate helicopter procedures were evaluated using a preference and utility analysis incorporating safety, regulatory, operational, economic, and societal criteria. The analysis assigned the highest weights to safety- and regulation-related factors, including obstacle clearance, emergency handling capability, and required pilot workload. Based on the resulting scores, a rearward angled-climb departure and a two-angle landing procedure were selected as the foundation for the standardized air-taxi TOL methodology.

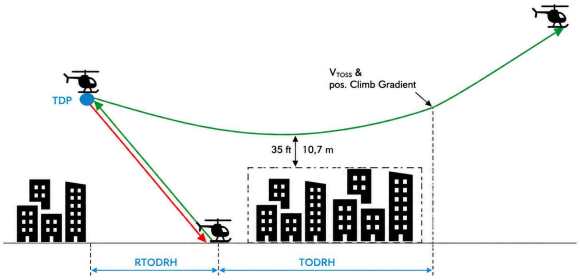


Figure 7 – Rearward angled-climb departure selected for adaptation to air-taxi operations.

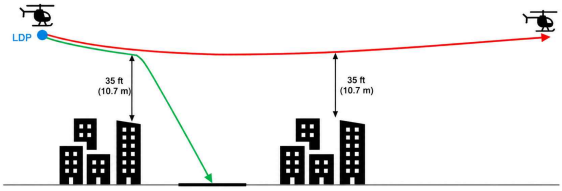


Figure 8 – Two-angle landing procedure selected for adaptation to air-taxi operations.

The selected helicopter procedures served as the basis for developing a standardized air-taxi TOL methodology. The procedure design incorporated the characteristics of the representative air taxi and the EASA obstacle-free reference volume [14] while retaining the operational principles of the selected helicopter procedures. To establish a common design framework, the Take-Off Decision Point (TDP) and Landing Decision Point (LDP) were fixed at a reference altitude of 61 m above ground level. The resulting methodology consisted of a rearward angled-climb departure and a two-angle landing procedure for urban air-taxi operations.

The developed methodology was subsequently applied to the six representative scenarios to evaluate its applicability under different operational environments. For each scenario, the proposed vertiport location was established based on the available space identified during the site assessment. The surrounding environment was analysed using Google Earth to identify buildings, transportation infrastructure, open areas, and other obstacles affecting the available approach and departure sectors. These site-specific constraints formed the basis for the trajectory design. While the standardized TOL methodology remained unchanged, the resulting trajectory geometry varied according to vertiport elevation, obstacle height, and the available maneuvering space. The geometric parameters adopted for each scenario are summarized in Table 2, while the resulting trajectory lengths and estimated operation times are presented in Table 3.

The Düsseldorf Airport scenario is used as a representative example to illustrate the application of the developed methodology. The same procedure development process was applied to the remaining scenarios, with the trajectory geometry adapted according to the local obstacle environment, vertiport elevation, and available maneuvering space. Figure 9 presents the application of the standardized TOL procedure to the Düsseldorf Airport scenario. A vertiport located on the roof of the airport hotel and parking structure was assumed, resulting in a vertiport elevation of 26 m above ground level. The landing trajectory was divided into two segments to maintain the final approach within the obstacle-free reference volume. The initial approach segment was defined by a horizontal distance of 120 m, followed by a final approach segment of 40 m. Based on the resulting geometry, an initial landing

Table 2 – Geometric parameters adopted for the development of the TOL procedures. All dimensions are given in metres (m).

Scenario	Vertiport Height	Obstacle-Free Volume Height	TDP/LDP Height	Horizontal Distance	Final Distance
Düsseldorf Airport	26	50	61	120	40
Hamburg Airport	22	41	61	60	30
Frankfurt Main Station	32	30	61	100	30
Hamburg Main Station	45	50	61	60	40
Pullach	17	31	61	50	30
Olching	14	47	61	50	40

Table 3 – Calculated trajectory lengths and operation times for the developed TOL procedures.

Scenario	Landing Distance (m)	Take-off Distance (m)	Landing Time (s)	Take-off Time (s)
Düsseldorf Airport	185	73	62	24
Hamburg Airport	114	68	38	23
Frankfurt Main Station	147	68	49	23
Hamburg Main Station	125	73	42	24
Pullach	97	59	32	20
Olching	112	68	37	23

angle of approximately 5° and a final landing angle of approximately 51° were obtained. The rearward departure was performed using a take-off angle of approximately 57°. Using the trajectory lengths reported in Table 3 and the assumed reference air-taxi climb and descent rate of 3 m/s, the resulting landing and take-off times were 62 s and 24 s, respectively.

