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Infrastructural and operational availability for air taxi operations at German aerodromes

Mert Çakır[a,*], Juliane Rösing[a], Lutz Wortmann[b]

[a] Institute of Transport Science, RWTH Aachen University, Mies-van-der-Rohe-Straße 1, Aachen, 52074, North Rhine-Westphalia, Germany
[b] Institute of Aerospace Systems, RWTH Aachen University, Wüllnerstraße 7, Aachen, 52062, North Rhine-Westphalia, Germany

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ABSTRACT

According to Flightpath 2050, door-to-door travel times of less than four hours are aspired for journeys within Europe. To accomplish this goal, on-demand air mobility (ODAM) can improve the conventional means of transportation with short travel times and comfort gains. This paper outlines a methodology for analyzing the availability of German aerodromes for air taxi operations. Analyses are based on the usage of hybrid-electric fixed-wing aircraft under visual flight rules (VFR) for ODAM. This future use-case is applied for the evaluation of infrastructural availability (quality) and operational availability in Germany. An aerodrome database and METAR weather database are developed and evaluated for the availability analyses. The main research finding is the availability of German aerodromes for small fixed-wing aircraft (according to EASA CS-23) operation under VFR for ODAM. The lack of suitable infrastructure for air taxi services (e.g., terminals, paved runways) at many small airfields limits the availability of the service. Furthermore, unsuitable weather conditions reduce operational availability, especially in winter, due to lack of visibility, e.g., snowfall. Current ODAM research has assumed continuous availability, causing an overestimation of availability. This paper provides a holistic approach in which the current state of aerodrome infrastructure and operational constraints are considered by the example of German aerodromes. Minimal infrastructure needed for this use-case is determined, main weather parameters causing operational constraints are detected and possibilities for increasing operational availability at aerodromes are revealed.

1. Introduction

The Flightpath 2050 goals include the ability that 90 % of travelers within Europe to complete their journey within four hours travel time (door to door). Furthermore, a coherent ground infrastructure shall be established for air travel including airports and vertiports. Also new aviation technologies shall help reduce the aviation emissions. By reaching these ambitious goals, the future of European aviation shall be shaped in a way to maintain the global leadership in the sector and best serve societal needs for transportation in a sustainable way (European Commission, 2011). To meet the challenge to reach these goals, the usage of advanced air mobility (AAM) for on-demand air mobility (ODAM) is a viable option for future transportation. For small air vehicles, AAM hereby further specifies into urban air mobility (UAM) and regional air mobility (RAM). The latter uses existing infrastructure e.g. with fixed-wing (hybrid-electrical) aircraft, aiming to improve the accessibility of regions with small aerodromes by fast and sustainable travel. (Bauhaus Luftfahrt e.V., 2024)

Numerous research studies in the field of AAM have been published in the past years. The popularity of AAM could be attributed to major traffic congestions, increase in travel demand and recent advances in technology. Countless challenges were identified towards the successful application of AAM in the near future (Shuang Wang, Changhong Zheng, Sebastian Wandelt, 2024; Sun et al., 2021; Wandelt et al., 2023). These include various technological aspects, policy related and societal aspects. E.g. societal acceptance and heterogeneities and the liability and standardization for future AAM operations were identified as potential challenges. Shuang Wang, Changhong Zheng, Sebastian Wandelt (2024); Sun et al. (2021)

In addition to general challenges of transport technology including interoperability (Shuang Wang, Changhong Zheng, Sebastian Wandelt, 2024) and competitiveness with other transportation modes (Sun et al., 2021), several operational and infrastructural challenges also exist. These include operational challenges due to planning and constraints identification (Sun et al., 2021) and reliability of operations (Shuang Wang, Changhong Zheng, Sebastian Wandelt, 2024). The infrastructural challenges are connected to the identification of suitable takeoff and

* Corresponding author.
E-mail address: cakir@via.rwth-aachen.de (M. Çakır).

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landing locations (Shuang Wang, Changhong Zheng, Sebastian Wandelt, 2024; Sun et al., 2021; Wandelt et al., 2023). Chen et al. (Chen et al., 2022) e.g. developed a novel grid-based variable neighborhood search heuristic for the selection of scalable vertiport hubs in highly restricted metropolitan areas with a focus on minimizing the total travel costs.

For ODAM with VTOL aircraft, several constraints are expected including aircraft noise and community acceptance, availability of take-off and landing areas incl. authority approval, capacity issues due to scalability of ODAM networks in both controlled and uncontrolled air space. These constraints could inhibit implementation or scale-up of ODAM (Vascik and Hansman, 2017a; 2017b), whereas many of these constraints are also applicable for operations with fixed-wing aircraft. Issues were identified as points to consider with significant technological uncertainty including electric aircraft operating standards and certification (lack of current standards), all-weather ops (further research and operational experience required for performance of new aircraft designs specifically with varying temperatures, reduced visibility, high winds, precipitation, and icing conditions) and the interaction of ODAM with other UAS (potential conflicts due to operations away from protected airport airspace).

In a previous work, the authors of this paper analyzed the fundamentals for the availability study of RAM-ODAM transport systems under realistic weather and operating conditions in Germany (Wortmann et al., 0000). This previous work was created since more realistic assessments of new transport systems were needed due to a general overestimation of the system availabilities in other works. To set the framework for subsequent work, a focus on several key factors was initially made including air taxi design, flight routings and trajectories, airside operational capacity and aircraft noise. It was determined that a serial-hybrid drive train shows greater efficiency for the proposed ODAM operations. The selection of potential air taxi routes and the assessment of optimal vertical flight trajectories was conducted showing dependencies of optimal cruising altitude with aircraft range and cruising speed. The need to consider airspace structures and approach and departure procedures was identified as these parameters may leads to a significant increase of flight routes. Potential aerodromes for future air taxi operations were clustered and a technical capacity assessment was conducted for the selected Augsburg airport. The latter showed a maximum capacity of 40 air taxi movements per hour, limited by apron capacity. For the turnaround process, the electrical charging was identified as the bottle neck for air taxi operations with the air taxi design. Furthermore, an initial noise assessment was conducted. Even though it is expected that (hybrid-) electrical aircraft will show lower noise emissions, it was inconclusive how residents would react to more frequent air taxi operations at rural aerodromes. Current noise regulations in Germany do not impede with daytime air taxis operations. However, night operations would cause a limiting factor for the introduction of air taxi operations in Germany.

Considering existing works and the previous work by the authors, several fields were identified for further research. Weather was identified as a key parameter potentially hindering operations at existing infrastructure (see Section 2). As in the authors previous work, only selected aerodromes were considered for a technical capacity assessment. The total availability of current German aerodrome system for the proposed ODAM operations were assumed.

Therefore, this current work aims to further evaluate the availability of the German aerodrome system by quantification of availabilities of the ODAM system. It shall be analyzed which infrastructural and operational (weather) parameters cause non-availabilities for the proposed air taxi services. The goal of this work is to support in the determination if air taxi systems are a viable option for future transportation to reach the ambitious goals set in Flightpath 2050.

This paper is organized as follows. In Section 2, relevant literature on ODAM services is introduced and discussed. Section 3 describes the methodology and data used for the availability study. The availability study is described in Section 4 considers the infrastructural and operational aspects of German aerodromes for air taxi operations. Finally, this paper concludes with Section 5 providing a summary of the findings and outlook for future works.

2. Literature review

A literature review was conducted in the fields of ODAM market potential, airport system availability and weather impact analysis on airport operations of ODAM transportation system.

The usage of ODAM for use cases in Germany with fixed-wing aircraft has been investigated by several researchers (Kreimeier, 2018; Paproth et al., 2020; Schuh et al., 2021; Sun et al., 2018), demonstrating a significant market potential for air taxi services with fixed-wing aircraft in Germany. Whereas generally the largest competitor to thin-haul air-mobility was identified as railway in the works of Sun et al. and Paproth et al. (Paproth et al., 2020; Sun et al., 2018), the main competitor in the business travel segment was identified as car transportation due to the low travel costs in the work of Schuh et al. (Schuh et al., 2021). Hence the most vital parameter for ODAM competitiveness was determined as the specific price per kilometer (Schuh et al., 2021). For all countries in Europe a large potential to benefit from air taxi service considering distances up to 450 km was shown (Sun et al., 2018). In particular it was mentioned that air taxi serving peripheral areas could aid to reach the Flightpath 2050 goals (Sun et al., 2018). This includes routes in northern, coastal Germany which were identified with high market potential due to the geographical advantage of air transport (Paproth et al., 2020). In his works Kreimeier (Kreimeier, 2018)considered the benefits of all-electric ODAM transportation which described potential bottlenecks may result from aerodrome infrastructure.

The focus of all these works (Kreimeier, 2018; Paproth et al., 2020; Schuh et al., 2021; Sun et al., 2018) was on the development of initial market potential therefore time of day and scheduling for air services where not included. By doing so, the allocation of the air taxi demand was unrestrictedly conducted to the proposed service. This causes an assumption of immediate availability for the air taxi connections overestimating the realistic availability of the ODAM transport system.

