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A method to determine the availability and performance of fixed-wing air taxis in real weather conditions for regional air mobility within Germany

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Abstract

The success of an on-demand air taxi transportation system depends, in part, on its availability during daily operations. To further analyze such a system, this paper introduces a method for determining the availability and performance of air taxis under real weather conditions. In the availability analysis, mainly the fulfillment of the visual meteorological conditions minima (VMC) is investigated, and in the performance analysis, it is checked if the performance is sufficient to operate in the given weather conditions. Therefore, the integration of weather data from the European Center for Medium-Range Weather Forecast (ECMWF) and real trajectories into the mission analysis tool of the aircraft preliminary design software Multi-disciplinary Integrated Conceptual Aircraft Design and Optimization Environment (MICADO) for small aircraft is carried out for the first time. This allows the estimation of the performance of air taxis under real weather and operating conditions already at the aircraft preliminary design stage and potential technical deficits can be identified at an early design stage. Two single engine, fixed-wing air taxi designs, one with a hybrid-electric powertrain and one with an all-electric powertrain, are investigated in this paper. The results show that the availability is strongly limited by the VMC minima). The maximum availability of the short reference flight route between Nuernberg and Egelsbach is 41.78 % and the maximum availability of the long reference flight route between Augsburg and Moenchengladbach is 20.48 %. The availability of the hybrid-electric air taxi is not limited, as all investigated flights under sufficient VMC can be performed with this aircraft while complying with the required reserves. However, the availability of the all-electric air taxis is limited due to its performance. Because of adverse wind conditions, not all flights investigated under sufficient VMC can be performed with the all-electric air taxi while complying with the required reserves, as the energy demand is too high. For the all-electric air taxi operating on the short reference flight route, a 13.2 % increase in gravimetric battery energy density (GBED) is needed to ensure sufficient performance. The findings indicate the necessity of considering the real operating conditions in the preliminary design of small aircraft.

Keywords Availability · Air taxi · Weather conditions · Fixed wing

1 Introduction

The development and entry into market of hybrid- and all-electric small aircraft is progressing steadily. For example, the Pipistrel Velis Electro is already in service and the Diamond eDA40 will be presented to the public in 2024 [1, 2]. Furthermore, there are a variety of conceptual studies and prototypes for hybrid- and all-electric small aircraft for regional air taxi services. A common feature of these aircraft designs is that, at least in the first stage of development, they are designed to operate under visual flight rules (VFR) while fulfilling the VMC minima in lower airspace. Under these operating conditions, the availability and performance

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of these air taxis is strongly affected by external influences due to adverse weather conditions. In this paper, a method to determine the availability and the performance of hybrid- and all-electric air taxis in real weather conditions on reference routes within Germany is shown. In this context, availability refers to the availability of the flight route and is defined as the ratio of the number of actual performed flights to the initial planned flights. The aircraft itself and the infrastructure of the airport are assumed to be available at all times. In this analysis, any aircraft downtime due to scheduled or unscheduled maintenance is not considered. Utilizing the results of this method, possible technical deficits and approaches to optimize these air taxis can be derived.

2 Fundamentals

At first, a literature review was conducted with the focus on the market potential and the availability of small fixed-wing aircraft.

Regional air mobility (RAM) is like urban air mobility (UAM), a part of the advanced air mobility (AAM) [3]. In the UAM field, intracity services with vertical takeoff and landing aircraft are considered. In the RAM field, the focus is on regional short-haul routes and intercity services. Here, fixed-wing aircraft are predominantly considered as air taxis in on-demand operation to achieve greater efficiency on the longer crusing distances compared to UAM [4].

Research of the Sun et al. [5] and Kreimeier [6] show a high market potential for RAM within Germany. Kreimeier [6] states that 96 % of the potential routes have a distance of less than 500 km. The focus here is on connections between smaller airports that are not necessarily IFR-equipped. Sun et al. [5] show that a travel time advantage in comparison to ground transportation or commercial airliners can be achieved on routes with a distance between 100 km and 500 km . Neither Kreimeier [6] nor Sun et al. [5] consider the impact of weather conditions. Studies on the influence of weather conditions on the availability of air taxis in the field of UAM were carried out by Reiche et al. [7], Chao et al. [8], and Sharma et al. [9]. In these studies, the availability of UAM aircraft across various regions within the U.S. is analyzed, utilizing meteorological aerodrome report data (METAR) from U.S. airports. The findings from this are that the availability is strongly influenced by the weather conditions and that the flyable hours under VFR are in part greatly reduced. In addition, a strong regional dependency is found due to different weather conditions in each region.

Crawford et al. [10] conducted investigations into the influence of meteorological conditions on the availability of RAM in various operational use cases within the U.S. Their study examined how weather-related factors affect the range limitations of electric aircraft by incorporating a variable energy reserve into the flight range analysis. Therefore, real routes of three regional airlines in USA were analyzed. They found that as weather conditions become more restrictive, the actual operational range of an aircraft decreases. The analysis of the aircraft performance is limited to the influence of the wind and the required reserves.

Cakir et al. [11] carried out investigations on the availability of German airports for operations with small fixed-wing air taxis. The determination of VFR availability was based on an analysis of METAR data. This investigation shows that the availability at German airports is reduced by unsuitable weather conditions.

The literature research has shown that further research activities on the influence of weather conditions in the RAM area in Germany should be carried out. Since a high market potential was predicted and the previous work largely uses the U.S. as use case or is limited to research on the availability of airports. In terms of performance analysis, previous studies are focused on the influence of wind and are neglecting the effects of precipitation and insect contamination.

Therefore, in this paper, a method to determine the availability and the performance of fixed-wing air taxis for RAM in Germany is developed. The entire route, consisting of the approach, departure, and the enroute segment, is considered. In addition, the influences of precipitation and insect contamination are taken into account in the performance analysis. The focus on VFR operations can be explained by the fact that a high market potential is seen for connections between small VFR-only airports [6], and that aircraft manufacturers such as Eviation [12] are developing in the first design stage aircraft for VFR operations.

In the following, the fundamentals to determine the availability and performance of air taxis in real weather conditions are summarized. These include weather data, trajectory data, and the used aircraft reference designs.

2.1 Weather data

The weather data used for the studies are reanalysis data from the ECMWF. The so-called ERA5 dataset has several characteristics that make it suitable for the analysis conducted [13]. They are globally available, whereas the area considered for this study is limited to $47^\circ - 56^\circ$ N in latitude and $5^\circ - 16^\circ$ E in longitude. In addition to a horizontal spatial resolution of 0.25° in longitude and latitude, numerous parameters of the ERA5 dataset also have a vertical resolution which is based on pressure-based model levels. Their spacing increases with altitude; meteorological data are available on 40 model levels up to an altitude of 5000 m, which corresponds to the height up to which the raw data were processed. For the given latitude and longitude range and spatial resolution, this corresponds to a horizontal grid size of 36×44 and to a horizontal distance between the grid points of 27.25 km in latitude and 15.52–18.92 km in longitude. The lowest model level is situated in close proximity to the Earth's surface, and the vertical spacing between two neighboring levels undergoes fluctuations over time. However, on the basis of a randomly chosen sample set, the average vertical distance between two neighboring model levels is about 20 m near the surface of the earth and about 200 m at an altitude of approx. 3 km. The entire grid consists of 63,360 grid points. The ERA5 data are available from 1940 to 5 days behind real time. The 20-year interval from 2001 to 2020 is taken into account for the performed analysis. Hourly data resolution is available over the entire observation period. Overall, the downloaded meteorological parameters provide all necessary information to describe the atmospheric state as needed for the availability analysis described in Sect. 3.2. A list of all parameters can be found in Table 6 in appendix A. Information regarding the acquisition of ERA5 data, its processing, and specific meteorological parameters can be found in [14].

