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Usage Monitoring of Helicopter Gearboxes with ADS-B Flight Data

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Abstract: Health and usage monitoring systems (HUMS) are the basis for condition-based maintenance of helicopters. One of the most critical systems in terms of safety and maintenance expense that can be monitored by HUMS are the main gearboxes of helicopters with turbine engines. While the health monitoring part of HUMS aims to model the health state from the collected sensor data with advanced algorithms, such as machine learning, the usage monitoring part tracks the time of use and operating parameters of the system, such as load, to determine lifetime consumption. In the presented work, a combination of automatic dependent surveillance-broadcast (ADS-B) flight data with a generic helicopter performance model is used to acquire torque profiles of the gearboxes. With damage accumulation methods, the load spectra are transformed to aggregated indicators that reflect the individual gearbox usage. The methodology is applied to samples of two helicopters from a five-year ADS-B data set of German helicopter emergency medical services (HEMS) acquired for the study. The results demonstrate the feasibility of the generic approach, which can support maintenance scheduling and new usage-based maintenance services independent of direct access to installed HUMS.

Keywords: HUMS; usage monitoring; PHM; helicopter; gearbox; ADS-B flight data; HEMS

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Citation: Hünemohr, D.; Litzba, J.; Rahimi, F. Usage Monitoring of Helicopter Gearboxes with ADS-B Flight Data. *Aerospace* **2022**, *9*, 647. https://doi.org/10.3390/aerospace9110647

Academic Editors: Bruno F. Santos, Theodoros H. Loutas and Dimitrios Zarouchas

Received: 28 September 2022
Accepted: 22 October 2022
Published: 25 October 2022

1. Introduction

Within the field of condition-based maintenance (CBM) in aerospace, HUMS play a unique role in the rotorcraft industry and can be considered as the origin of today's prognostics and health management (PHM) [1]. The primary reason for the development of HUMS in the 1980s was to increase the safety of helicopter operations in the face of technical malfunctions that led to various accidents [2]. Over time, and after the initial safety enhancements, the focus shifted to the general economic benefits of enabling CBM [3].

HUMS provide insights into the monitored helicopter systems through two main functionalities: health monitoring (HM) and usage monitoring (UM), as shown in Figure 1. HM is the analysis of the reaction of the monitored system to the various environmental influences and its internal technical health state, which is a typical PHM task. The reactions are recorded by sensors, e.g., accelerometers, and further processed by various algorithms to provide a diagnosis or prognosis of the system state. In the past two decades, the advancement of signal processing and machine learning has provided the means to improve the performance of HM in HUMS and PHM applications, for example, in machinery diagnosis [4].

While HM concentrates on inferring the health state from the responses, UM is the analysis of actual inputs, influences, and operating conditions of the system that may have an impact on the health state. The design of a technical system requires an underlying assumption about the reference usage profile, which can be defined by operational and environmental specifications, to achieve a reliability goal. When the system is produced and enters the operational phase, the usage can be tracked and compared to the design parameters [5]. This provides a baseline of the used life of a component or system. If the actual operation of an individual system is known, the usage can be extrapolated into the future and thus serve as a baseline approach for prognosis [5]. By relating usage and maintenance data, it is possible to optimize maintenance services and parts logistics [6].

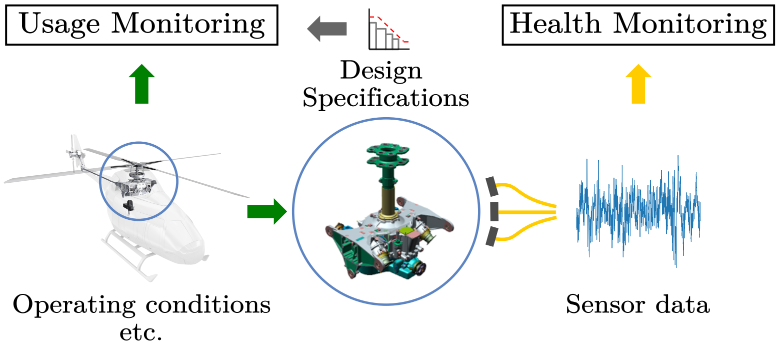


Figure 1. Overview of the health and usage monitoring of a helicopter gearbox.

1.1. Usage Monitoring of Helicopter Main Gearboxes

Even though PHM has achieved tremendous progress, aircraft maintenance programs mainly follow a scheduled maintenance program [7]. These schedules depend on basic usage indicators, flight hours (FH) and flight cycles (FC), which trigger inspections, overhauls and replacement of life-limited parts. While they provide indicators that are easy to document and manage, they do not take into account the different operating and environmental conditions during these intervals and lack the possibility to adjust for the individual usage. During the design phase for a new helicopter model, the aircraft manufacturer has to make assumptions about the typical flight profiles and the conditions surrounding the helicopter to specify requirements. These requirements impact the system design as well as the maintenance policy to conservatively maintain the airworthiness of the entire fleet [8].