Airport availability modelling was conducted with a systems-level approach to airport and runway availability assessments by Rakas and Hecht (Rakas and Hecht, 2007). It was highlighted by the authors that both arrival and departure should be analyzed individually due to different requirements for both CNS equipment (e.g. ILS) and weather (e.g. visibility). Therefore, the work shows major influence of weather conditions to airport availability. Rakas and Hecht (Rakas and Hecht, 2007) recommend further research around airport effectiveness and availability due to its usefulness for capacity estimation and necessity of airport modernizations caused by the increase in air traffic demand. Weather was already described in Section 1 as a key parameter which could restrict the availability of future ODAM transport systems, which needs further analysis (Vascik and Hansman, 2017a). Adkins et al. (Adkins et al., 2020) described in his work that without good weather products, aircraft may be unnecessarily grounded and therefore delayed decreasing the service quality and profitability. Therefore, a new future data collection method architecture was introduced (crowdsensing) by using non-professional sensors in urban areas. The goal is to enhance reliable weather information required e.g. for flight planning.

Analysis of weather impact on airport performance was conducted in various previous works (Chao et al., 2021; Crawford et al., 0000; Reiche et al., 2021; Schultz et al., 2018; Sharma et al., 2023). Most of these works are based on the usage of METAR weather as the primary data source (Crawford et al., 0000; Reiche et al., 2021; Schultz et al., 2018; Sharma et al., 2023). Schultz et al. (Schultz et al., 2018) analyzed airport performance for conventional air transport using EUROCONTROLs ATMAP algorithm (Atmap weather alorithm, 1005). A historical dataset for one year of European flights were the basis for the high level performance analysis conducted by categorizing operational days in good/bad with a scoring system. The analysis included a total

of five weather classes each (visibility and ceiling, wind, precipitations, freezing conditions, dangerous phenomena). The results showed that the usage of the ATMAP scoring system resulted in difficulties for operational performance analysis, as it was linked to higher probabilities for delays rather than aircraft cancellation rates (operational performance analysis).

Reiche et al., Chao et al., Sharma et al. and Crawford et al. (Chao et al., 2021; Crawford et al., 0000; Reiche et al., 2021; Sharma et al., 2023) conducted weather impact analysis specifically for AAM operations. Crawford et al. (Crawford et al., 0000) investigated weather-related considerations for electrified regional air mobility operations. The authors analyzed the impact of range limiting constraints to the electrical drivetrain by introducing a variable energy reserve consideration for the flight range. It was determined that when flight conditions become increasingly constraining, the effective range of an aircraft with the same design range shrinks. The results indicate that weather effects are significant for day-to-day conditions on flight operation and therefore need to be considered for initial vehicle design. Sharma et al. (Sharma et al., 2023) quantified the weather effect on AAM operations for the US, to understand the viability of AAM operations by region. Historical METAR weather data were used to evaluate the potential number of flying hours and the leading causes of non-flyable hours. Weather parameters analyzed include the temperature, wind, visibility and sky conditions (cloud ceiling) for a total of 91 US airports.

The works of Reiche et al. and Chao et al. (Chao et al., 2021; Reiche et al., 2021) further focused on UAM operations with VTOLs. Reiche et al. (Reiche et al., 2021) developed a framework for multi-city UAM weather analysis in the U.S to understand potential UAM weather opportunities and challenges. Key element of the analysis is the introduction of the weather impact score scheme which is used for the historical weather data analysis. The latter includes the categorization of operations as æweather impacted" if they are above a predefined impact threshold score. The developed impact score scheme was also used in Chao et al. (Chao et al., 2021) work, in which a weather impact assessment for UAM operations in Chicago and Dallas metropolitan areas were conducted. The assessment was conducted on urban travelling traffic patterns and climatic conditions based on NOAA weather data, to determine the chances of operations with UAM.

The commonality of all these current works (Chao et al., 2021; Crawford et al., 0000; Reiche et al., 2021; Sharma et al., 2023) is the result that AAM operations are significantly impacted by weather. These works further describe that regional differences in weather conditions are reflected in AAM availability as well. Some US regions require large amount of non-VFR operations due to the weather (Crawford et al., 0000) and some specific US areas show nearly double the availability for AAM operations compared to others (Sharma et al., 2023). Reiche et al. (Reiche et al., 2021) analysis further shows approx. half of UAM operations per day with potential weather impacted hours and again different regions with different favorable conditions for UAM. In particular, UAM operations in Chicago may be hindered by harsh winter conditions (Chao et al., 2021; Sharma et al., 2023), while operations in Denver may be hindered by low visibility (Chao et al., 2021). Chao et al. (Chao et al., 2021) generally describes low temperature, snow, low visibility and strong winds as the weather phenomena with most impact on flight operations.

All in all, the literature review showed that further research is required in the field of AAM with an emphasis on regional weather impact to assess the availability of the proposed air taxi services. Current works (Chao et al., 2021; Crawford et al., 0000; Reiche et al., 2021; Sharma et al., 2023) in this field show a one-sided application to use cases within the U.S. which causes a lack of consideration of European AAM use cases. This does not match the significant market potential identified for air taxi services with fixed-wing aircraft in Germany by multiple previous works (Kreimeier, 2018; Paproth et al., 2020; Schuh et al., 2021; Sun et al., 2018). It is important to mention that these works focus on analyzing the initial market potential for the ODAM transport system in Germany, therefore various hindering factors where not considered causing an overestimation of the transport system availability.

The previously mentioned weather impact analysis works specifically for AAM operations showed that weather can restrict flight operations and therefore the availability of the transport system (Chao et al., 2021; Crawford et al., 0000; Reiche et al., 2021; Sharma et al., 2023). These works were conducted to give a general weather impact analysis for AAM operations not considering specific AAM aircraft in the analysis (e.g. air taxi models). Reiche et al. (Reiche et al., 2021) describes their own work to be used as baseline for analyzing potential UAM weather barriers associated with a variety of aircraft and operations. Also, Crawford et al. (Crawford et al., 0000) described that future studies should include different (hybrid-) electrical aircraft to understand sensitivities in the work results. Further, Reiche et al. (Reiche et al., 2021) describes that operational weather forecasting is required to improve safety and reduce operational impacts due to adverse weather conditions, which will be key to building community acceptance of urban air mobility.

Therefore, the novel scientific contribution of this work is the application of specific aircraft performance data to the availability analysis for air taxi operations. For this, a hybrid-electrical fixes-wing aircraft design study shall be used for the proposed ODAM use case. The analysis shall be conducted in Germany as significant ODAM market potential was demonstrated and the current lack of European use cases in other works was shown. The proposed use case and aircraft performance data provide the possibility to conduct a specific availability analysis for the German aerodromes with an emphasis on operational performance data. For this, METAR weather for an extensive time period of 20 years shall be used to gain broader knowledge about rare but operationally significant weather phenomena.

The goal of this work is to support the evaluation if air taxi systems are a viable option for future transportation to reach the ambitious goals set in Flightpath 2050. Therefore, in this paper, the current status of the German aerodrome system shall be analyzed for the proposed ODAM with fixed-wing aircraft. The following questions shall be answered:

- How many current German aerodromes are infrastructurally available for ODAM with fixed-wing aircraft?
- How many current German aerodromes are operationally available for ODAM with fixed-wing aircraft?

German aerodromes are analyzed for their infrastructural availability with the ODAM to determine if the status quo of the aerodrome provide a possibility for integration into current infrastructure. It is analyzed which parameters cause non-availabilities for the proposed air taxi services. Historical weather data is used for quantification of the operational availability of the current German aerodrome system. Weather parameters causing non-availabilities shall be highlighted.

3. Methodology and data

In this section, the methodology and data used in this paper are presented. For this, the research design is described in Section 3.1. The central data used in this paper consist of the air taxi, the aerodrome data and the weather data, which are presented in the Sections 3.2-3.4.

3.1. Research design

As described in Section 1, the goal of this paper is to support the evaluation if air taxi systems are a viable option for future transportation. To achieve this, the availability of German aerodromes for ODAM with fixed-wing aircraft shall be evaluated. In this paper initially, German aerodromes are analyzed for their infrastructural and operational availability separately.

In general, the term availability is defined as the ability of an item or system to be in a state to perform as and when required. This state is set under given conditions and with the assumption that necessary external resources are provided. Among other things this mentioned ability of a

system to be in a state to perform is depending on the system's reliability. The latter is the ability of an item or system to perform a required function under given conditions for a given time interval (Deutsche Institut für Normung, 0000; Eberlin and Hock, 2014).

Furthermore, the total availability of complex systems results from the multiplication of the availability of all subsystems (series circuit). To increase the total availability of the system redundancies should be implemented in the system design through a combination of parallel circuits with series circuits (Arnold et al., 2008).

The quality of services is defined as the ability to fulfill the needs and expectations of a customer (Deutsche, 0000). Aerodrome systems shall be in a state to perform the required system function with a certain quality at the time demanded.

German aerodromes are analyzed for their infrastructural availability (Section 4.1) with ODAM to determine if the status quo of the aerodrome provide a possibility for integration into current infrastructure. It is analyzed which parameters cause non-availabilities for the proposed air taxi services. Historical weather data is used for quantification of the operational availability (Section 4.2) of the current German aerodrome system. Weather parameters causing non-availabilities shall be highlighted.

For the infrastructural availability of German aerodromes for air taxi operations, the transport system considered consists of the aerodromes given infrastructure (status quo, Section 3.3) paired with the air taxi as the vehicle to be operated (Section 3.2). The system function is considered of sufficient quality if the transport system is available for safe operations without considering a time specific demand. This means that current aerodromes must be infrastructurally equipped for the proposed ODAM operations with fixed-wing aircraft operations. To determine availability, first the minimum requirements for ODAM are defined. It is then examined which German aerodromes meet these requirements and the restrictions that lead to a high degree of exclusion are identified. From this, conclusions can be drawn whether it is possible to adapt the infrastructure or the vehicle to improve the availability.