2.2 Aircraft reference designs

For this study, an air taxi with a hybrid-serial powertrain (hybrid air taxi) and one with an all-electric powertrain (all-electric air taxi) is used. These air taxis in fixed-wing configuration are designed using MICADO for small aircraft according to EASA CS-23. MICADO is developed and evolved by the Institute of Aerospace Systems (ILR) of the RWTH Aachen University. In MICADO, it is possible to design an aircraft according to given top level aircraft requirements (TLAR) within minutes. Subsequently, various post processing tools can be used to analyze and evaluate the results. Further information on the functionalities of MICADO for small aircraft can be found in [6, 15]. Both air taxis are based on a previous designed Cirrus SR22T with a conventional powertrain. This baseline design is adapted according to the TLAR shown in Table 1.

The wing loading W/S = 121.3 kg/m^2 and the power-to-mass ratio P/M = 0.1439 kWkg^{-1} are equal for both air taxis and are based on the design of the Cirrus SR22T [16]. The hybrid air taxi is designed for a range of 550 km and the all-electric air taxi for a range of 210 km. The duration of the holding segment, which can be flown in addition to the above given range, is 45 min and it is flown with 55 % of the maximum available power. The maximum takeoff mass (MTOM) is limited to 2000 kg, as a registration in Echo-Class (Germany) should be possible. This limitation can in case of the all-electric air taxi only be fulfilled with a reduced cruise speed of 200 km/h. The cruise speed of the hybrid air taxi is 240 km/h to gain an advantage in travel time in comparison to other modes of transport (e.g., train, MPT, and airliner) [17]. The passenger capacity for both air

Table 1 Air taxi TLAR

Parameter	Requirements	
	Hybrid	All-electric
Design Range (DR) [km]	550	210
Holding (55% Power) [min]	45	45
PAX [-]	4	4
Cruise speed [km/h]	240	200
Max. takeoff mass [kg]	≤ 2000	≤ 2000
Takeoff/Landing distance [m]	≤ 700	≤ 700
Wing loading [kg/m^2]	121.3	121.3
Power to mass ratio [kW/kg]	0.1439	0.1439

Table 2 Air taxi characteristics

Parameter	Hybrid	All-electric
MTOM [kg]	1364	1978
OEM [kg]	921	1614
Payload [kg]	364	364
Fuel mass (range + holding) [kg]	79	0
Fuel tank capacity [kg]	124	0
Wing span [m]	10.1	12.8
Wing area [m^2]	11.2	16.2
Max. glide ratio cruise [-]	15.1	19.7
Hybridization degree [%]	10	100
Nominal power E-Engine [kW]	196.2	284.0

Table 3 Selected flight routes within Germany

Flight route		Distance [km]
EDFE - EDDN	Short route	187–205
EDMA - EDLN	Long route	510–521

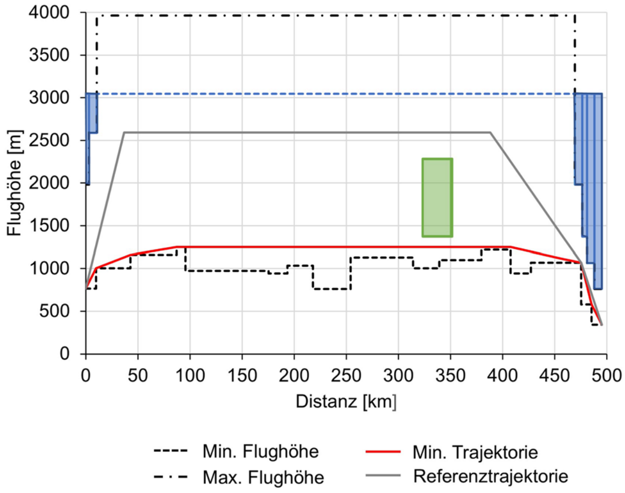

Fig. 1 Vertical trajectory of the long route from Augsburg to Moenchengladbach (between CRP)

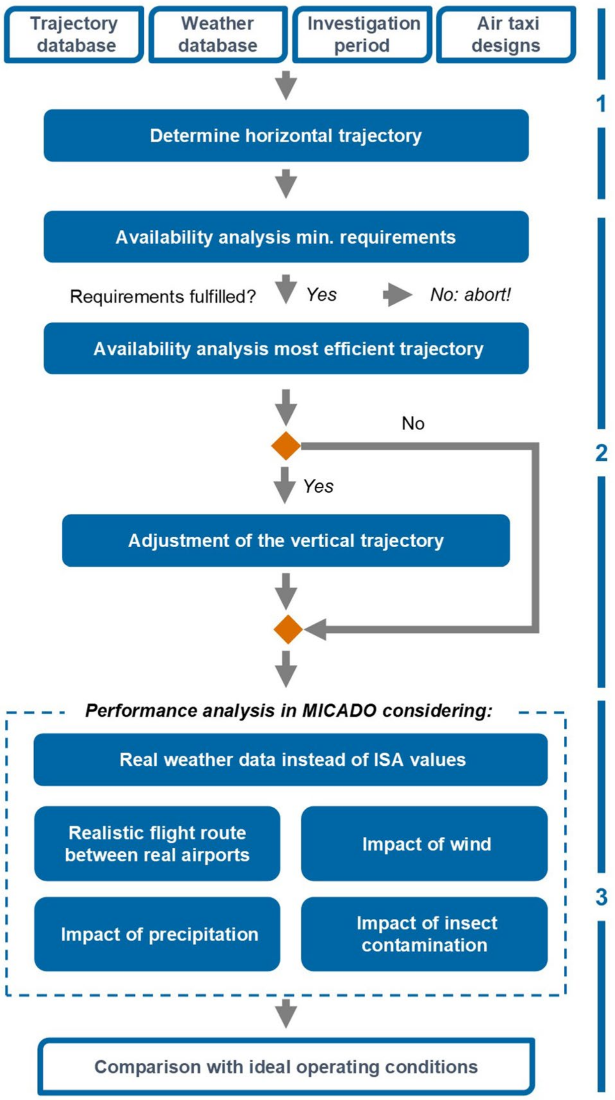

Fig. 2 Overview process to determine the availability and performance characteristics

taxis is four including one pilot. To ensure the operation on regional airports with short runways, the takeoff and landing distance has to be shorter than 700 m. The used airfoil for both designs is an NLF0414F with natural laminar flow characteristics. The design results for the hybrid and all-electric air taxi are shown in Table 2. Further details on the design process of the hybrid air taxi are given in [17].