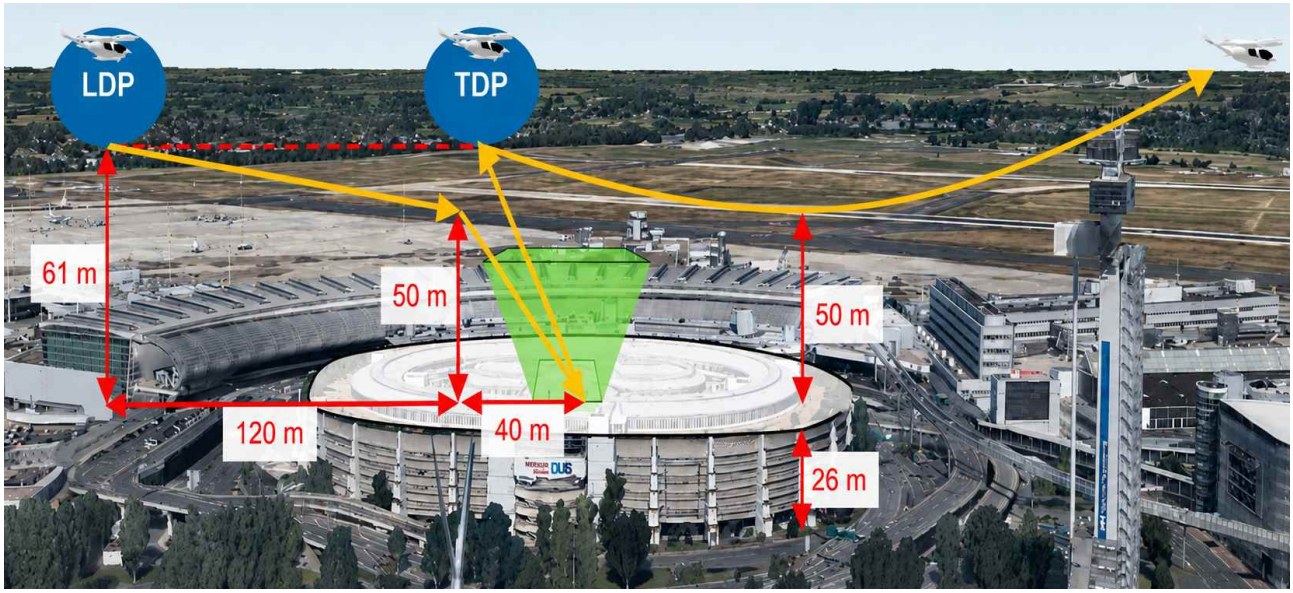


Figure 9 – Application of the standardized air-taxi TOL procedure to the Düsseldorf Airport scenario.

5. Simulation and Visualization Setup

Based on the design process described in the previous section, the proposed take-off and landing procedures were implemented and simulated in AnyLogic for all representative scenarios. The simulation model incorporated the developed arrival and departure trajectories, vertiport operations, and ground handling processes. For each scenario, handling times were estimated and integrated into the operational sequence to assess throughput and operational feasibility. The resulting trajectory

configurations were evaluated with respect to safety considerations, obstacle clearance, operational efficiency, and passenger demand. The selected procedures were subsequently visualized using MATLAB and Google Earth to verify trajectory geometry, approach and departure sectors, and their compatibility with the local operating environment.
The following subsections present the implementation and results of the individual scenarios, including the developed trajectory geometries, operational constraints, and corresponding take-off and landing procedures.

5.1 Vertiport Setting - Space requirements

1. Scenario 1: Düsseldorf Airport

   The Düsseldorf scenario considers a terminal-proximate rooftop vertiport located on the elevated structure directly in front of the terminals (parking garage / hotel roof). Based on the recommendation provided by EASA [15], the vertiport layout is constrained by the available roof footprint and aligned with the feasible approach and departure sectors. Figures Figure 10,11, and 12 show the pad configurations used for the three demand cases: 1000 flights/day: 4 pads, 2000 flights/day: 6 pads, and 3000 flights/day: 10 pads, all accommodated within the same rooftop envelope.

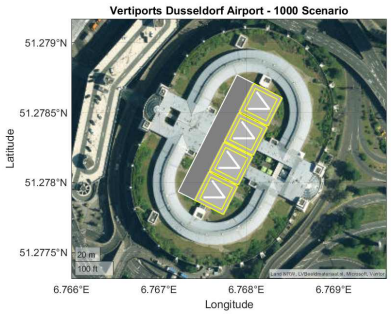


Figure 10 – 1000 flights/day

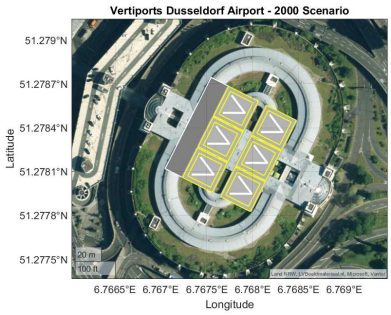


Figure 11 – 2000 flights/day

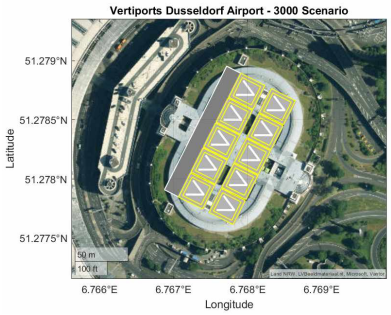


Figure 12 – 3000 flights/day

2. Scenario 2: Hamburg Airport

   The figure shows the VertiHub modeling for Hamburg Airport (HAM) and the corresponding landing pad layouts used for the simulation. The top row illustrates (Figure III.5) the preliminary landing pad layouts at the selected location on the airport side, with the number and placement of the landing pads scaled to the three demand scenarios (1,000 / 2,000 / 3,000). Since Hamburg is severely constrained by its runway system and limited operational area, the landing pad layout was configured to support orderly operations in the terminal area under these spatial constraints and to serve as the basis for the subsequent simulation of takeoff and landing procedures.