The basic dataset used for the infrastructural availability analysis includes all German aerodromes. The aerodrome database serves as the data basis for reviewing the minimum requirements. The infrastructure requirements result from the operational needs of the ODAM operation and from the technical specifications of the air taxi used. The result of the infrastructural availability provides a list of German aerodromes which are currently available for the application of the proposed ODAM system.

For the operational availability of German aerodromes for air taxi operations, the transport system considered also consists of the aerodromes given infrastructure (status quo, Section 3.3) paired with the air taxi as the vehicle to be operated (Section 3.2). The system function is considered of sufficient quality if the transport system is available for safe operations at a certain time under the given weather conditions (Section 3.4). Therefore, the time-based availability is considered as defined in (Deutsche Institut für Normung, 0000), which is the key difference in comparison to the infrastructural availability study in Section 4. For this, the ratio of the up time (availability) to the given total time is analyzed. The results of the operational availability analysis are therefore quantifiable and weather parameters causing non-availabilities for individual aerodromes are identified.

Finally, the results of both the infrastructural and operational availability are combined to evaluate if the air taxi systems are a viable option for future transportation from the point of total aerodrome availability in Germany for ODAM (Section 4.3).

3.2. Air taxi design and resulting operational requirements

For this paper an air taxi with a hybrid-serial powertrain is used. This air taxi in fixed-wing configuration is designed utilizing the preliminary aircraft design software Multidisciplinary Integrated Conceptual Aircraft Design and Optimization Environment (MICADO) for small aircraft according to EASA CS-23 (EASA, 2018). MICADO is developed and evolved by the Institute of Aerospace Systems (ILR). Within MICADO it is possible to design an aircraft according to given top level aircraft requirements (TLAR) in minutes. Various post processing tools can be used to analyze and evaluate the results (Kreimeier, 2018; Strathoff et al., 2020). The design of the used air taxi is based on the Cirrus SR22T, which is one of the best-selling general aviation aircraft worldwide (Gen, 2024). This makes this aircraft suitable as a reference design for this study. An existing MICADO design of the Cirrus SR22T with conventional powertrain is used as a baseline and is adapted with respect to the TLAR shown in Table 1. The design results are given in Table 2 and a visualization of the air taxi is shown in Appendix A. For further information about the design of the air taxi the reader is referred to previous work from the authors (Wortmann et al., 0000).

Table 1
Top level aircraft reuqirements (TLAR)

Range	550 km
Holding	45 Minutes
Cruise Speed	240 km/h
Cruise Altitude	1000 ft
Powertrain	Hybrid-electric
Payload 3	PAX
Crew	1 Pilot

Table 2
Aircraft design results

MTOM / MLM / MRM	1364 kg
OEM	921
Wing loading	121.2 kg/m2
Power to mass ratio	0.14 kW/kg
Wingspan	10.67 m
Powertrain	Hybrid-serial
Hybridization degree	10 % (Energy)

Based on this design, the resulting operational limitations are explained in the following. The available runway distance and wind conditions are the limiting factors. It is assumed that the aircraft is certified for operation on both paved and unpaved runways. Calculations in MICADO have shown that the takeoff distance (TD) on a paved runway at sea level is 468 m under International Standard Atmosphere (ISA) conditions. The required TD increases with increasing elevation and air temperature. The landing distance (LD) on a paved runway at sea level and ISA conditions is 524 m.

The modeling of takeoff and landing distance increments with increasing elevation whereas air temperature is considered based on the increments specified in the Cirrus SR22T flight manual (Cir, 2003). In addition, surcharges for specific runway conditions must be considered. These surcharges and the resulting distances are listed in Table A.1 for takeoff and landing and are based on an aviation safety notice of the Luftfahrt-Bundesamt of Germany and information from the CirrusSR22T flight manual (AOP, 2018; Cir, 2003; Luf, 1975). In addition, the crosswind component must not exceed 10.29 m/s and the tailwind component must not exceed 5.14 m/s during takeoff and landing to ensure safe operation. Additional information for required TD and LD calculations and surcharges for specific runway conditions are given in Appendix A.

3.3. Aerodrome database

The aerodrome database provides an informational basis for the availability study of German aerodromes. The database consists of relevant aerodrome data points extracted from AIP Germany (including the supplemental AIP VFR) as the primary source (DFS, 2912). The AIP Germany is an official document for the purpose of flight information, published and regularly updated on behalf of the Federal Ministry for Digital and Transport (BMDV). This ensures that the published flight

Table 3
Restrictions infrastructural availability of aerodromes for ODAM

Parameter	Restriction
Number of Runways	Min. 1
Approach	VFR permitted
Noise restriction	None for the air taxi operations
Airport coordination	Level 1 and 2 provide available capacity
Apron capacity	At least 1 available stand for air taxi operations
Operating time	VFR allowed min. 6 hours per day, no PPR in these 6 hours
Refueling	Av Gas (100LL) or conventional gasoline available
Power connection	Available or upgradeable
Runway dimensions	$LDA > 524m$ + RWY elevation correction + RWY surface correction; $TORA > 468m$ + RWY elevation correction + RWY surface correction; Width > $18m$
Runway surface bearing	$MTOW > 1,370kg$
Runway surface condition	Asphalt, concrete, grass; No water landing site

Table 4
List of parameter limits for air taxi operations at aerodromes

Parameter	Parameter limits for air taxi operations near aerodromes
(I) Visibility (EASA, 2023)	Airspace G: min. 1,500 m Airspace D CTR: min. 5,000 m
(II) Cloud minima (EASA, 2023)	Airspace G: Cloud coverage: max. 4/8 (max. METAR reporting “SCT”) Cloud height: min. 1,000 ft AGL Airspace D CTR: Cloud coverage: max. 4/8 (max. METAR reporting “SCT”) Cloud height: min. 1,500 ft AGL
(III) Runway arrival performance (AOP, 2018; Cir, 2003; Luf, 1975; Wortmann et al., 0000)	Wind speed and direction: • Runway performance calculations for arrival and departure directions
(IV) Runway departure performance (AOP, 2018; Cir, 2003; Luf, 1975; Wortmann et al., 0000)	• Crosswind: max. 20 kts • Tailwind: max. 10 kts
(V) Wind speed - Ground Handling (ICAO Doc. 9157, 2020)	Max. 30 kts
(VI) Wind gusts (EASA, 2018)	Max. 7.62 m/s (25 ft/s)
(VII) Air temperature (AOP, 2018; Cir, 2003; Luf, 1975; Wortmann et al., 0000)	-20 ° C to +35 ° C
(VIII) Special weather phenomena	thunderstorms (“TS”), hail (“GR”), fog (“FG”), squalls (“SQ”), smoke (“FU”), volcanic ash (“VA”), sand (“SA”), dust or sand whirls (“PO”), funnel clouds (“FC”), sandstorms (“SS”), dust storms (“DS”)

information data are highly reliable, up-to-date, and permanently available free of charge.

As of May 2022, Germany has a total of 442 aerodromes for operations with civil, fixed-wing aircraft published in the AIP. All aerodromes are analyzed and included into the database. The database itself is primarily based on the AIP VFR, which provides an excerpt from the AIP with additional information regarding VFR flights including aeronautical charts. The latter suit the usage of hybrid-electric fixed-wing aircraft under VFR for the planned ODAM.

The list of aerodromes provided in the AIP VFR Chapter AD 2 (R. Eisenschmidt GmbH, 2022) contains information on the aerodrome category, the geographical reference location and locally available flight operation rules (NVFR, IFR). It also includes information regarding aircraft compatibility, operating hours, flight operations, customs and availability of fuel, oil, maintenance, and hangars.

Most of the aerodromes in the AIP VFR are provided with a visual flight chart and an aerodrome chart. All available charts were analyzed for each aerodrome to further expand the database. Visual flight charts contain information on aerodrome altitude, radio frequencies, airspace category at the aerodrome, existence of a transponder/radio mandatory zone or aerodrome traffic zone, existing approach, and departure routes, IFR corridors, holding areas, compulsory reporting points (designation and location), altitude restrictions and aerodrome traffic circuits (for each runway). Aerodrome charts contain further important information on the geographical position of the aerodrome (longitude, latitude, reference altitude), the runways (number, dimensions, length, width, characteristics, load-bearing capacity, take-off run available (TORA) and landing distance available (LDA)) and the availability of General Aviation Terminals (GAT).

The AIP Germany provides a total of 61 aerodromes for civil aircraft operations of which the majority are included in subchapter AD 2 (DFS, 2912). Four additional military aerodromes with joint-civilian IFR use have been included in the database as well (chapter MIL AD 2, DFS (2912)).

Combination of the information published in the AIP and the AIP VFR covers a total of 442 aerodromes in Germany for civil fixed-wing operations, with 58 data parameters for each of the aerodromes in the database. The database is used in both the infrastructural and operational availability analysis of German aerodromes.