2.3 Trajectory data

The availability is estimated using predefined flight routes within Germany. For the determination of the horizontal and vertical trajectory, each flight route is divided into three segments: departure, enroute, and arrival segment. This is necessary as the active runway direction is depending on the wind direction and according to the Aeronautical Information Publication (AIP) for VFR different departure and approach procedures have to be used [18]. This result in different horizontal trajectories for each flight route. The departure segment extends from the runway threshold of the departure airport to the used compulsory reporting point (CRP) and the arrival segment extends from the used CRP to the runway threshold of the arrival airport. The enroute segment results as the connection of the CRP. The information about the departure and arrival procedures is stored in an arrival and departure trajectory database. This database contains information about the coordinates of the way points, the distance from or to the threshold of the runway, the minimum and maximum permissible altitude at each way point, and the altitude at each way point resulting from climb with a constant rate of climb to overfly the CRP at a requested altitude. In this case, a way point is a point on the trajectory where either the true course or the glide slope is changing. The definition of the enroute segment is made considering the airspace structure in the lower airspace in Germany. Highly frequented airspaces (e.g., approach sector of Frankfurt Airport) will most likely not be available for VFR traffic at anytime. As a conservative estimation, all controlled airspaces will be circumnavigated. After defining the horizontal trajectory, the vertical trajectory is estimated considering the minimum safe altitude (MSA), the airspace structure, and the most efficient vertical trajectory for the given air taxi. In a previous work of the authors, a selection of ten flight routes between 11 airports is made considering the passenger demand [17]. From these ten routes, the longest flight route between Augsburg (EDMA) and Moenchengladbach (EDLN) as well as the shortest flight route between Egelsbach (EDFE) and Nuernberg (EDDN) have been selected as reference flight route to show the results of the developed method. The selected flight routes are shown in Table 3. The distance of the short flight route between Egelsbach and

Nuernberg varies between 187 km and 205 km. A flight can be operated with both the hybrid and the all-electric air taxi. A flight along the long flight route from Augsburg to Moenchengladbach can only be operated using the hybrid air taxi. This flight route is with a distance of up to 521 km longer than the design range of the all-electric air taxi. Figure 1 shows as an example the vertical trajectories of the long flight route between Augsburg and Moenchengladbach.

The vertical trajectory with lowest possible altitude (Min. trajectory) is designed following the MSA. The reference trajectory (Ref. trajectory) is determined according to a parameter study and is the trajectory with lowest CO_2 emissions [17]. In the parameter study, the trade-off between energy savings at higher cruising altitudes with increased aerodynamic efficiency and the energy required to reach a given altitude is investigated. For the trajectory shown in Fig. 1, the Ref. trajectory is valid for the hybrid air taxi. The cruise altitude is chosen using the cruising levels according to the Standardised European Rules of the Air (SERA) [19]. In this example, the cruise altitude of the Ref. trajectory for the flight between Augsburg and Moenchengladbach is 8500 ft. Every cruising level between the Ref. trajectory and the Min. trajectory is usable. Further information about the determination of the Ref. trajectory for the hybrid air taxi can be found in [17].

Compared to the hybrid air taxi, the all-electric air taxi operates at a reduced cruising speed and the most efficient cruising altitude is reduced to 3300 ft, which is the cruising altitude of the Min. trajectory for the flight routes between Egelsbach and Nuernberg (see Fig. 17). The information about the defined enroute flight routes is stored in an enroute trajectory database. This database contains information about the coordinates of the way points, the distance from the CRP at each way point, the minimum and maximum permissible altitude at each way point, and the altitude of the Min. and Ref. trajectory.

At this point, we can conclude that for a given horizontal trajectory, there can be multiple vertical trajectories.

3 Methods

In this section, the method to determine the availability and the performance of air taxis in real weather conditions is explained. This method can be divided into the three steps determination of the horizontal trajectory, availability analysis, and performance analysis. The process of the method is displayed in Fig. 2.

The first two steps are performed using MATLAB scripts and the third step is made in the mission analysis module of MICADO for small aircraft. Inputs are the weather and trajectory database as well as the investigation period and the air taxi designs. The investigation period consists of several investigation times which can be every hour of each day in the period between 2001 and 2020. The process described in the following is performed separately for each investigation time.

3.1 Step 1: Determination of the initial trajectory and discretization

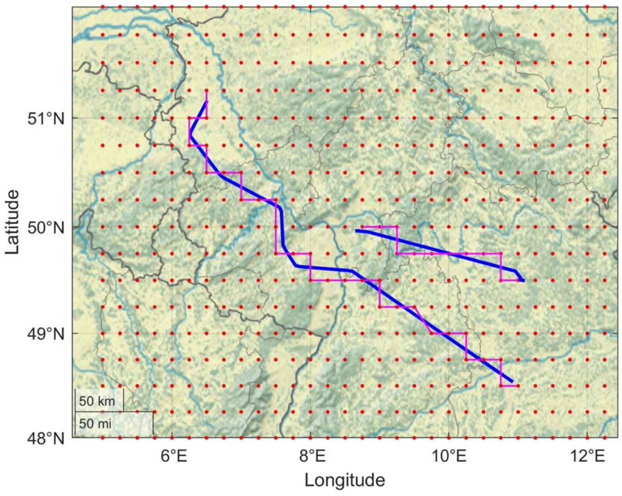

Fig. 3 Grid resolution (red dots), horizontal trajectories (blue lines), and used nearest grid points (magenta lines) for the short and long route

The horizontal trajectory has to be defined for each investigation time using the predefined departure, enroute, and arrival trajectories as described in Sect. 2.3, because the used trajectory is depending on the wind direction. According to the active runway at the departure and arrival airport, the departure and arrival trajectories are chosen. The enroute trajectory results as connection between the CRP of the used approach and departure trajectories. After determining the horizontal trajectory, the associated vertical trajectories (Min. trajectory and Ref. trajectory) can be taken from the trajectory database.

Since the weather data must be obtained at discrete points, the definition of the trajectory is followed by a discretization with an defined step size of 5 km. This is set to ensure a sufficiently accurate coverage of the weather data with moderate computational effort. At each discrete point, the longitude, latitude, distance to the departure airport, altitude of Min. and Ref. trajectory, and the heading are calculated and the weather data are provided. The discretized trajectory is used as input for the availability analysis in step 2. The trajectory and weather data are transferred in a database.

3.2 Step 2: Availability analysis

The procedure of the availability analysis for a certain discretized trajectory can be divided into three steps. First, the availability analysis under consideration of the minimum

Table 4 Weather parameters used for the performance analysis

Parameter	
Density	Temperature
Pressure	Pressure sea level
Wind speed	Wind direction
Liquid water content	

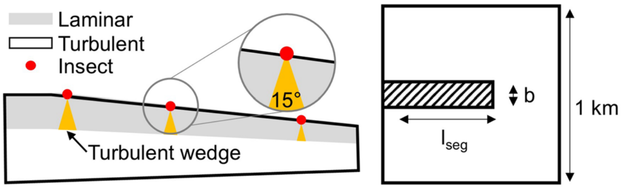

Fig. 4 Left: insect contamination on wing; right: potential impact volume in relation to reference volume

requirements is performed. Second, the availability analysis at the most efficient trajectory is conducted. Third, in case the Ref. trajectory is unavailable, the vertical trajectory is adjusted. In this context, minimum requirements means that a flight along the Min. trajectory considering VMC minima according to SERA [19] is investigated. The availability analysis at minimum requirements can also be divided into three main steps. First, the weather conditions at each discrete point at the investigation time are determined. Therefore, in addition to the weather data, the discretized trajectories including the coordinates (latitude–longitude–altitude) of every route point are required. Considering this information, the nearest grid point of the ERA5 data grid is determined for each discrete point. The weather data at this grid point are assigned to the discrete point. This procedure is used, because spatial interpolation can lead to large deviations for some weather parameters (e.g., wind speed from opposite direction) and a uniform method should be used [14]. The horizontal trajectories for the long and the short route and the used nearest grid points are shown in Fig. 3.