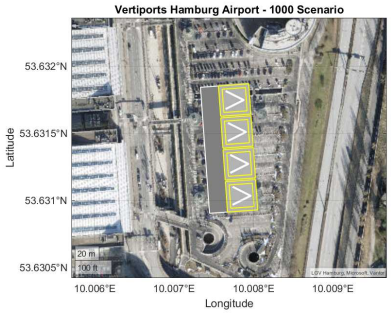


Figure 13 – 1000 flights/day

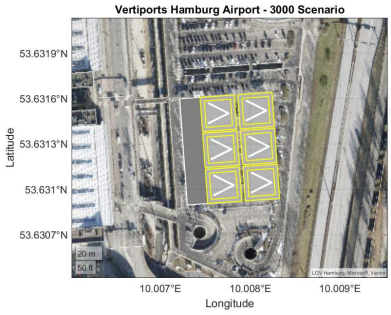


Figure 14 – 2000 flights/day

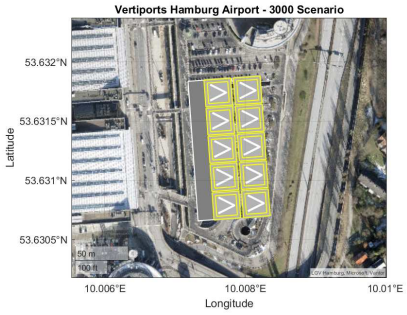


Figure 15 – 3000 flights/day

3. Scenario 3: Frankfurt Train Station

Frankfurt Main Station was selected to represent a constrained railway-station environment with high passenger demand and limited space for vertiport development. The available roof area of the station building provides sufficient space for individual landing pads; however, its width is insufficient to accommodate the complete vertiport infrastructure, including passenger circulation, emergency access, and ground handling facilities. Consequently, additional structural extensions would be required to satisfy the operational space requirements. The station forecourt offers additional capacity but is intensively used by pedestrians, taxis and public transport services. The high level of ground activity limits the direct integration of vertiport facilities at ground level. Therefore, larger vertiport configurations, comprising approximately 6–10 landing pads, would require an elevated platform to maintain uninterrupted ground operations, whereas smaller configurations of up to four landing pads could be accommodated on the station roof. These space limitations directly influence the vertiport layout and the available approach and departure sectors considered during the TOL procedure design.

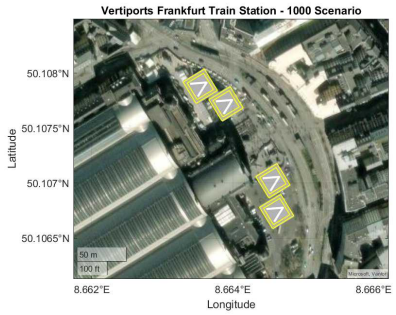


Figure 16 – 1000 flights/day

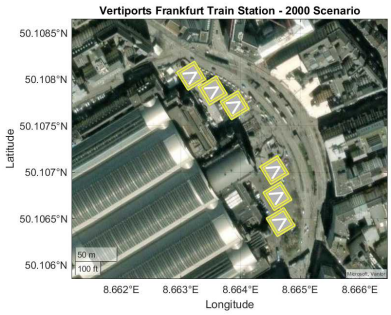


Figure 17 – 2000 flights/day

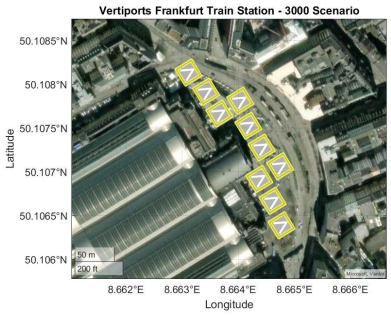


Figure 18 – 3000 flights/day

4. Scenario 4: Hamburg Train Station

   Hamburg Main Station represents a high-demand intermodal hub requiring a vertiport with increased operational capacity. The covered railway tracks north of the station provide sufficient space to accommodate the required vertiport infrastructure, including landing pads, passenger handling, and ground support facilities. Compared with Frankfurt Main Station, the available area allows a more integrated vertiport layout without major space constraints.

   The location also offers favorable operational characteristics for TOL procedures. Apart from the adjacent station buildings, the surrounding open space provides unobstructed approach and departure sectors, minimizing conflicts with urban obstacles during arrival and departure operations. Consequently, the track-cover area was selected as the preferred vertiport location for the Hamburg Main Station scenario.