3.4. METAR weather database

As described in Section 2, weather data is a key factor for aerodrome operations thus also for airport operational availability. To comprehensively investigate the effects of weather of ODAM systems, the use of high-quality weather data is necessary. For this purpose, METAR data is used, as it provides an airport centric weather data with an intent for operational use. The development of the historical METAR weather database is based on all retrievable METAR weather data from the Automated Surface Observing System (ASOS) of the Iowa Environmental Mesonet (Iow, 2022). For the procurement of the historical data, only aerodromes in Germany are used. A timespan of 20 years was chosen for the procurement with the aim to include significant and rare adverse weather conditions in this historical timespan. Therefore, weather data

in the years 2001-2020 are procured. METAR weather data for a total of 53 German aerodromes could be procured for the given timespan. Out of 53 aerodromes 3 aerodromes are excluded from further analysis: Berlin Tegel (EDDT, defunct airport (Ber, 2022)), Aachen Merzbrõck (EDKA, insufficient datapoints) and Pirna-Pratzschwitz (EDRA, insufficient datapoints). Therefore, the resulting weather database includes a total of 50 German aerodromes (see Appendix B). For further information about the procurement, processing, and validation of the METAR weather database the reader is referred to Hagemann and Gollnick (Hagemann and Gollnick, 2809).

4. Availability study of German aerodromes for air taxi operations

In this section, the availability of German aerodromes for the proposed air taxi operations are analyzed. Firstly, the infrastructural analysis is provided in Section 4.1. Subsequently the operational availability analysis is conducted in Section 4.2. In a last step, the total availability analysis for German aerodromes is provided in Section 4.3.

4.1. Infrastructural availability analysis

As mentioned in Section 3.1, the infrastructural availability is analyzed to conclude whether German aerodromes are currently available for the application of the proposed ODAM system. To determine availability, first the minimum requirements for ODAM are defined in Section 4.1.1 and the results of the infrastructural availability analysis are evaluated in 4.1.2. It is examined which German aerodromes meet these requirements and the restrictions that lead to a high degree of exclusion.

4.1.1. Parameter restrictions for infrastructural availability

Regarding the infrastructure availability for ODAM at the airport, there are some parameters in the aerodrome database that have no influence (e.g. local noise abatement procedures or existence of general aviation terminals). These do not lead to the exclusion of air taxi operations, as they are either not a necessary criterion or do not allow a conclusive assessment due to a lack of data. These will not be considered further. In addition, some basic assumptions are made. Firstly, it is assumed that each aerodrome within the database has at least one runway where VFR approaches for civil operations are always permitted. Secondly, it is assumed that there are no noise restrictions at the aerodromes for this use case. This is initially confirmed for daytime operation by a noise study of the aircraft used by previous work from the authors (Wortmann et al., 0000). Furthermore, the fully coordinated airports are excluded (see Section 3.3). Due to the characteristics of ODAM and the need for short-term services, these operations require capacity to be available for most of the day. This does not apply to fully coordinated airports. Additionally, the ODAM requires available apron capacity for at least one aircraft at the aerodromes. If the connections are in high demand, additional stands will be required. However, capacity is not considered further below, but is taken into account by excluding coordinated aerodromes. Depending on the frequency of ODAM operations to the aerodrome and considering the capacity in detail may lead to availability restrictions and must be assessed on a case-by-case basis. This requires comprehensive capacity studies which consider existing traffic and future expansions shown in previous work by the authors (Wortmann et al., 0000). The aerodrome database parameters that cause restrictions are presented in Table 3.

As the aerodromes used for ODAM must be accessible regularly and at short notice, the minimum operating time is set to 6 hours per day (no PPR operations). To ensure operational continuity, it is also necessary to be able to refuel and recharge the battery of the aircraft at the approaching aerodromes. Regarding the power supply for the hybrid-electrical air taxi, it is assumed that this can be installed if necessary. The required runway lengths for landing and take-off result from the calculations presented in Section 3.2. Correction factors for temperature and runway slope are not included for the runway because runway slope data is not included in the aerodrome database. The temperature data also varies depending on the time of day and season; therefore, temperature data must be checked on a case-by-case basis (see operational availability, Section 4.2). The values given for the runway lengths therefore indicate the minimum runway design required at a reference temperature of 15 ×C and a slope of 0 ×. Surface bearing and condition are also determined by the air taxi specifications. No restriction is introduced regarding handling services and equipment. On the one hand, it can be assumed that these can be upgraded if necessary. Secondly, the databases used do not provide comprehensive information for all aerodromes in this respect, so that no fully comparable information is available and therefore not considered.

4.1.2. Evaluation of infrastructural availability

The airport database contains a total of 442 aerodromes in Germany (Section 3.3). Due to the restrictions mentioned in Section 4.1.1, not every aerodrome is suitable for ODAM. In this section it is examined in detail which restrictions affect the infrastructural availability of the aerodromes. It should be noted that some of the restrictions are unchangeable, while other restrictions could be adapted under certain circumstances and thus increase the infrastructural availability.

To obtain the infrastructural availability for German aerodromes the restrictions mentioned in Section 4.1.1 are applied to each of the 442 aerodromes contained in the database (Section 3.3). To analyze which restrictions have a major impact on infrastructural availability, the number of breaches of each restriction are checked (see Fig. 1). In 318 cases the operating time does not comply with the limits set. This is due to the large number of small aerodromes without regular and commercial operations, for which regular operations on every day of the week would not be viable given current demand and high employee costs. The situation is similar for the refueling restriction, which is breached 170 times. This means that 38.5 % of aerodromes do not have the possibility of refueling with AvGas or conventional gasoline. Aerodromes for which no refueling information is available in the database are conservatively considered as aerodromes without refueling facilities. These are mainly small aerodromes where there is no corresponding demand. Some aerodromes are not suitable for air taxi operations due to their runway dimensions (21.3 % of aerodromes). A total of seven aerodromes in the database are coordinated (Level 3) and therefore classified as unavailable. The runway conditions and surface are only in very few cases a reason for exclusion.

If all the restrictions are considered as proposed, this means that 112 aerodromes or 25.3 % of the German aerodromes are infrastructurally available for immediate air taxi traffic. These aerodromes are spread all over Germany. In terms of runway design, these are the values for the reference temperature of 15 ×C. If 35 ×C is taken as the highest possible operating temperature for air taxis (see Section 3.2), the number of aerodromes is reduced by two to a total of 110 aerodromes.

Some of the restrictions cannot be overcome without major construction work at the aerodromes. For other restrictions, however, an adjustment is conceivable in case of increased demand at the aerodromes. A final assessment would need to be made on a case-by-case basis. It is determined that the most frequently breached restriction is the aerodrome operating time (see Fig. 1). Extending operating time does not require any adaptation of infrastructure, technology or aircraft design, so a change at individual aerodromes could be conceivable if there is sufficient demand. By extending the operating time, 100 additional aerodromes will become available, resulting in a total of 212 available aerodromes (see Fig. 2).

The second reason for exclusion of aerodromes in infrastructural availability is the possibility of refueling. The large number of aerodromes without refueling facilities is caused by aerodromes for which no information can be provided in the database. For these aerodromes it is assumed that no adequate refueling possibilities are provided. It can

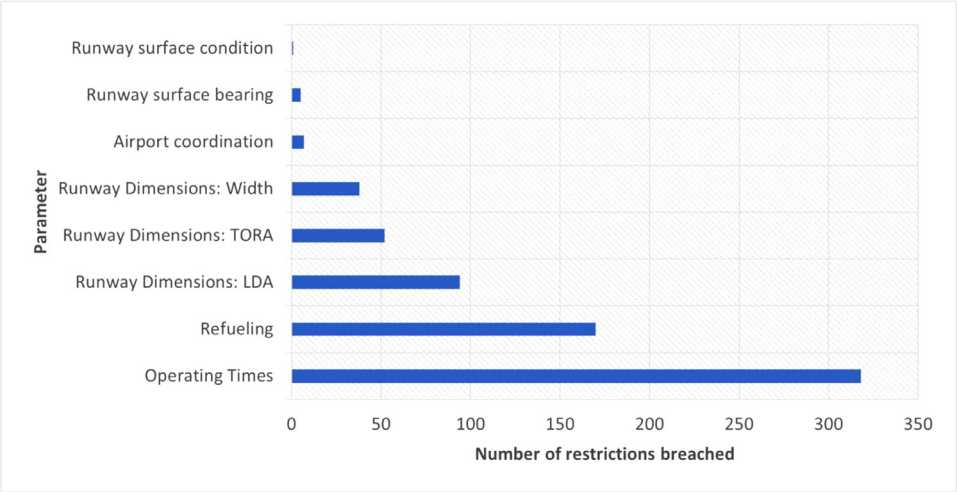


Fig. 1. Number of restrictions breached per parameter; own illustration based on aerodrome database