The second step includes the evaluation of the defined incident categories at each route point at the investigation time. Specifically, the categories of temperature, visibility, cloud cover, wind, icing, and precipitation (water level height on the runway) are monitored. As the exact distribution of the cloud in a grid cell is not given in the ERA5, data assumptions are made to investigate the fulfillment of the VMC minima. For the airports, the main cloud ceiling (coverage ≥ 0.5) has to be 2000 ft above the ground level and for the enroute segment vertical separation of 1000 ft between main cloud ceiling and current altitude is assured. For coverage below 0.5, it is assumed that it is possible to circumnavigate latterly around the clouds with negligible increase in distance. Taking into account the defined limits of each category, their compliance is checked by comparing them with prevailing conditions of the real atmosphere. It is determined for the given investigation time for each discrete point whether an operation is feasible or not and which incident category causes a possible unfeasibility. A list of the categories including the associated limits can be found in the appendix A. Finally, exact values of the route availability are determined from the results of step 2. This is carried out by evaluating the availability of every discrete point for the investigation time including departure and arrival airport. Only if, at a point, the limits of any incident category are not exceeded, this discrete point is available. The entire route is available when each discrete point including departure and arrival airport is available. Thus, the total availability of the route over the entire investigation period, the impact of each considered incident category, and the availability depending on certain investigation times and intervals are calculated.

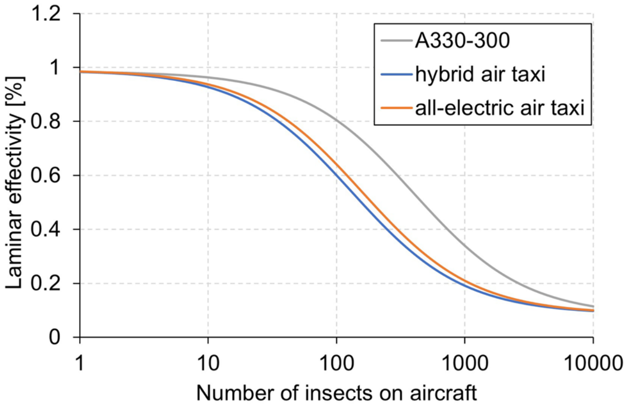

Fig. 5 Laminar effectivity [%] in dependence of the number of insects on the aircraft. Adapted from [30]

If the availability at minimum requirements is not given, the flight cannot be performed at this investigation time and the process to determine the availability and performance is aborted.

If the availability at minimum requirements is given, the flight can be performed at this investigation time and the availability analysis of the most efficient vertical trajectory is carried out. This analysis follows the same procedure as mentioned above for the availability at minimum requirements. If the availability at the most efficient vertical trajectory is not given, the vertical trajectory is adjusted and the availability at trajectories with cruising levels between the cruising altitude of the min and the Ref. trajectory are investigated. Here, a constant cruise altitude is used and step climbs and descends are not considered. As mentioned in Sect. 2.3, the most efficient trajectory is depending on the aircraft, the cruise altitude, and the cruise speed. For the performance analysis described in step 3, the most efficient of the available trajectories is selected for the respective investigation time.

3.3 Step 3: Performance analysis

After the flight route availability is given according to the VMC minima, the determination of the flight performance parameters at the selected trajectory and the given weather conditions is conducted in the performance analysis.

The performance analysis is an extension of the existing MICADO module *missionAnalysis*. In *missionAnalysis*, the predefined mission is divided into mission segments, and for each segment, the required thrust to maintain in a steady flight condition is determined based on the force equilibrium. Based on the required thrust, the required energy demand can be calculated. In addition to the energy demand, several other flight performance parameters (e.g., flight time) are estimated [6, 15]. In the past, the calculations in *missionAnalysis* are made using the International Standard Atmosphere (ISA) and a generic trajectory. The impacts of environmental factors like wind, precipitation, and insect contamination have been neglected. The following section explains the integration of real weather and trajectory data as well as the methods used to determine the effects of the environmental factors.

Within the performance analysis, a real trajectory considering the airport elevation, the departure and arrival routes, the topography, and the airspace structure in Germany is used for the calculation in *missionAnalysis*. Furthermore, the calculations are made using real weather data instead of values from the ISA. Therefore, the weather data are retrieved from the weather database for each mission step. The used parameters are shown in Table 4. [13] The liquid water content (LWC) is calculate by multiplying the specific rain water content with the density of the moist air.

Impact of wind The speed of the air taxi measured with respect to the ground is influenced by the wind. This ground speed is determined from the wind speed, wind direction, the airspeed, and the track using the relation from the MATLAB function *driftcorr* [20]. The heading and correction angle are determined in addition to the ground speed. From this, an air range (AR) and a ground range (GR) can be determined for each segment. The GR is the distance that has to be flown to accomplish the mission and the AR is the distance flown in relation to the air at the same time. An increased AR leads to an increase in energy consumption and flight time.

Impact of precipitation Precipitation on the wing leads to a change in its aerodynamic characteristics. Numerical and experimental investigations demonstrate that except for high angles of attack, the lift is decreased and the drag is increased. The changes of the lift and drag are highly dependent on the airfoil an the amount of precipitation [21–23]. However, complex numerical and experimental investigations of the impact of precipitation on the airfoil characteristics are not feasible in the preliminary design stage. Flight test has shown that atmospheric particles (primarily ice crystals in high clouds) on the leading edge of the wing lead to a partially or fully a loss of the laminarity. The losses are limited to the time when the aircraft is within the clouds [24]. Pohya et al. [25] used this to estimate the efficiency of aircraft with hybrid laminar flow control when flying in cirrus clouds. Hence, in the used method, the increase in drag is realized by a transition from laminar to full-turbulent flow with the assumption that the laminarity is lost when flying through precipitation outside of clouds. The decrease in lift is not considered. Once the air taxi flies through a precipitation zone, the flow over the wing is assumed to be fully turbulent from the leading edge onward and a turbulent polar is used to determine the drag coefficient. After passing through the precipitation zone, it is assumed that the wings will dry out and a laminar flow will be re-established. In this case, a laminar polar is used to determine the drag coefficient. If the weather parameter LWC is greater than a defined threshold (0.03 g/m^3), it is assumed that the air taxi is in a precipitation zone. The threshold correspondences to the LWC of drizzle. [26] The laminar and fully turbulent polars are determined using the MICADO module *calculatePolar*. While determining the laminar polar, it is assumed that the transition point is located at 40 % of the chord length c. This assumption is made using an ILR internal workflow, which is used for hybrid laminar flow studies [27].

Impact of insect contamination Insect contamination on the wing leads to an increase of drag. This impact is particularly noticeable when using laminar profiles and operating at low altitudes near ground level. For example, bug wiper systems are used to remove insects from the leading edge of glider wings during flight to increase the performance [28]. Studies by Wicke [29] and Pohya [30] on the impact of insect contamination on the effectiveness of natural laminar flow and hybrid laminar flow control applications show a significant negative effect on the energy consumption of commercial transport aircraft. The method developed by Wicke [29] and Pohya [30] for the determination of laminar effectiveness in dependence of the insect contamination is adapted in the following for the application case of short-range operation of small aircraft. The aim is to determine the drag increase due to insect contamination. As shown in Fig. 4 (left), insects adhering to the leading edge of the wing create a turbulent flow in an area behind the impact point. The angle of these turbulent wedge is assumed to be 15 ° [30]. With the increased turbulent flow area and the decreased laminar flow area, the drag is increased. Hence, the laminar effectivity η_{lam} is decreased. The drag coefficient of the contaminated wing $C_{D_{\mathrm{ins}}}$ is estimated using Eq. 1. Here, $C_{D_{\mathrm{turb}}}$ and $C_{D_{\mathrm{lam}}}$ are the drag coefficients from the turbulent respectively laminar polar, which are used in MICADO

$$C_{D_{ins}} = C_{D_{lam}} + \left(C_{D_{turb}} - C_{D_{lam}}\right) * \left(1 - \eta_{lam}\right). \tag{1}$$

The values are determined based on the angle of attack requirements for the specific mission segment. The laminar effectivity is determined as a function of the number of insects on the aircraft, as shown in Fig. 5. The study of