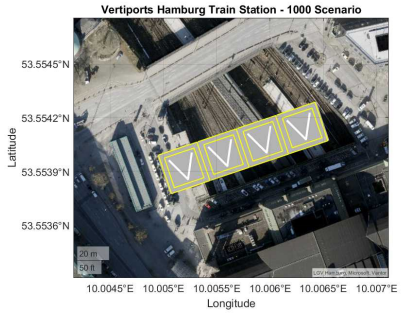


Figure 19 – 1000 flights/day

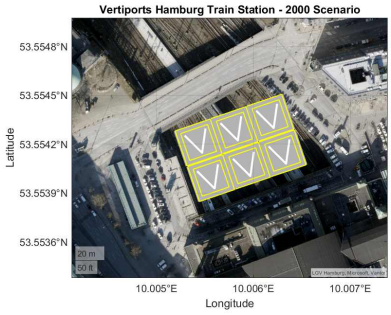


Figure 20 – 2000 flights/day

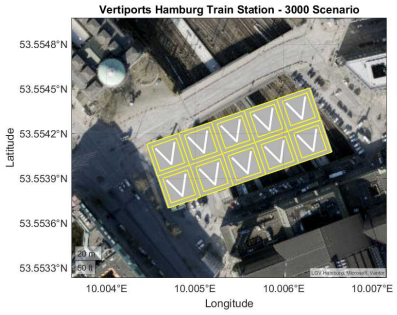


Figure 21 – 3000 flights/day

5. Scenario 5: Suburb - Residential area (Pullach im Isartal)

   Residential vertiports are intended for commuter operations with lower passenger demand than airports and railway stations. Accordingly, they require fewer landing pads, basic ground sup-

port facilities, and shorter ground handling times, while maintenance activities are not considered. The roof of the shopping centre was selected as the preferred vertiport location due to its available space and direct accessibility. Depending on the operational demand, the layout accommodates between two and five landing pads. Lower-capacity configurations provide greater separation between landing pads, whereas higher-capacity layouts utilize most of the available roof area. These space requirements directly determine the vertiport layout and the corresponding TOL procedure design.

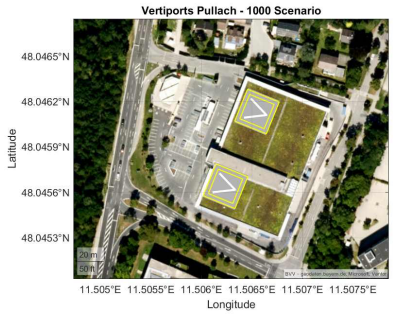


Figure 22 – 1000 flights/day

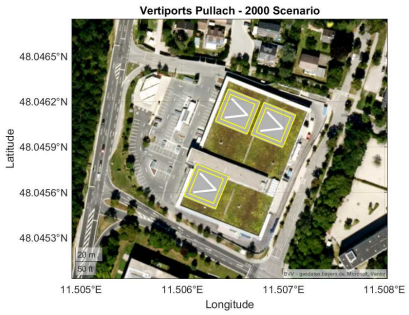


Figure 23 – 2000 flights/day

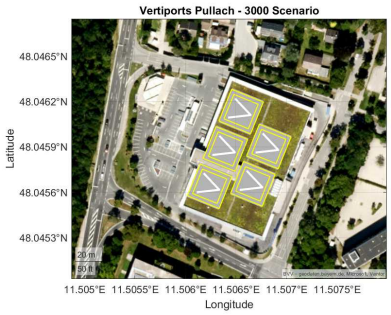


Figure 24 – 3000 flights/day

6. Scenario 6: Suburb - Sports Club (Golfclub Olching)

   The Olching scenario represents a suburban vertiport with limited available space for ground infrastructure. Similar to the Pullach scenario, the vertiport is intended for commuter operations and therefore consists of basic passenger handling facilities without maintenance infrastructure.

   The clubhouse area does not provide sufficient space to accommodate the required landing pad configurations. Consequently, the roof of the adjacent parking structure was selected as the preferred vertiport location. Although the available length permits the installation of up to three landing pads, the maximum configuration of five landing pads cannot be accommodated while satisfying the minimum EASA space requirements. Considering the expected commuter demand in the suburban operating environment, the reduced-capacity configuration was considered operationally acceptable.

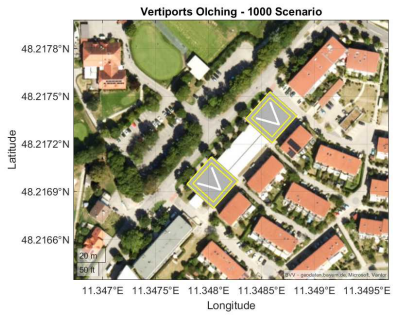


Figure 25 – 1000 flights/day

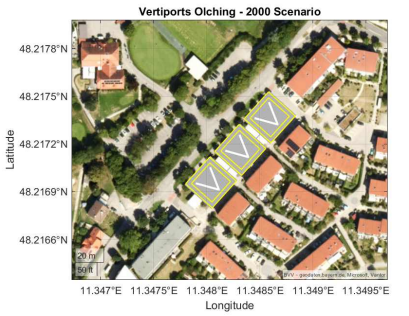


Figure 26 – 2000 flights/day

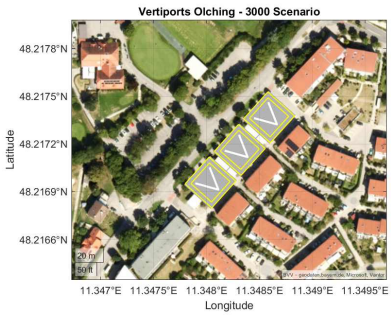


Figure 27 – 3000 flights/day

5.2 TOL Direction Setting - Approach and Departure Angles

After defining the vertiplace locations, the corresponding approach and departure sectors were assessed for all six representative scenarios. The objective of this analysis was to identify feasible arrival and departure directions while considering local infrastructure, operational constraints, ground-risk exposure, and regulatory restrictions. Furthermore, since Wind direction directly dictates the lift efficiency, fuel consumption, and aerodynamic stability of helicopters and air taxis during vertical operations. Failing to account for it can trigger dangerous control losses, such as Loss of Tail-Rotor Effectiveness or Vortex Ring State, endangering passenger safety [16, 17].Therefore, we analyses the wind data from closest weather stations and the resulting sectors for all scenarios are illustrated in Figures 28 - 33.