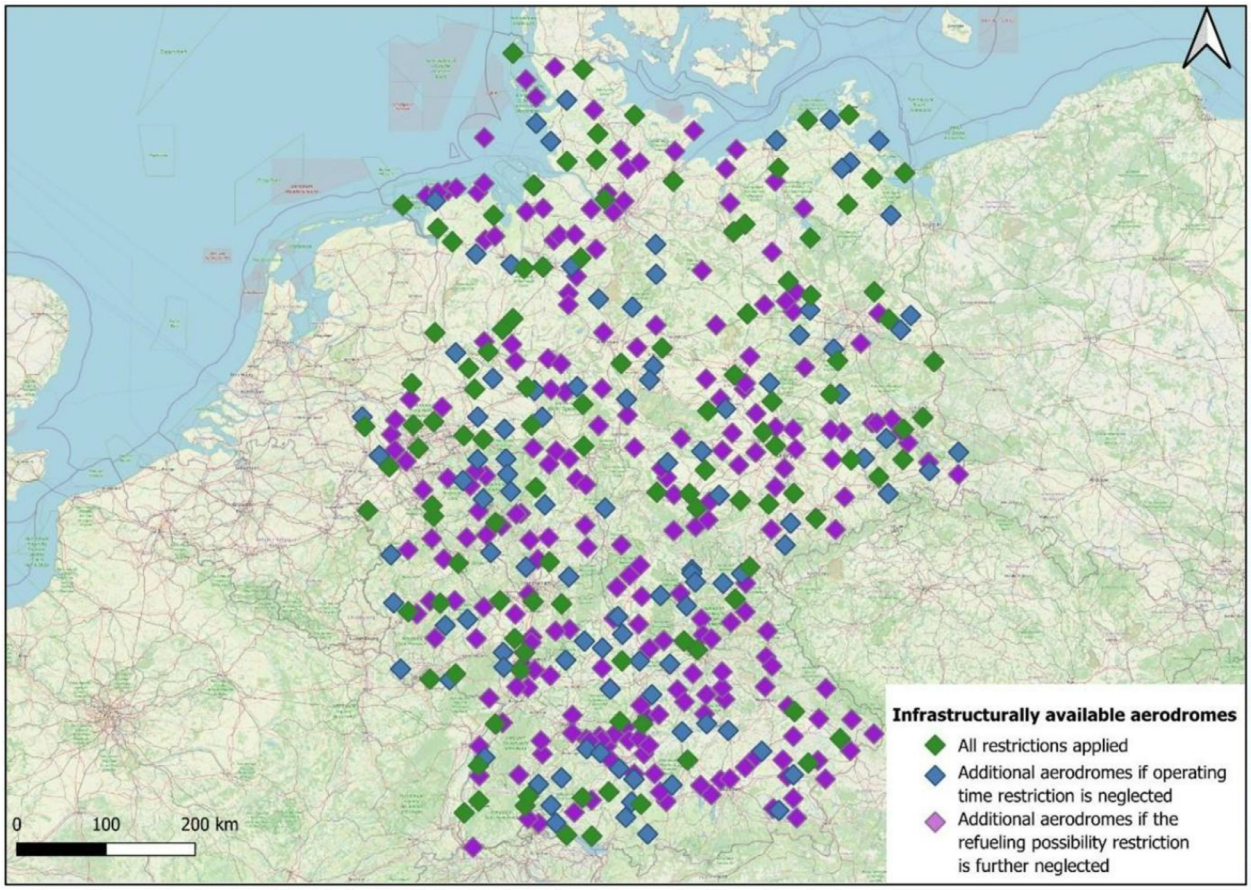


Fig. 2. Infrastructurally available aerodromes, neglecting various restrictions; own illustration, map based on OSM

be assumed that some of the aerodromes without a corresponding entry in the database nevertheless have refueling facilities. In addition, mobile refueling trucks may be a viable option to provide refueling facilities at aerodromes, thus eliminating the reason for exclusion. This could reduce or eliminate this reason for the unavailability of aerodromes.

The initial analysis of infrastructural availability identified 112 available aerodromes for the proposed ODAM operations. As previously discussed, the top two restricting parameters (sufficient operating times and refueling) could be justifiably excluded from the analysis. This would lead to a total of 306 infrastructurally available aerodromes in Germany (see Fig. 2). Runway dimensions are identified as the third reason for the unavailability of aerodromes. These result in a total of 125 aerodromes not being available. To change this, infrastructural adaptions need to be made, which require considerable effort or are not possible at all. Particularly in view of the introduction of ODAM, it is currently unlikely that there will be sufficient demand in the near future to overcome the number of legal obstacles to justify structural changes. In summary, of the 442 aerodromes in Germany, approximately 25.3 %

show immediate infrastructural availability for air taxi operations considering all restrictions. If individual restrictions that can be adapted to an increase in demand are neglected, the infrastructural availability of airports can be increased. By neglecting these restrictions, it is assumed that the aerodromes will improve their operating times and refueling options in the future. If the operating time is extended, which is possible without construction changes, 212 of the aerodromes would be available (48.0 %). If it is also assumed that refueling would be possible at all aerodromes due to higher demand, 306 airports would be available (69.2 %). Fig. 2 shows that the density of initially available aerodromes is lower in central Germany, especially in Lower Saxony and Hesse, than in other parts of the country. If the aerodromes excluded due to time or refueling constraints are added, the result is a convenient network for future air taxi services in Germany with only very few poorly connected areas, for example in the center of Lower Saxony.

4.2. Operational availability of German aerodromes for air taxi operations

In this section, the operational availability of German aerodromes for the proposed air taxi operations is analyzed and the results are quantified and evaluated. Firstly, the parameter restrictions are provided in Section 4.2.1. Using historical weather data, the results of the analysis including the main weather parameters causing non-availabilities are identified (Section 4.2.2).

4.2.1. Parameter restrictions for operational availability

Weather parameters have a major influence on the operational performance of aircraft. As described in Section 3.4 the METAR weather database is used for the analysis of the operational availability of the given aerodromes for the ODAM with the air taxi (Section 3.2). Several weather restrictions are given for VFR operations within Airspace G and D CTR, which are provided in the EASA SERA.5001 and SERA.5005 (EASA, 2023). The METAR database provides the data parameters to be checked for operational availability. Table 3 includes all data parameters considered for the operational availability study. According to the Standardized European Rules of the Air visibility of at least 5,000 m is required for aircraft operating in Airspace D CTR and min. 1,500 m for operations within Airspace G (EASA SERA.5001 and SERA.5005 (EASA, 2023)).

Specific requirements are given in EASA SERA.5001 and SERA.5005 (EASA, 2023) for the cloud minima. The latter requires a combination of adequate cloud coverage within a specific cloud height. Cloud coverage requirements are given in EASA SERA.5001 and SERA.5005 (EASA, 2023), where it is described that aircraft shall keep clear of clouds and with the surface in sight (Airspace G). For this analysis it is assumed that if the cloud coverage is less than 50 %, sporadically located clouds are accepted and the operation with a flight path in accordance with the minimum criteria for cloud coverage are met (incl. 1,500 m horizontal separation in Airspace D CTR). Therefore, the METAR reported cloud coverage shall not be reported as broken (“BKN”) or overcast (“OVC”), so the coverage level does not exceed 4/8. According to EASA SERA.5005(b)(1) (EASA, 2023) the cloud height limit for operations within Airspace D CTR requires 1,500 ft AGL. Within Airspace G, no significant cloud coverage is allowed up to 1,000 ft AGL (EASA SERA.5001 (EASA, 2023)) in order to ensure a minimum safety altitude of 1,000 ft AGL over populated areas at all times (EASA SERA.5005(f)(1) (EASA, 2023)). Subsequently, for the parameter “Cloud minima” an operational height margin of min. 1,000 ft AGL for Airspace G and min. 1,500 ft AGL for Airspace D CTR shall always be available in which no significant cloud coverage (50 %, max. METAR reporting “SCT”) is active, so air taxi operations can safely operate to and from aerodromes.

It is assumed that runways are considered as available, if at least one arriving and one departing operational direction are simultaneously available for operation. To check this requirement, calculations for LDA and TORA are conducted for each weather data set. As described in Section 3.2, LDA and TORA calculations correlate with runway elevation, air temperature, runway surface type and head-/or tailwinds (wind direction and speed). Additionally, crosswinds shall not exceed a limit of 20 kts and tailwinds shall not exceed a limit of 10 kts.

Due to occupational safety considerations for ground handling personnel a 30 kts wind speed limit is defined. This is the limit described in ICAO Doc. 9157 as the uncritical velocity for aircraft jet blast ((ICAO Doc. 9157, 2020), chapter 1.4.15) which causes an adverse effect on the servicing crew and equipment ((ICAO Doc. 9157, 2020), chapter 3.4.5.1). It is assumed that critical velocities of aircraft jet blast and wind speeds have similar adverse effects. The aircraft design provides operational limits regarding the wind gust speeds of 7.62 m/s (25 ft/s) (EASA CS 23.345 (EASA, 2018)). Due to technical restrictions for electrical components of the air taxi, an air temperature range between -20°C to +35°C is required for safe operations.

Several special weather phenomena also limit the ability for safe air taxi operations at aerodromes potentially causing the exceedance of operational limits for the air taxi in the air or safe ground operations at the aerodrome (e.g. due to deteriorated visibility). Therefore thunderstorms (“TS”), hail (“GR”), fog (“FG”), squalls (“SQ”), smoke (“FU”), volcanic ash (“VA”), sand (“SA”), dust or sand whirls (“PO”), funnel clouds (“FC”), sandstorms (“SS”) or dust storms (“DS”) are all considered not to be within the limits of safe operations.

4.2.2. Evaluation of operational availability

For the evaluation of the operational availability for each aerodrome, a total of eight parameters for operational availability (see parameters I-VIII in Table 3) are analyzed. Every parameter is evaluated separately for each METAR weather data point. As described in Section 3.4, the METAR weather database consists of METAR weather data for a total of 50 German aerodromes in the timespan of 2001-2020. Typically, the weather data is recorded on an hourly basis. This results in 24 data points per day, for a total of 7,305 days in the 20-year historical timespan. Therefore, a total of 175,320 historical datapoints are expected for each aerodrome as a data basis.