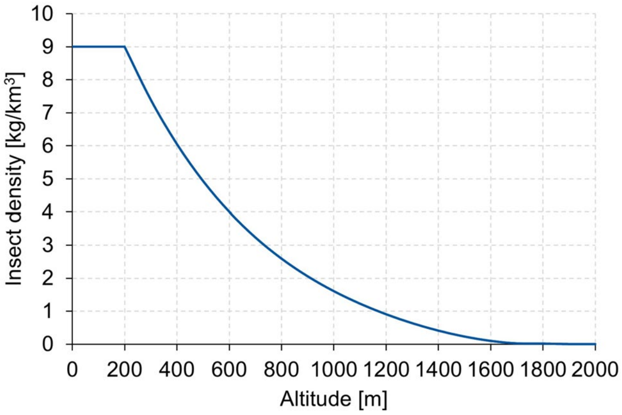

Fig. 6 Insect density in dependence of the altitude. Adapted from [31]

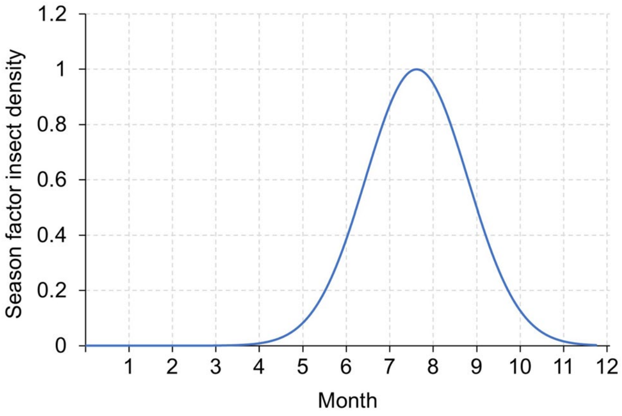

Fig. 7 Insect density in dependence of the season. Adapted from [29, 30]

laminar effectivity as a function of number of insects is performed by Pohya [30] using an Airbus A330-300 reference aircraft.

First, the laminar flow area without insect contamination is determined. Second, insects are placed iteratively and randomly on the leading edge of the wing, the tail plane, and the engine nacelle, which reduces the laminar flow area. The ratio of initial to remaining laminar flow area at each iteration determines the laminar effectivity. The laminar effectivity for the hybrid and all-electric air taxi is scaled by the wingspan. In contrast to Pohya [30] and Wicke [29], in this study, the number of insects on the aircraft is not constant for each flight cycle, but it is estimated separately for each mission and investigation time. The number of insects on the aircraft is depending on the altitude, the season, and the cross section of the wing. As shown in Fig. 6, the insect density ρ_{ins} is constant up to a height of 200 m above ground level and decreases exponentially to zero at height of 1800 m above ground level [31]. A season factor f_{ins} to scale the insect density throughout the year is presented in Fig. 7 [29, 30].

The number of insects per mission segment $N_{ins_{seg}}$ is calculated according to Eq. 2 using the ratio between insects in the reference volume V_{ref} (1 km^3) and the insects in the volume which is created by multiplying the wing cross section area (wing max. thickness t_{w} $*$ wing span b) by the length of the current mission segment l_{seg} (see Fig. 4 right)

$$N_{ins_{seg}} = \frac{\rho_{ins} \times f_{ins}}{m_{ins}} \times \frac{t_w \times b \times l_{seg}}{V_{ref}}. \tag{2}$$

Here, $m_{ins} = 3.4 * 10^{-5}$ kg is the median mass of insects in the air [32]. For the calculation of η_{lam}, the sum of all insects from the segments is used. Finally, the flight performance parameters (e.g., energy consumption, flight time, and AR) are calculated considering the above-mentioned impacts. A comparison between these parameters and those obtained under ideal weather conditions is conducted in the performance analysis.

4 Results

In this section, the results of the availability and performance analysis are presented after explaining the selected operating conditions. The analysis is carried out using both the hybrid and the all-electric air taxi. The operation takes place under VFR in the daylight hours between 9 a.m. and 4 p.m.. This time slot is chosen as it corresponds to the day with the shortest daylight duration in List, Germany, so that a VFR operation within this time slot is possible at any place and any time within Germany [33]. An hourly departure is assumed and the availability of the route is checked at the departure time for all route points. The results are described on the basis of the long and the short route from the route presented in Sect. 2.3. The average distance, including departure and arrival routes, for the short route between Nuernberg (EDDN) and Egelsbach (EDFE) is 196.9 km. The average distance for the long route between Augsburg (EDMA) and Moenchengladbach (EDDN) is 515.4 km.

4.1 Availability analysis

In this case an availability of 50 % means that half of the initially planned flights are not performed due to insufficient weather conditions. Here, no separation between the