The airport scenarios exhibited the most restrictive operating environments.

1. At Düsseldorf Airport, the approach and departure sectors were primarily influenced by the location of the proposed vertihub relative to the passenger terminals and surrounding airport infrastructure. The selected sector configuration shown in Figure 28 represents a compromise between operational safety and passenger accessibility while preserving the expected travel-time advantage of urban air mobility. At Hamburg Airport, the crossed runway configuration significantly reduced the available operating area. As illustrated in Figure 29, the resulting approach and departure sectors were constrained by existing runway operations and airport protection areas, requiring careful separation between arriving and departing traffic.

2. For the railway station scenarios, existing transportation corridors played a dominant role in sector design. At Frankfurt Main Station, the railway tracks provided a natural arrival and departure corridor that enabled operations while avoiding nearby high-rise buildings and sensitive facilities. The resulting sector configuration is shown in Figure 30. A similar effect can be observed at Hamburg Main Station, where the dense urban environment limited the available operating space. Consequently, the approach and departure sectors illustrated in Figure 31 were aligned with existing transportation infrastructure and available open corridors through the city environment.

3. The residential scenarios were characterized by a different set of constraints. In Pullach, the approach and departure sectors shown in Figure 32 were selected to maximize operations above forests and open areas while minimizing overflight of residential developments and environmentally sensitive regions. In Olching, illustrated in Figure 33, the presence of recreational facilities, residential areas, and associated noise-sensitive environments further restricted the available operating sector. As a result, the feasible arrival and departure directions were limited to a relatively narrow operating envelope.

A comparison of all six scenarios reveals that the available approach and departure sectors vary considerably depending on the surrounding operational environment. Airport locations are predominantly constrained by existing aviation infrastructure and runway operations, railway station locations benefit from naturally defined transportation corridors, and residential locations are primarily influenced by environmental, societal, and land-use considerations. Nevertheless, all scenarios demonstrate that feasible TOL operations can be established through the definition of location-specific approach and departure sectors while maintaining a common operational framework.