Calculations for required TORA and LDA are conducted according to Section 3.2 with wind corrections specified in Table A.1. For these calculations, runway information is extracted from the aerodrome database. The latter include the aerodrome elevation, runway direction, TORA, LDA, surface type and surface strength for each runway. In combination with the weather data the final TORA and LDA values are calculated by conducting elevation correction, temperature correction, surface correction and head-/tailwind correction.

The operational availability is evaluated for the given METAR weather data point by checking the availability for all parameters. The given METAR weather data point is considered as available if all eight parameters were evaluated as available. Thus, if any of the eight parameters are considered as unavailable, the given METAR weather data point is overall considered unavailable as well. If any of the eight parameters cannot be evaluated due to incomplete data sets, the given METAR weather data point is overall assessed as incomplete accordingly. Therefore, the operational availability study connects all parameter analysis in a series circuit (see Section 3.1).

For the 50 aerodromes considered a total of 5,674,842 METAR data points were analyzed in the 20-year timespan. Appendix B includes a table with detailed output of the operational availability study for all 50 aerodromes based on all METAR data evaluated. As shown in Fig. 3, the operational availability study for the METAR database of 5,674,842 METAR data points shows the following result:

- 4,304,206 data points are operationally available (75.85 %)
- 919,117 data points are not operationally available (16.20 %)
- 451,519 data points are incomplete (7.96 %)

For the approx. 1.37 million data points evaluated as not operationally available or incomplete, a further analysis is conducted to evaluate which parameters mainly cause non-availabilities. As shown in

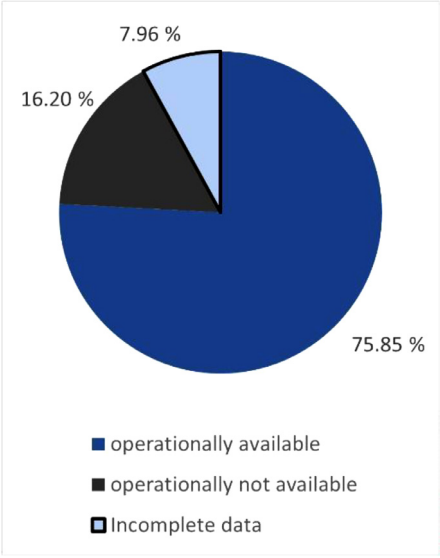


Fig. 3. Operational availability of analyzed METAR data set for all 50 aerodromes in the 20-year timespan (2001-2020)

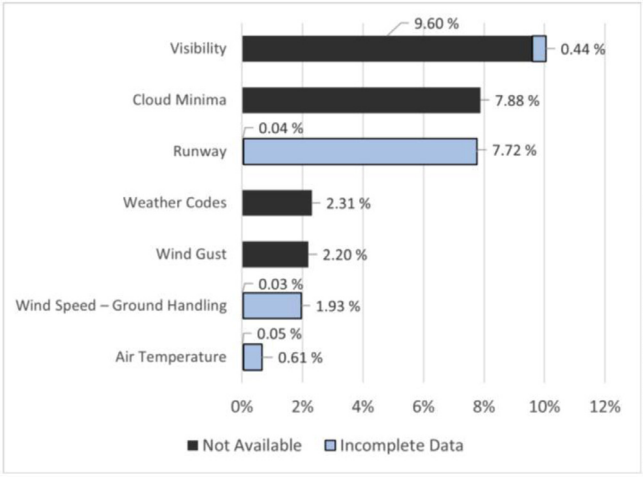


Fig. 4. Operational non-availabilities and incomplete data by parameter of analyzed METAR data set for all 50 aerodromes in the 20-year timespan (2001-2020)

Fig. 4, these parameters are visibility, cloud minima and runway availability which all restrict the operational availability for the described VFR operations with the air taxi. The operational availability for the parameter for "runway" consists of a variety of parameters mandatory for the runway performance calculations (see also Section 4.2.1). Therefore if e.g. air temperature or wind direction data is not provided in the METAR data point, the parameter "runway" is evaluated as "incomplete data".

A complete list of results for the operational availability study of German aerodromes for ODAM is included in Appendix B. Table 5 lists the top eight aerodromes sorted by the highest operational availability, based on the METAR database. These aerodromes do not further enable simple classification, as the aerodromes are very different from each other.

The aerodromes in Table 5 are located all over Germany and vary significantly in aerodrome size, including small airfields northern Germany (Emden (EDWE), Kiel-Holtenau (EDHK)), large international airports (Dõsseldorf (EDDL), Leipzig-Halle (EDDP)) and one aerodrome in southern Germany (Donaueschingen-Villingen (EDTD)). METAR aerodromes with the lowest elevation (EDWE) and highest elevation (EDTD) are also represented in this top eight sample.

The results (see Table 5 and B.1) show that there is a very broad weather data basis for each aerodrome considered in the operational availability study. Aerodromes showing the highest data count are international airports (München, Stuttgart) or (former) military airports with joint civil operations (Frankfurt-Hahn, Fritzlar, Rostock-Laage, Cuxhaven-Nordholz, Niederstetten). Magdeburg-Cochsted is an exemplary aerodrome which only has a small weather data basis of 28,661/175,320 data points considered for the 20-year time period. Therefore, only a small amount of historical data was considered, as other historical METAR weather data was not available.

For these aerodromes, other weather data would be required to have more significant results regarding the operational availability for ODAM. The local METAR weather data collection could be further enhanced by implementing more permanent weather stations also at smaller aerodromes. To enlarge the weather data base ERA5 weather data could be used, which is provided by ECMWF (Eur, 2024). Through atmospheric reanalysis of the global climate, ERA5 data provides an estimation of various weather parameters for the Earth. The data is provided as a grid in various height levels which could enable the analysis for the complete flight trajectory for an historical timespan. Compared to the aerodrome centered analysis provided in this study (METAR data), this would give more significant results for the operational availability of the complete flight trajectory. As described in Section 2, other data collection methods (crowdsensing) could be used in the future to enhance reliable weather information required e.g. for flight planning (Adkins et al., 2020).

Fig. 5 pictures a map of Germany including all 50 analyzed aerodromes considered for this operational availability study. The initial location of the analyzed 50 aerodromes provide generally a good coverage of Germany. Only three regions show poorer coverage by default which are visible in the map: rural areas between Nõrnberg and Kassel, rural areas between Berlin and Hamburg and the south-east border of Bavaria with the Czech Republic.

The results for the operational availability study of German aerodromes for ODAM are also presented in Fig. 5. The aerodromes are marked with diamonds which include a color coding indicating the operational availability of all METAR data analyzed.

In Fig. 5 it is visible that the operational availability for the METAR aerodromes, based on the METAR database are mostly larger than 70 %. In the complete list of evaluation results (see Appendix B) it is notable that that all 50 aerodromes show operational availability of min. 64.15 % (Frankfurt-Hahn airport (EDFH)), while the highest operational availability is reached at Emden airfield (EDWE) with 96.06 % of METAR data analyzed for each aerodrome. Furthermore, it is visible in Fig. 5 that, with the given graphical classification for operational availability of aerodromes, the seven aerodromes with operational availability lower than 70 % tend to be located in southern Germany. Nonetheless, these aerodromes still show an adequate level of operational availability for ODAM operations (min. 64.15 %), but the comparably lower operational availability could cause some flight cancellations and monetary compensations for passengers. It is important to note for these aerodromes other complementary aerodromes are located in the vicinity with higher operational availabilities (e.g. Mõnchen Airport for Ingolstadt or Augsburg, Dõsseldorf or Mn̲nchengladbach for Weeze). Therefore, in general all 50 aerodromes considered in this operational availability study show adequate operational availabilities for ODAM for the METAR data points analyzed within the 20-year timespan.