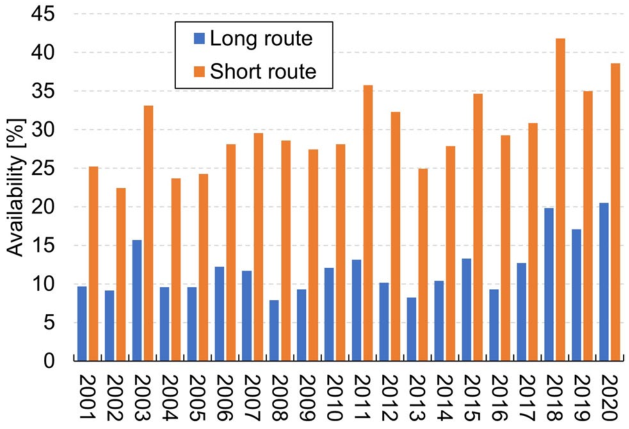

Fig. 8 Availability per year between 2001 and 2020

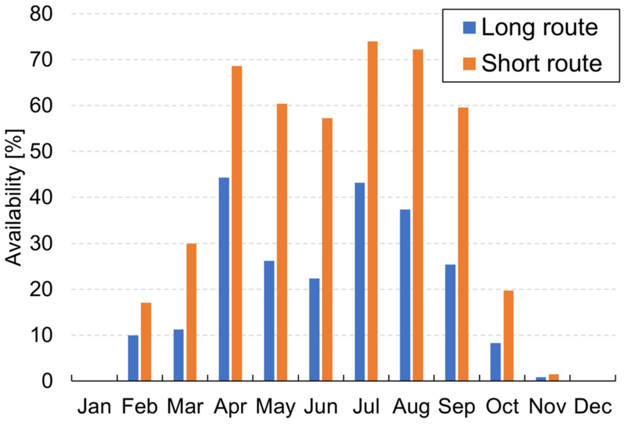

Fig. 10 Monthly availability. Average values for 2018–2020

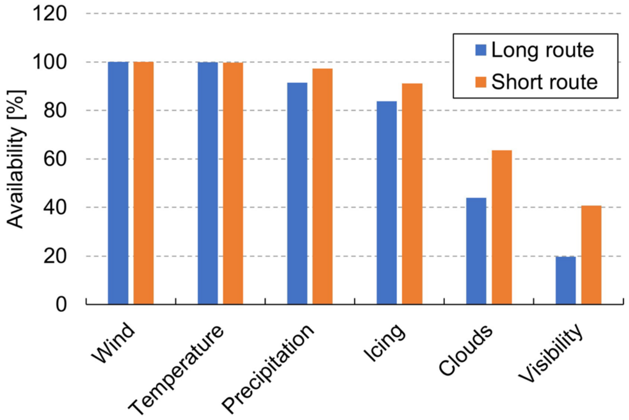

Fig. 9 Availability depending on the incident categories

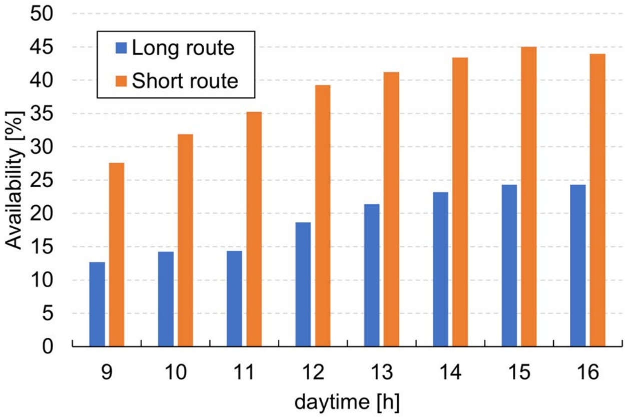

Fig. 11 Hourly availability. Average values for 2018 to 2020

hybrid and all-electric air taxi is made, as the limiting factors are independent from the aircraft. In Fig. 8, the availability per year between 2001 and 2020 is shown. It can be seen that the availability varies from year to year and that the short route has a significant higher availability. The average availability on the long route is 12.07 % and the average availability on the short route is 30.07 %, which is 149 % higher than for the long route. The maximum availability is achieved on the long route in 2020 with 20.48 % and on the short route in 2018 with 41.78 %. The return flight routes from EDLN-EDMA and EDFE-EDDN show nearly identical results. The average deviation is 0.07 percentage points.

In Fig. 9, the availability in dependence of the incident categories is shown. It can be seen that the availability is almost not affected by the incident categories wind (99.99 %) and temperature (99.74 %) and that the availability is mainly limited due to visibility and clouds. The influence of incident category visibility is stronger than the influence of incident category clouds.

For both flight routes, high availabilities are achieved in the years 2018, 2019, and 2020. These years are considered for the following detailed analysis.

In Fig. 10, the monthly availability is shown as average values for the period from 2018 to 2020. As expected, the availability is higher in the spring and summer months.

However, the availability can also be reduced in the spring and summer time due to persistent adverse weather conditions. For example, the availability of the analyzed flight routes is lower in May and June than in April. The drop of the availability in May and June is caused by a decrease of the availability of the incident categories visibility and clouds. The availability the other incident categories are above 90 % in the summer half year between April and September (see Figs. 18 and 19). When considering the availability over the entire operating day, as presented in Fig. 11,

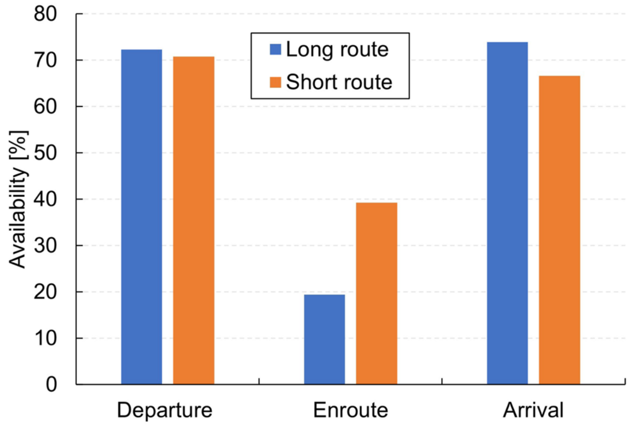

Fig. 12 Availability depending on the flight segments

Table 5 Minimal and reference cruise altitudes

	Flight route	MinAlt [ft]	RefAlt [ft]
Long route	EDMA - EDLN	4100	8500
	EDLN - EDMA	4100	9500
Short route	EDDN - EDFE	3300	3300
	EDFE - EDDN	3300	3300

it can be noted that the availability increases throughout the day as the availability of the incident categories visibility and clouds are increasing during the day (see Figs. 20 and 21).

For instance, the availability on the short route is 27.58 % when departing at 9 a.m., and it reaches its maximum value of 45.02 % at 3 p.m. throughout the day. When analyzing availability for the departure, enroute, and arrival segments, it is evident that the enroute segment is restricting. As illustrated in Fig. 12, the availability on the enroute segment on the long route is 52.86 percentage points lower than the availability of the departure segment and 54.50 percentage points lower than the availability of the arrival segment. It can also be analyzed that the higher availability of the short route is mostly due to the higher availability of the enroute segment.

4.2 Performance analysis

After identifying generally operable flight times using the availability analysis (step 2), the performance analysis (step 3) checks whether the performance of the air taxi is sufficient to operate in the given weather conditions. The results of the performance analysis are shown for the hybrid and the all-electric air taxi for the year 2020 with an hourly departure between 9 a.m. and 4 p.m.. The performance of the hybrid air taxi is investigated on the long route between EDMA and EDLN and for the all-electric on the short route between EDDN and EDFE. Both the outbound and inbound trips are considered. As presented in Table 5, each route is assigned a reference altitude (RefAlt) and a minimum cruising altitude (MinAlt). These altitudes were obtained from the Min. and Ref. trajectories described in Sect. 2.3. As described in Sect. 2.3, the used cruise altitude lies in between the MinAlt and the RefAlt depending on the weather conditions.

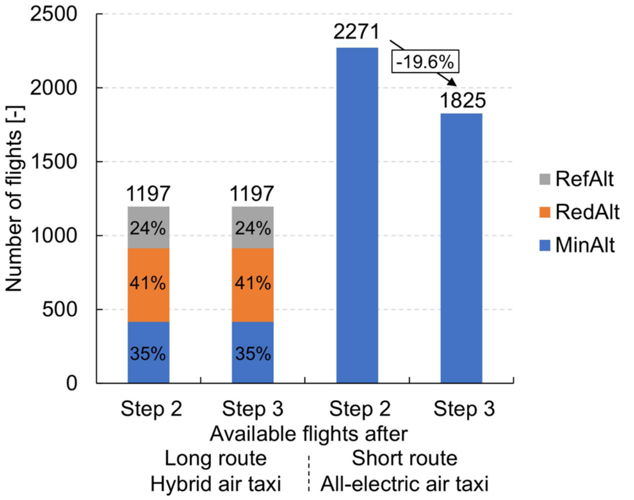

Fig. 13 Availability after performance analysis

For the flight routes used by the all-electric airtaxi, the MinAlt is equivalent to the RefAlt, since this is the most efficient cruise altitude for the given circumstances, ensuring that the aircraft operates with maximum efficiency.

In Fig. 13, the availability after step 2 and step 3 of the hybrid as well as the all-electric air taxi is compared. As shown in Sect. 4.1, the availability after step 2 of the hybrid air taxi on the long route is 20.5 %, and in total, 1197 flights can be performed. Of the total amount of flights, 24 % are performed at the RefAlt, 35 % at the MinAlt, and the remaining 41 % are performed at any cruising level between RefAlt and MinAlt. This cruising altitude is indicated in Fig. 13 as reduced altitude (RedAlt).