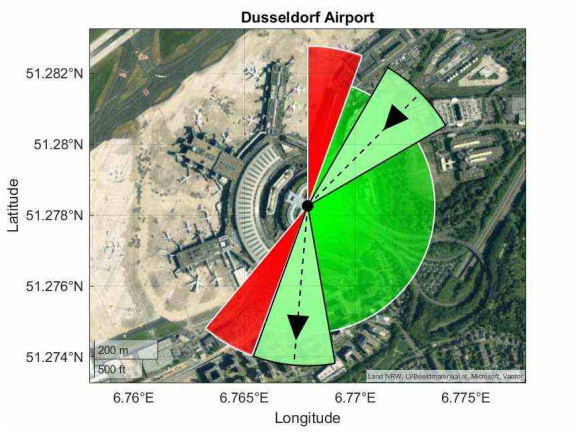


Figure 28 – Düsseldorf Airport - approach and departure angles

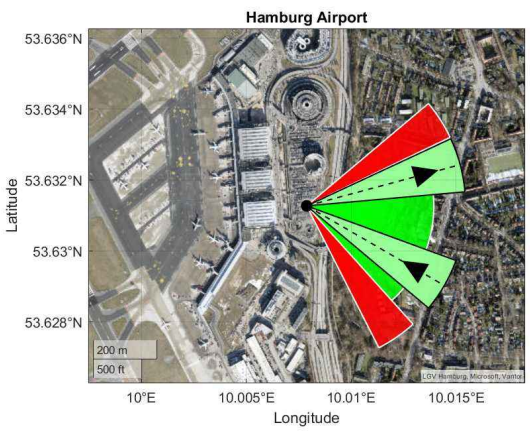


Figure 29 – Hamburg Airport - approach and departure angles

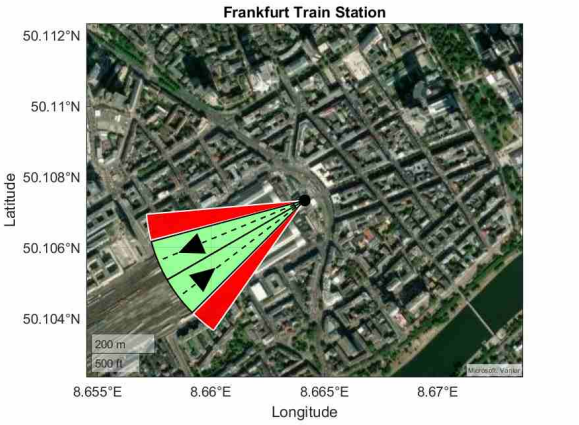


Figure 30 – Frankfurt Train Station - approach and departure angles

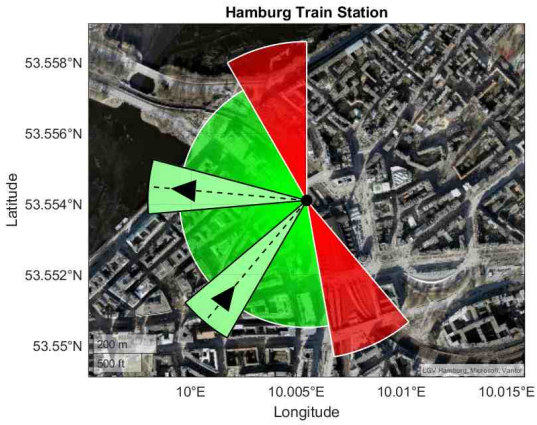


Figure 31 – Hamburg Train Station - approach and departure angles

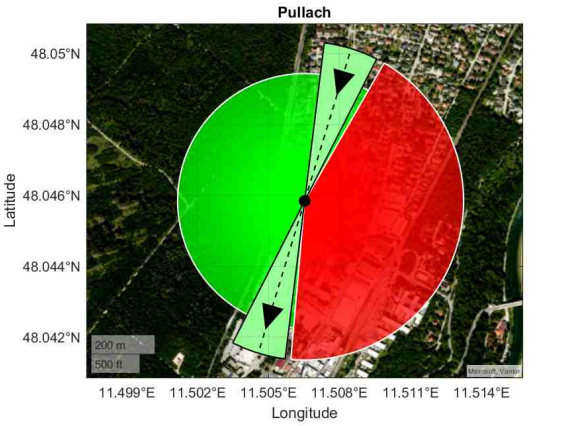


Figure 32 – Pullach im Isartal - approach and departure angles

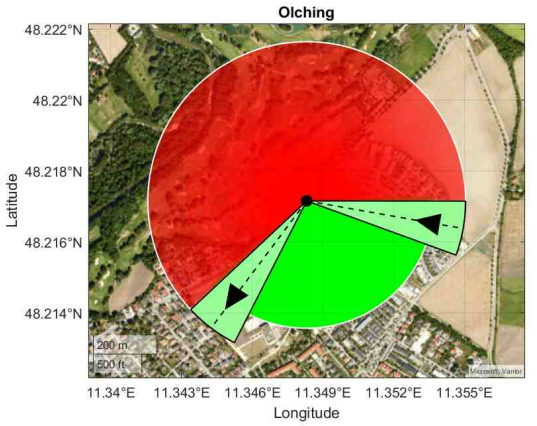


Figure 33 – Golfclub Olching - approach and departure angles

5.3 AnyLogic Simulation Environment

The developed TOL procedures were implemented within an AnyLogic-based simulation environment to evaluate their operational feasibility under realistic traffic conditions. For each representative scenario, a three-dimensional operational model was created incorporating the corresponding vertiplace infrastructure, surrounding urban environment, ground transportation network, and aircraft movements. Figures 34 - 39 represents selected snapshots from the simulation environment for the airport, railway station, and residential scenarios. The figures depict different phases of operation, including Airtaxi approaching the vertiplace, landing, ground handling activities, take-off operations, and departures toward the designated exit points. Simultaneous aircraft movements can be observed both on the ground and within the terminal airspace, allowing the interaction between arriving and departing traffic to be assessed.

The simulation environment provides a visual and operational representation of the proposed procedures and enables the identification of potential conflicts, congestion effects, and infrastructure limitations. Furthermore, it supports the evaluation of UAM traffic organization, vertipad utilization, and Airtaxi sequencing under different demand levels. The resulting simulations confirmed that the developed TOL procedures can be executed within the selected operational environments while maintaining structured traffic flows throughout the terminal area.