4.3. Total availability analysis

In a final analysis, the results of the infrastructural availability analysis (Section 4.1.2) and the operational availability analysis

Table 5
List of aerodromes with METAR data (2001-2020) reporting times other than XX:50 h

Aerodrome	Data Count	Operationally Available	Not Operationally Available	Incomplete Data
Emden (EDWE)	46,319	96.06%	3.16%	0.78%
Donaueschingen-Villingen (EDTD)	36,575	87.81%	5.78%	6.41%
Leipzig-Altenburg (EDAC)	78,508	87.67%	4.23%	8.10%
Kiel-Holtenau (EDHK)	132,926	86.63%	9.59%	3.78%
Leipzig-Halle (EDDP)	139,699	85.08%	12.92%	2.00%
Magdeburg-Cochstedt (EDBC)	28,661	83.96%	10.16%	5.88%
Zweibrücken (EDRZ)	60,070	83.93%	7.66%	8.41%
Düsseldorf (EDDL)	139,698	83.56%	12.21%	4.22%

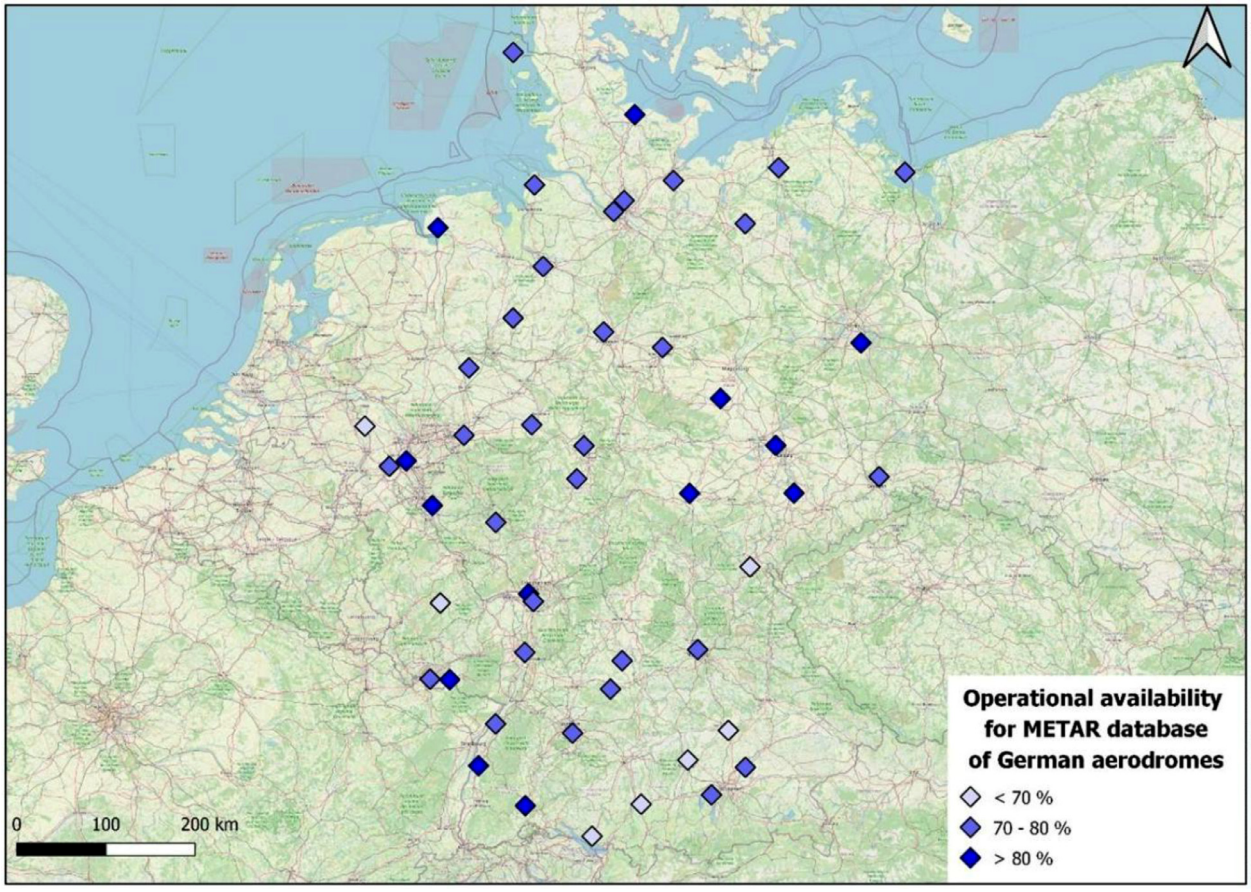


Fig. 5. Operational availability for METAR aerodromes, based on the METAR database

(Section 4.2.2) are combined to evaluate if the air taxi systems are a viable option for future transportation from the point of total aerodrome availability in Germany.

The sample of 50 aerodromes with METAR weather data (see Section 3.4) are used as the baseline for the total availability analysis in this section. Fig. 6 shows the total availability of German aerodromes for the proposed ODAM application. It is visible that a total of 35 German aerodromes remain available, if the results of both the infrastructural and operational analysis are combined, and all restrictions are considered.

Seven aerodromes are infrastructurally not available due to Level 3 coordination compared to the initial sample of 50 German aerodromes. The infrastructural unavailability for only eight aerodromes is caused by the unavailability of compatible fueling services or inadequate operating times. Both could be provided without major infrastructural changes, by extending the operating times and providing mobile fueling trucks, as described in Section 4.1.2. Therefore, these aerodromes are additionally depicted in the Fig. 6, which would increase the number of German aerodromes available for ODAM to 43 out of 50 considered (see Appendix C for the list of infrastructurally not available aerodromes).

In comparison to the operational availability results (see Fig. 5), the total availability results in Fig. 6 further provide a fairly good coverage of Germany. However, the non-availability of level 3 coordinated airports Berlin, Hannover and Stuttgart cause new regions with poorer coverage which are visible in the map: the area between Augsburg and Karlsruhe (including Stuttgart metropolitan area), the area between Paderborn and Hamburg (including Hannover metropolitan area) and a large area in north-east Germany (including Berlin metropolitan area). The poorer coverage in these new regions is caused by the non-availability of other aerodromes in the vicinity by default, as the number of METAR aerodromes considered are limited.

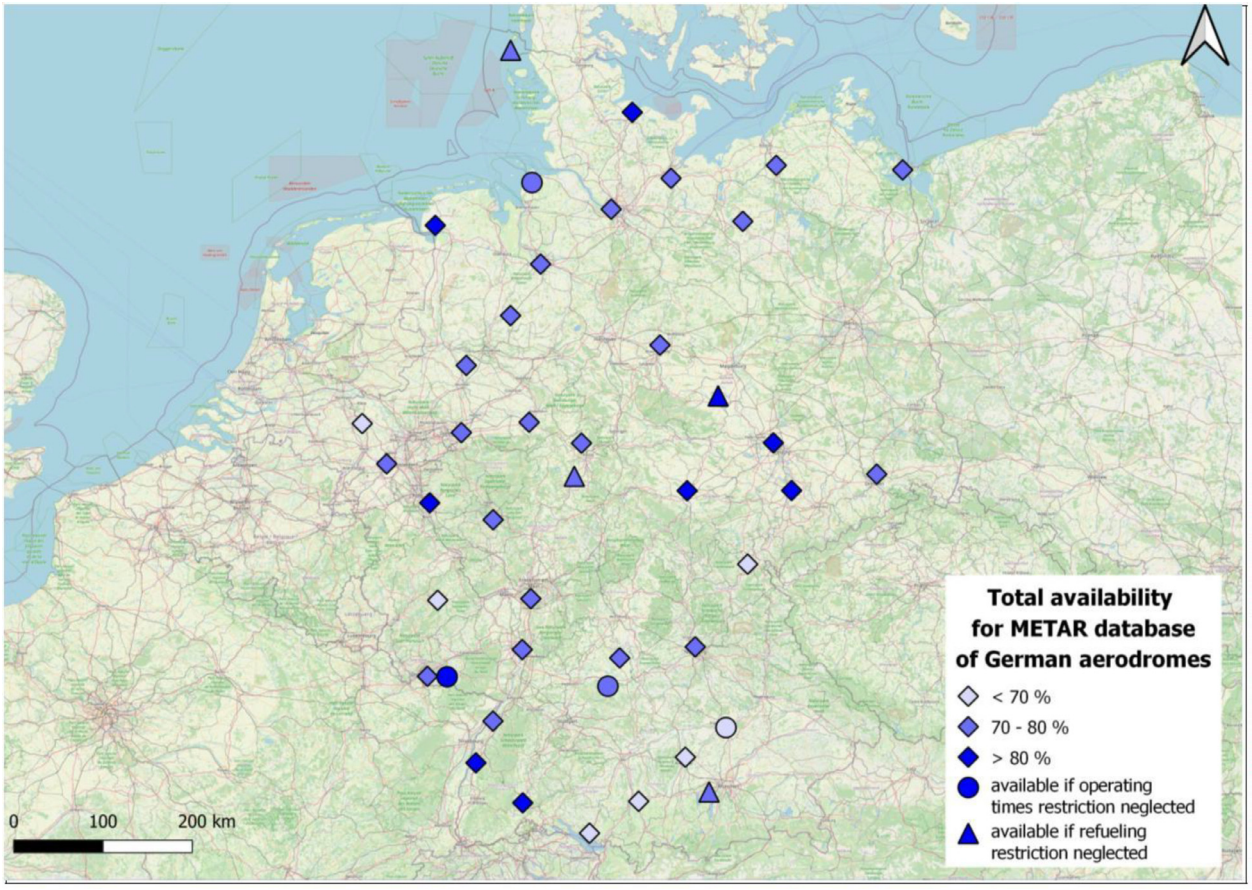


Fig. 6. Total availability for METAR aerodromes, based on the METAR database

Nonetheless, these regions could possibly be available for future ODAM transport, as Fig. 2 shows that there are up to 306 infrastructurally available aerodromes in Germany. The operational availability of the excluded aerodromes is comparably high as shown in Fig. 5. With the assumption that weather conditions do not significantly change in the vicinity of the analyzed METAR aerodromes, it is expected that many of the 306 aerodromes show similar results for operational availability. To definitively evaluate this assumption, a case-by-case analysis would be required for these additional aerodromes, only possible with further historical weather data basis which should be available also for small aerodromes. As described in Section 4.2.2, the usage of ERA5 weather data or other new data collection frameworks would be a valid option to consider in future works. If these additional aerodromes show high total availability, the possible network of German aerodromes for ODAM operations would be further enlarged.