It is noted that all 1197 flights can be performed as the required fuel mass never exceeds the fuel tank capacity of 124 kg. This shows that the performance of the hybrid air taxi is sufficient for this application case. However, if the required fuel mass exceeds the design fuel mass of 79 kg, the payload has to be reduced to not exceed the MTOM. In this case the payload needs to be reduced by a maximum of 9.4 kg. If the flights should be performed with the full payload, the number of available flight decreases to 1097. The

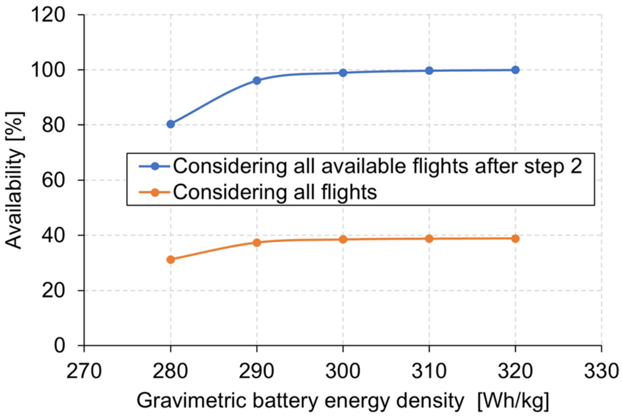

Fig. 14 Availability of the all-electric air taxi on the short route depending on gravimetric battery energy density

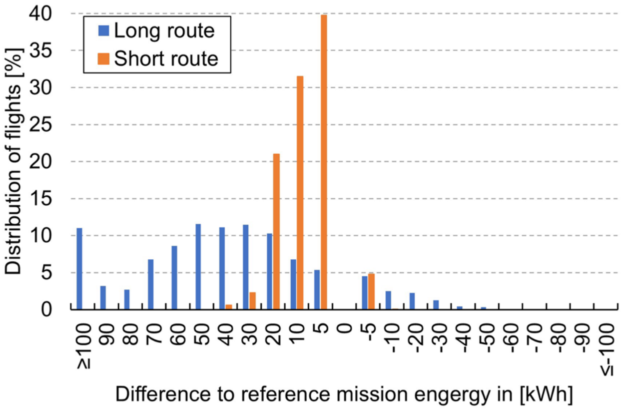

Fig. 15 Difference in mission energy demand between the real and reference mission for the hybrid air taxi on the long route and for the all-electric air taxi on the short route

flight with the highest energy demand - critical case - occurs when departing at 11 a.m. on March 23, 2020 on the flight route from EDMA to EDLN. In this case, the air taxi is flying in a headwind field and the AR is 27.2 % higher than the GR. The flight time increases by 26.4 % compared to the reference case when wind, insect contamination, and precipitation influences are not considered. The mission energy demand (MED) has increased by 19.8 %. In this case, the increase in energy demand is entirely caused by the headwind field. Since there are almost no insects in the air in March, there was no precipitation at that departure time.

The availability of the all-electric air taxi after step 2 on the short route is 38.9 % and a total amount of 2271 flights can be operated. They are performed entirely on the MinAlt. After step 3, only 1825 flights are effectively operational. This reduction of 19.6 % is a result of insufficient battery capacity. The installed battery has a capacity of 185.2 kWh and a GBED of 280 Whkg^{-1}. For the all-electric air taxi, the flight with the highest energy demand - critical case - occurs when departing at 3 p.m. on August 26, 2020 on the flight route from the EDFE to EDDN. The MED is 213.5 kWh which is an increase by 22.7 % in comparison to the reference mission. In addition, the AR is 47.9 % and the flight time is 45.3 % higher than the reference values. In this case, the increase in MED is caused by a headwind field (91 %) and the impact of insect contamination (9 %). Accordingly, the performance of the all-electric air taxi is not sufficient in real weather conditions. To provide the energy needed to perform all possible flights after step 2 in 2020 without design and MTOM changes, the GBED would need to be increased by 13.2 % to 317 Whkg^{-1}. However, the majority of flights can be operated with a moderate increase in GBED. Figure 14 shows that the availability increases to 96.1 % when considering all available flight after step 2 (2271) with a GBED of 290 Whkg^{-1}, and to 99 % with a GBED of 300 Whkg^{-1}. In general, the MED can be increased or decreased because of the strong impact of the wind. When analyzing the MED of all available flights of the hybrid air taxi on the long route, the variation in MED is caused to 80.55 % by the wind, to 19.30 % by insect contamination, and to 0.15 % by precipitation. The MED variation of all available flights of the all-electric air taxi on the short route is caused to 78.00 % by the wind, to 20.12 % by insect contamination, and to 1.88 % by precipitation. The impact of the precipitation on the MED is low as there are only seven flights on the long route and 52 flights on the short route with occurrence of precipitation and VMC compliance simultaneously.

The strong impact of the wind can also be seen when analyzing the range difference between the AR and the GR. On the short route, the AR of 83.61 % of all flight is higher than the GR which means that these flight are operated in a headwind field. On the long route, 79.35 % of the flights are operated in a headwind field.

The combined impact of wind, precipitation, and insect contamination is also shown in Fig. 15 . Here, the distribution of the flights over the difference in MED between the real and reference mission is analyzed. Insect contamination, precipitation, and headwind lead to a increase in MED. Whereas the tailwind leads to decrease in MED. For the investigated flights in 2020, the real MED is higher than the reference MED (positive differences) on 95.16 % of all flights on the short and on 88.72 % on the long route. This corresponds to the fact that the majority of flights are operated in a headwind flied, and for the majority of flights, an additional energy is required in comparison to the reference mission. However, the difference to the

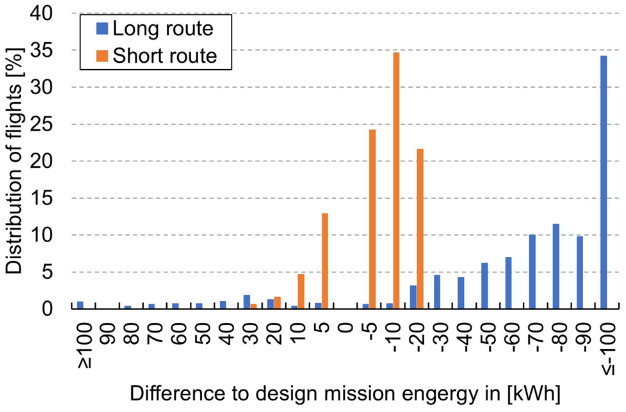

Fig. 16 Difference in mission energy demand between the real and design mission for the hybrid air taxi on the long route and for the all-electric air taxi on the short route

design MED is crucial for the performance-related availability. The distribution of flights over the difference in MED between the real and design mission is given in Fig. 16. Here, the real MED is higher than the design MED on 19.6 % of all flights on the short and 8.35 % on the long route. On the long route operating with the hybrid air taxi, an increase in real MED above the design MED (positive differences) can be tolerated by carrying more fuel and decreasing the payload. In case of an operation with the all-electric air taxi on the short and increase in real MED above the design MED, the flight cannot tolerated and the flight cannot be performed. This indicates that especially for the preliminary design of all-electric air taxis, the impact of real weather conditions should be taken into account and the design by ISA conditions is with respect to the daily availability misleading.