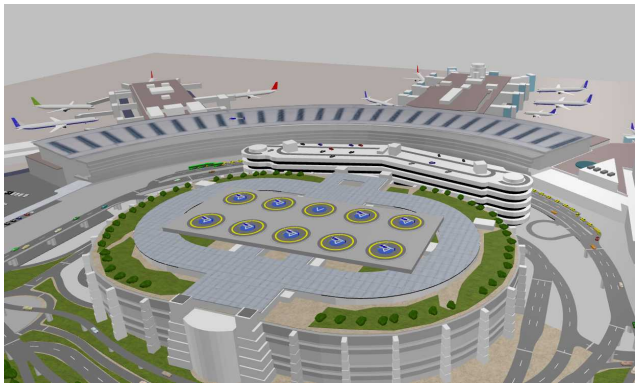


Figure 34 – Düsseldorf Airport

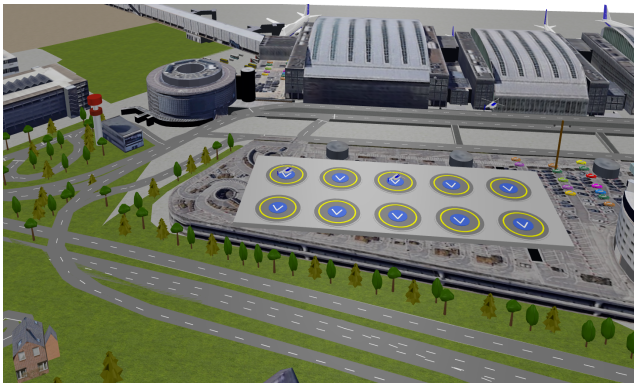


Figure 35 – Hamburg Airport

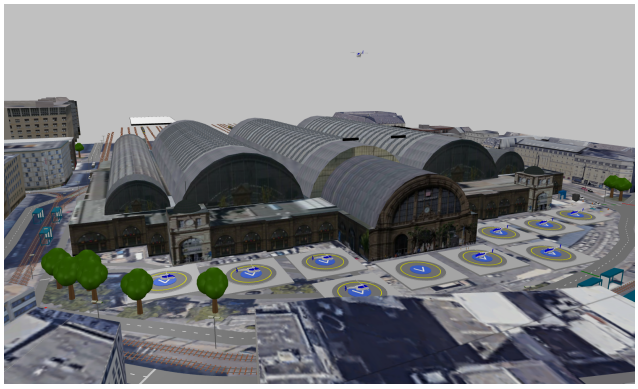


Figure 36 – Frankfurt Train Station

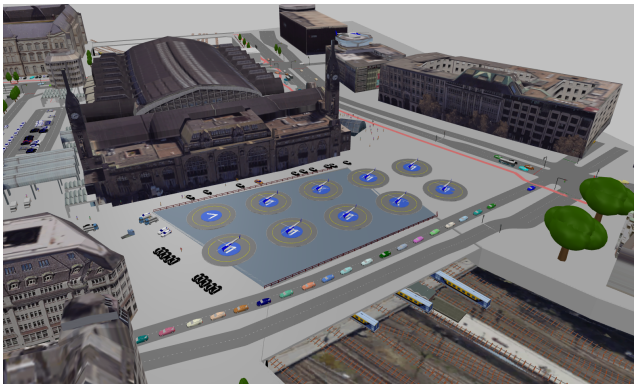


Figure 37 – Hamburg Train Station

Final Take-off and Landing Trajectories:
The previous section demonstrated the operational implementation of the developed procedures within the AnyLogic simulation environment. Figures 40–45 present the corresponding TOL trajectories in detail, including the complete approach and departure geometry as well as the associated altitude profiles. The trajectories were derived based on the selected vertiplace locations, route definitions, demand-driven infrastructure sizing, and wind-dependent operating sectors. Each procedure consists of an entry point, a landing decision point (LDP), the landing site, a take-off decision point (TDP), and an exit point.
The airport scenarios shown in Figures 40 and 41 exhibit the highest trajectory density and the largest number of operational pads. At Düsseldorf Airport (Figure 40), multiple arrival and departure trajectories converge towards common entry and exit points, forming a fan-shaped traffic structure that supports high-capacity operations. In contrast, Hamburg Airport (Figure 41) demonstrates a stronger separation between arrival and departure sectors, reducing potential conflicts between inbound and outbound traffic while maintaining operational efficiency.
The railway station scenarios illustrated in Figures 42 and 43 reveal the influence of dense urban environments on trajectory design. At Frankfurt Main Station (Figure 42), the final trajectories are organized along distinct arrival and departure corridors, resulting in a clear separation of operational flows within the constrained urban environment. A similar configuration can be observed at Hamburg Main Station (Figure 43); however, the available operating area is more compact, leading to a denser trajectory layout and a narrower operational sector.
The residential scenarios presented in Figures 44 and 45 exhibit considerably simpler trajectory structures. Compared with the airport and railway station environments, Pullach (Figure 44) and Olching (Figure 45) require fewer operational pads and consequently fewer approach and departure trajectories. The resulting procedures are characterized by compact terminal areas and short transition segments between decision points and landing sites, reflecting the lower operational demand and reduced infrastructure requirements.
A comparison of all six scenarios highlights the strong influence of the operational environment on the

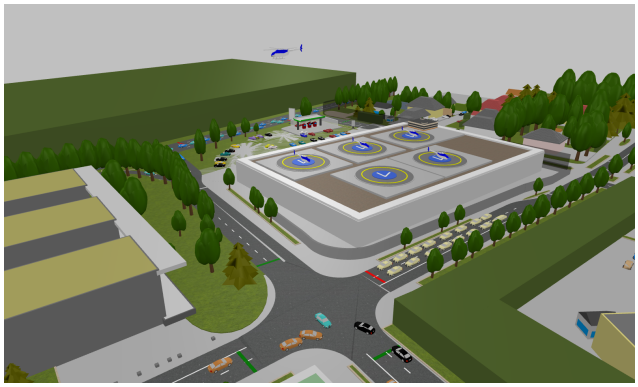


Figure 38 – Pullach im Isartal



Figure 39 – Golfclub Olching

resulting TOL architecture. Airport locations result in high-capacity hub-like operations with numerous parallel trajectories, railway station locations require corridor-based procedures adapted to dense urban surroundings, and residential locations lead to compact low-density operations. Despite these differences, all scenarios follow the same procedural framework consisting of common entry and exit points, predefined decision points, and standardized approach and departure procedures. The resulting trajectories therefore represent the final operational implementation of the proposed TOL concept and provide the basis for the subsequent simulation and performance assessment.