5. Conclusion and outlook

This paper provides an analysis of the infrastructural, operational, and total availability of German aerodromes for ODAM. In comparison to previous works, specific aircraft performance data of a hybrid-electrical fixed-wing air taxi design was used for the analysis. Together with other input data (e.g. aerodrome database and METAR weather data), this provided the possibility to conduct a more in-depth availability analysis for the aerodromes with an emphasis on operational performance data. Furthermore, the analysis was conducted in Germany as in other works a significant ODAM market potential was demonstrated there and a current lack of European use cases was shown.

The integration of new ODAM into existing aerodromes was identified as a relevant issue, as the infrastructural availability results show up to 306 (69.2 %) German aerodromes currently being infrastructurally available for ODAM. The main parameters causing non-availability for this analysis were identified as operating times and refueling possibilities. The operational availability analysis showed that the majority of the 50 aerodromes considered show high operational availability. The parameters visibility, cloud minima and runway operability were identified as the key parameters causing non-availability. Nonetheless, 75.85 % of the investigated historical time points at the aerodromes all over Germany were operationally available according to the weather data analysis. Combining the infrastructural and the operational availability, a total availability for up to 43 German aerodromes was shown which provide evenly coverage of Germany. Only three major regions within Germany were identified with poorer availability of aerodromes for ODAM.

All in All, considering the location of the 43 German aerodromes the results of the total availability analysis show that the current aerodrome system in Germany already provides a significant network of infrastructurally and operationally available aerodromes for future ODAM operations with fixed-wing aircraft. This underlines the readiness of German aerodromes and provides the baseline for the possibility to use ODAM in Germany to contribute to reach the ambitious goals of Flightpath 2050.

Due to the research design, not all infrastructurally available airports could be analyzed for operational availability, as METAR weather data are only procurable for a smaller sample. It is expected that more German aerodromes are available for ODAM. Considering the limitations of this work, further research with a larger weather data basis is required to demonstrate the nationwide high operational availabilities. There-

fore, it was identified that METAR weather data collection should be further enhanced by implementing more permanent weather stations in particular at smaller aerodromes. ERA-5 weather data could provide a vital source to enhance the significance of current results and provide a possibility to further analyze the operational availability for complete flight-trajectories. Further, this work was solely based on the analysis of VFR operations for ODAM. The usage of IFR operations for the air taxi service could enhance the operational availability as the influence of visibility and cloud minima (limiting parameters) could be mitigated. It would be important to find out whether new limitations would emerge. Lastly, as many air taxis are still in development, this framework could be applied to other air taxi designs, other weather data and aerodrome systems as well, to evaluate the readiness for ODAM with fixed-wing aircraft for different regions worldwide. In terms of availability, the next step is to examine the en-route part of the various routes. It is important to evaluate the extent to which the requested routes are available for a particular aircraft configuration due to weather conditions, whether there are alternative routes and what technical improvements can be made to increase the availability en-route. A high degree of route flexibility and availability is particularly important for the ODAM application. The availability of the aerodromes can then be combined with the en-route availability and an overall statement can be made for the route. Future operators can use this to assess whether they can operate a route profitably.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Mert Çakır: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Juliane Rösing:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Investigation. **Lutz Wortmann:** Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Formal analysis, Methodology.

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Appendix A. Air taxi information

The increase of take-off distance (TD) and landing distance (LD) are modeled with the followings equations, were T is the actual air temperature at airport elevation:



Fig. A1. Air taxi designed with MICADO

Table A1
Surcharges for specific runway conditions(Takeoff)

	Takeoff	
Runway condition	Additional distance	Resulting distance
Slope	$\Delta slope$: per 1 % slope +10 % of $TD_{X°C}$	$TD_1 = TD_{X°C} + \Delta slope$
Gras (dry)	Δgrasdry +20 % of TD_1	$TD_2 = TD_1 + \Delta grasdry$
Gras (wet)	Δgraswet +10 % of TD_2	$TD_3 = TD_2 + \Delta graswet$
Water	$\Delta water$ +30 % of TD_3	$TD_4 = TD_3 + \Delta water$
Snow	$\Delta snow + 50\%$ of TD_4	$TD_5 = TD_4 + \Delta snow$
Headwind	$\Delta wind$: Per 12 kts headwind -10 % of TD_5	$TD_6 = TD_5 + \Delta wind$
Tailwind	$\Delta wind$: Per 2 kts tailwind +10 % of TD_5	$TD_6 = TD_5 + \Delta wind$

Table A2
Surcharges for specific runway conditions (Landing)

	Landing	
Runway condition	Additional distance	Resulting distance
Slope	$\Delta slope$: per -1 % slope +10 % of $TD_{X°C}$	$LD_1 = LD_{X°C}$
Gras (dry)	$\Delta grasdry$ +20 % of LD_1	$LD_2 = LD_1 + \Delta grasdry$
Gras (wet)	$\Delta graswet$ + 10 % of LD_1	$LD_3 = LD_2 + \Delta graswet$
Water	$\Delta water + 30\%$ of LD_3	$LD_4 = LD_3 + \Delta water$
Snow	$\Delta snow + 50\%$ of $LD4$	$LD_5 = LD_4 + \Delta snow$
Headwind	$\Delta wind$: Per 12 kts headwind -10 % of LD_5	$LD_6 = LD_5 + \Delta wind$
Tailwind	$\Delta wind$: Per 2 kts tailwind +10 % of LD_5	$LD_6 = LD_5 + \Delta wind$

$$TD_{15°C}(m) = 468m + 0.0155 * elevation(ft) \quad (A.1)$$

$$TD_{X°C} = TOD_{15°C}(m) + 2.05 * (T(°C) - 15°C) \quad (A.2)$$

$$LD_{15°C}(m) = 524m + 0.0049 * elevation(ft) \quad (A.3)$$

$$LD_{X°C} = LD_{15°C}(m) + 1.97 * (T(°C) - 15°C) \quad (A.4)$$

Appendix B. Operational availability study results, based on all METAR data evaluated

*Data Count: Number of METAR weather data procured for the defined historical timespan (2001-2020)

Table B1
Operational availability study results, based on all METAR data evaluated, sorted by highest operational availability

Aerodrome	Data Count*	Operationally Available (%)	Aerodrome	Data Count*	Operationally Available (%)
EDWE	46,319	44,496 (96.06%)	EDOP	72,707	54,374 (74.79%)
EDTD	36,575	32,117 (87.81%)	EDLP	148,166	110,777 (74.77%)
EDAC	78,508	68,828 (87.67%)	ETNL	170,243	126,773 (74.47%)
EDHK	132,926	115,156 (86.63%)	EDDN	139,671	103,897 (74.39%)
EDDP	139,699	118,861 (85.08%)	EDHI	84,736	62,646 (73.93%)
EDBC	28,661	24,064 (83.96%)	EDFE	58,803	43,382 (73.78%)
EDRZ	60,070	50,415 (83.93%)	EDDM	174,401	128,620 (73.75%)
EDDL	139,698	116,737 (83.56%)	EDDG	139,728	102,913 (73.65%)
EDDE	132,277	109,475 (82.76%)	EDDS	164,177	120,698 (73.52%)
EDDF	139,648	113,947 (81.60%)	EDDR	139,659	102,659 (73.51%)
EDDB	139,687	113,715 (81.41%)	EDDH	139,562	101,736 (72.90%)
EDTL	113,773	92,003 (80.87%)	ETMN	169,294	122,077 (72.11%)
EDDK	139,552	112,769 (80.81%)	EDAH	65,360	47,108 (72.07%)
EDDC	139,725	111,497 (79.80%)	EDTY	37,223	26,737 (71.83%)
EDLW	131,646	103,817 (78.86%)	EDLN	108,265	77,622 (71.70%)
ETHN	167,457	131,813 (78.71%)	EDHL	84,694	60,689 (71.66%)
ETHF	170,419	133,066 (78.08%)	EDGS	82,707	58,892 (71.21%)
ETND	69,733	54,014 (77.46%)	EDMO	63,436	44,573 (70.26%)
EDDV	139,626	107,652 (77.10%)	ETSI	99,250	69,226 (69.75%)
EDXW	99,487	76,667 (77.06%)	EDJA	88,326	60,743 (68.77%)
EDDW	139,590	107,368 (76.92%)	EDMA	124,630	85,509 (68.61%)
EDSB	143,211	109,365 (76.37%)	EDLV	105,714	72,503 (68.58%)
EDFM	86,511	65,786 (76.04%)	EDQM	95,440	62,675 (65.67%)
EDVE	71,034	53,369 (75.13%)	EDNY	147,952	95,525 (64.56%)
EDVK	111,535	83,657 (75.01%)	EDFH	173,331	111,198 (64.15%)

Appendix C. Infrastructurally not available METAR aerodromes in Germany

Table C1
List of aerodromes included in the METAR database with causes for infrastructural unavailability for air taxi operations

	Infrastructurally unavailable due to: Aerodrome	Level 3 coordination	Operational times	Refueling is not available / no info
Berlin Brandenburg	X			
Duesseldorf	X			
Frankfurt-Main	X			
Fritzlar		X		
Hamburg	X			
Hamburg-Finkenwerder		X		
Hannover	X			
Ingolstadt/Manching		X		
Magdeburg/Cochstedt		X		
Muenchen	X			
Nordholz		X		
Oberpfaffenhofen		X		
Schwaebisch Hall		X		
Stuttgart	X			
Zweibruecken		X		

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