Table 6 Downloaded ERA5 parameters

Parameter
Cloud base height
Fraction of cloud cover
Geopotential at surface
Logarithm of surface pressure
Mean sea level pressure
Snow depth
Snowfall
Specific cloud ice water content
Specific cloud liquid water content
Specific humidity
Specific rain water content
Specific snow water content
Surface pressure
Temperature
Total cloud cover
Total precipitation
U-component of wind
V-component of wind
Vertical velocity

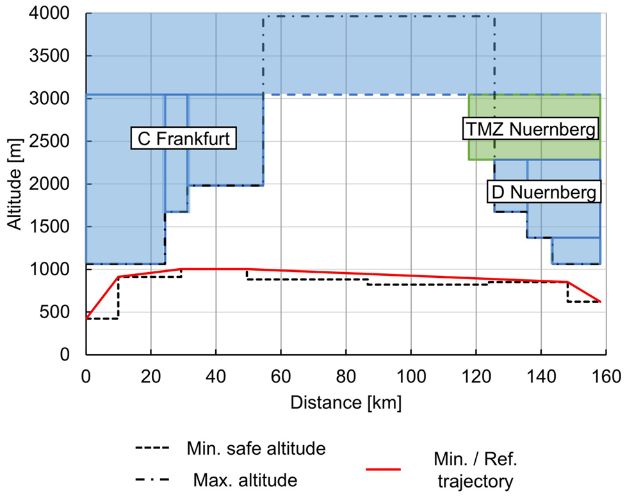

Fig. 17 Vertical trajectory of short route from Egelsbach to Nuernberg (between CRP)

5 Conclusion

The aim of this research was to develop a method to determine the availability and the performance of hybrid and all-electric air taxis in real weather conditions on reference routes within Germany. For this purpose, weather data from ECMWF were evaluated and the availability was determined taking into account the VMC minima. In addition, the mission analysis of MICADO for small aircraft was extended by integrating weather data to include the ability to estimate performance in real weather conditions. Here, the influences of real atmospheric conditions, wind, precipitation, and insect contamination are considered. The analysis shows reduced availability due to weather conditions and that visibility and cloud clearance are the limiting factors for VFR operation. The availability increases as the flight route distance decreases and the bottleneck consistently is the enroute segment.

Table 7 Incident categories and limits at the airport (valid for step 2)

Category	Limit airport
Wind	Headwind < 18 m/s
	Crosswind< 10.29 m/s
	Tailwind < 5.14 m/s
Clouds	If Coverage ≥ 0.5
	Clearance > 2000 ft
Visibility	Airspace G > 1500 m
	Airspace D(CTR) $>$ 5000 m
Icing	If Temperature $\leq 0\,^{\circ}$C
	Water content < 0.01 g/kg
Temperature	$< 35\,^{\circ}$C
	$> -20\,^{\circ}$C
Precipitation	Water level height on RWY
	<0.003 m

Table 8 Incident categories and limits at enroute segment (valid for step 2)

Category	Limit enroute
Wind	Groundspeed > 0 ms^{-1}
	Correction angle $< 90\,^{\circ}$
	Avg. Headwind < 28.75 ms^{-1}
Clouds	If Coverage ≥ 0.5
	Clearance airspace E, G High > 1000 ft
	Clearance airspace G > 100 ft
Visibility	Airspace E, G High < 5000 m
	Airspace G > 1500 m
Icing	If Temperature $\leq 0\,^{\circ}$C
	Water content < 0.01g/kg
Temperature	$< 35\,^{\circ}$C
	$> -20\,^{\circ}$C
Precipitation	–

The results of the performance analysis indicate that the performance of the hybrid air taxi is sufficient and only the VMC minima are limiting. In contrast, both the VMC minima and the performance limit the availability of the all-electric air taxi. Generally, wind strongly affects the energy demand. Despite being small, the impact of insect contamination on energy demand is significant. Precipitation did not have an significant impact, since nearly no rain occurred during the analyzed days in the performance analysis.

In further research, the optimization of availability will be investigated. Promising approaches involve performing the enroute segment under instrument flight rules and circumventing areas with inadequate weather conditions.

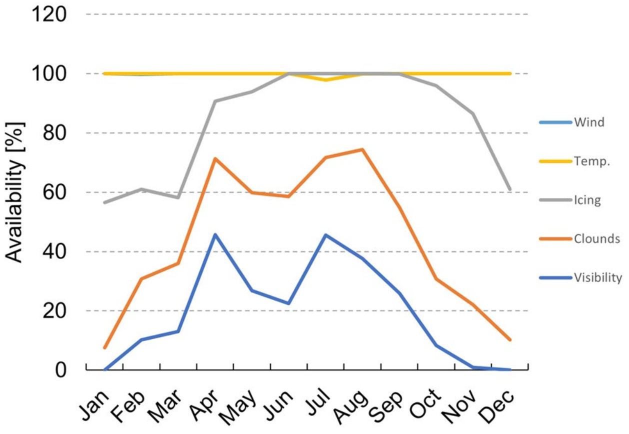

Fig. 18 Availability of the incident categories in dependence of the month for the long route

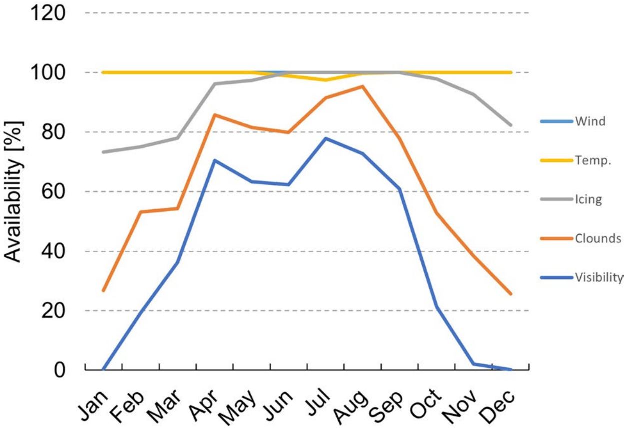

Fig. 19 Availability of the incident categories in dependence of the month for the short route

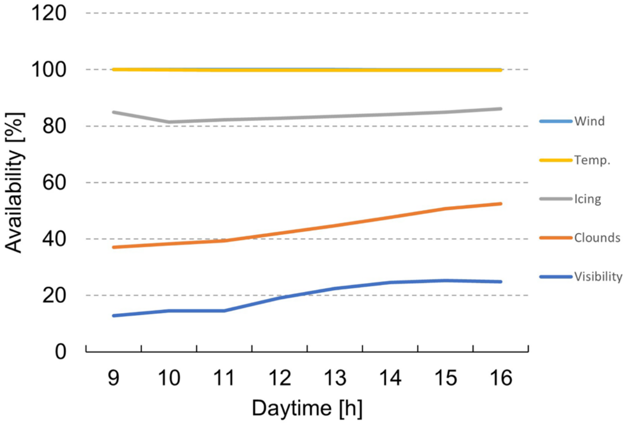

Fig. 20 Availability of the incident categories in dependence of the daytime for the long route

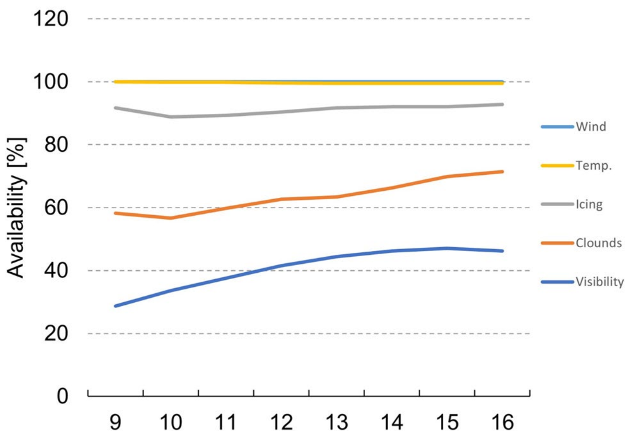

Fig. 21 Availability of the incident categories in dependence of the daytime for the short route

Appendix A

In the following additional information is provided for the vertical trajectories (see Fig. 17), the ERA5 parameters utilized(see Table 6), the incident categories and limits for the availability analysis (see Tables 7, 8), and the availability of theincident categories (see Figs. 18, 19, 20, 21).

Author contributions L.W. wrote the main manusscript text. S.H. contributed to section 2.1 and 3.2. All authors reviewed the manuscript.

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Data Availability Not applicable

Declarations

Conflict of interest The authors have no conflict of interest to declare that are relevant to the content of this article.

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