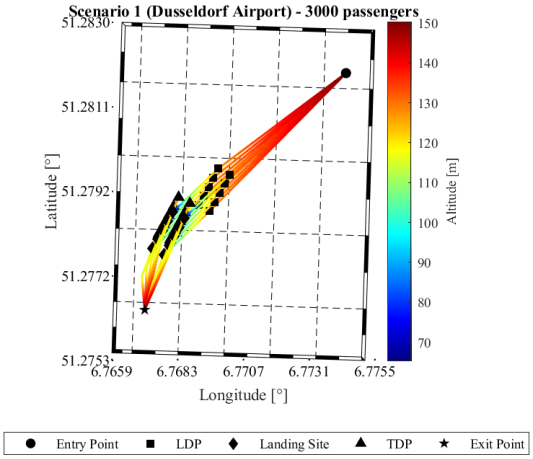


Figure 40 – TOL Trajectories: Scenario 1

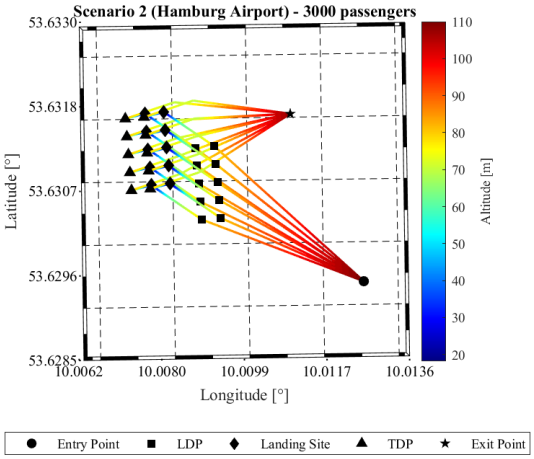


Figure 41 – TOL Trajectories: Scenario 2

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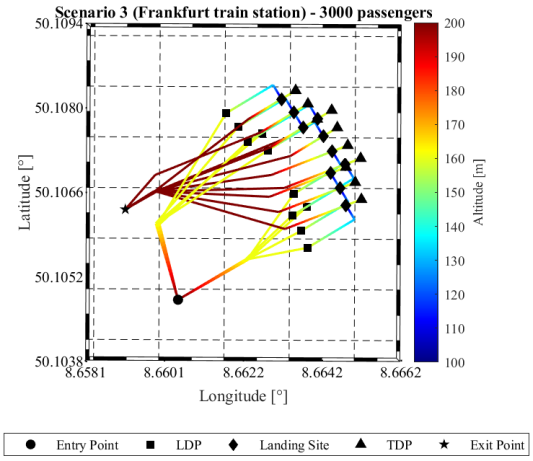


Figure 42 – TOL Trajectories: Scenario 3

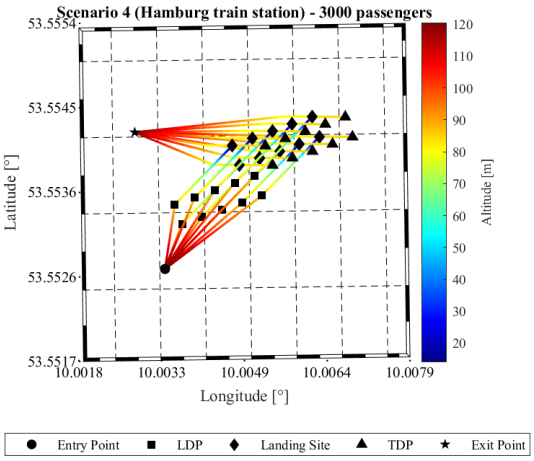


Figure 43 – TOL Trajectories: Scenario 4

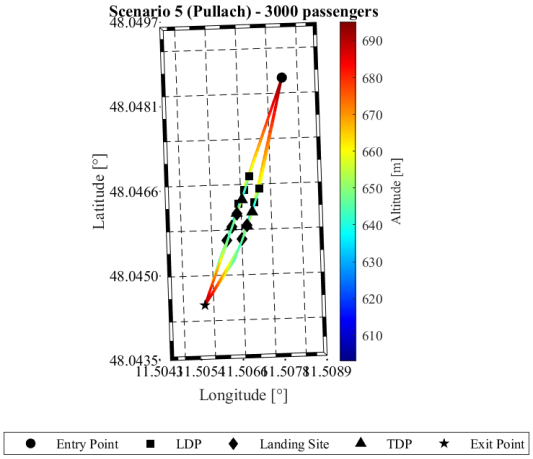


Figure 44 – TOL Trajectories: Scenario 5

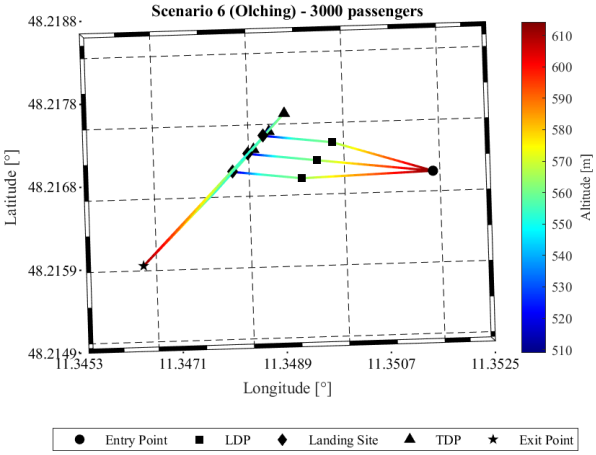


Figure 45 – TOL Trajectories: Scenario 6

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