One of the most critical systems in helicopters is the transmission path. The helicopter main gearbox (MGB) transforms the high output speed of the turbine engines into the low rotor speed and splits the power between the other subsystems, such as the tail rotor or oil pumps [9]. Even though medium-size helicopters are usually equipped with two turbine engines, the gearbox is a single critical load path without redundancy. The helicopter propulsion, lift and flight maneuvering all depend on the transmission [3]. This leads to high safety factors in its design and the need to monitor its condition. Due to its complexity and high integration into the helicopter, HUMS are beneficial to prevent unscheduled maintenance and facilitate scheduled maintenance events of the MGB, even though their implementation in maintenance organizations is still slow [6]. One of the reasons for this is that the benefits of HUMS are not yet fully exploited, which is why the industry is demanding better integration of credits for usage monitoring into maintenance programs [8].

Since the start of HUMS development, usage monitoring has played an important role in research activities [10]. In the past, there have been several studies on the usage monitoring of helicopter systems with direct access to HUMS data. A large two-year study of the Federal Aviation Administration (FAA) documented the comparison of assumed and real usage spectra of a military helicopter fleet [11]. They identified flight regimes from recorded flight data of the fleet and created new adapted usage spectra for structural components. Using the specific usage spectra, the authors proposed a usage credit plan based on a damage index to allow for the extension of the lifetime of life-limited components. Other studies researched the recognition of specific flight regimes, e.g., hovering or specific turns, within flight data as well. A certain usage or life consumption of helicopter systems and components can be associated with these specific regimes. Thereby, the knowledge of the typical regimes within the specific helicopter missions is translated into usage. Recent studies researched different data mining techniques for this task, e.g., for structural UM [12]. Chin et al. presented methods for the flight phase identification in helicopter flight data for anomaly detection [13] and applied clustering methods on the ADS-B data of an helicopter air taxi operator [14]. Hoole et al. researched the flight regime recognition in ADS-B data as well and stated the importance of developing more representative design usage spectra [15].

The usage monitoring of helicopter gearboxes has been studied in the context of fatigue life estimation since the 1980s [16,17]. Though mostly concentrated on the design phase of the MGB, some literature has already presented devices for operational phase and usage monitoring. For example, Fraser developed a measuring system for the engine torque of a *Sikorsky Sea King* helicopter with the deduction of usage [16].

As gearboxes also play a vital role in other industries, there are new advances in characterizing certain operational usage profiles as an approach to further optimizing maintenance and services. Foulard et al. calculated the remaining service life of automotive transmission systems depending on the individual driver's driving profile [18]. For wind turbine gearboxes, Pagitsch et al. suggested a load-based maintenance approach as a compromise between investment and the potential to reduce costs. They calculated the load of wind turbine gearbox bearings with the help of operational data and derived a remaining useful lifetime [19].

In summary, it can be said that even though the concepts of usage monitoring are well known and have been introduced in various industries, there is a large lack of data to further enhance and validate HUMS strategies for helicopters [6]. The researched aviation literature relies on direct access to flight data to analyse the operations and environmental conditions, which might be one of the reasons that there is not a lot of recent research on usage monitoring of helicopter MGBs. In other industries, the rise of available operational data is presumably one of the main drivers in the increased interest in UM methodologies.

1.2. Access to Data and Reality Gap

For the assessment of new PHM and HUMS approaches, data sets of the system domain need to be available. Typically data from the industry are highly restricted and not accessible to the scientific community because they hold strong value for the owners [20]. This applies not only to direct sensor data, relevant for health monitoring, but also to aircraft operational data that provide insights into the usage of systems. System manufacturers and maintenance organizations typically have no direct access to the OEMs' data records either and only receive design usage profile requirements. Researchers have to rely on the few open accessible data sets to benchmark their PHM approaches, which are seldom from real-world operational systems. If no data set is suitable for their purpose, there are two remaining possibilities: first, they can simulate data, but only under a set of assumptions about the real-world application, and second, they can build costly test beds in lab environments with few environmental influences. Currently, all three approaches (open accessible data sets, simulations and experiments) are failing when researching the long-term usage of aircraft and the specific operational and environmental influences. Even though OEMs often have access to more data, installing UM systems is expensive and oftentimes not desired by operators. A more cost-efficient solution for flight data recording and usage monitoring could thus support OEMs' business as well. Therefore, this paper presents a usage monitoring methodology for helicopter main gearboxes that can support maintenance, system manufacturers and OEMs with open access ADS-B data and tools available to researchers independent of access to recorded HUMS data.

In Section 2, an overview of the structure and use of ADS-B data is given, and the developed usage monitoring methodology described. For the application of the developed methodology, a long-term ADS-B flight data set was acquired. The data set comprises a fleet of HEMS helicopters in Germany and is discussed in more detail in Section 3. In Section 4, the methodology is applied on a small subset of two helicopters with long-term data, and the results of the UM are assessed and discussed. The paper concludes in

Section 5 with an outline of the potential uses of the data set as well as the generic usage monitoring approach.

2. Usage Monitoring Methodology

An overview of the methodology is shown in Figure 2. It is divided into the two main parts: *Data Acquisition* and *Usage Monitoring*.

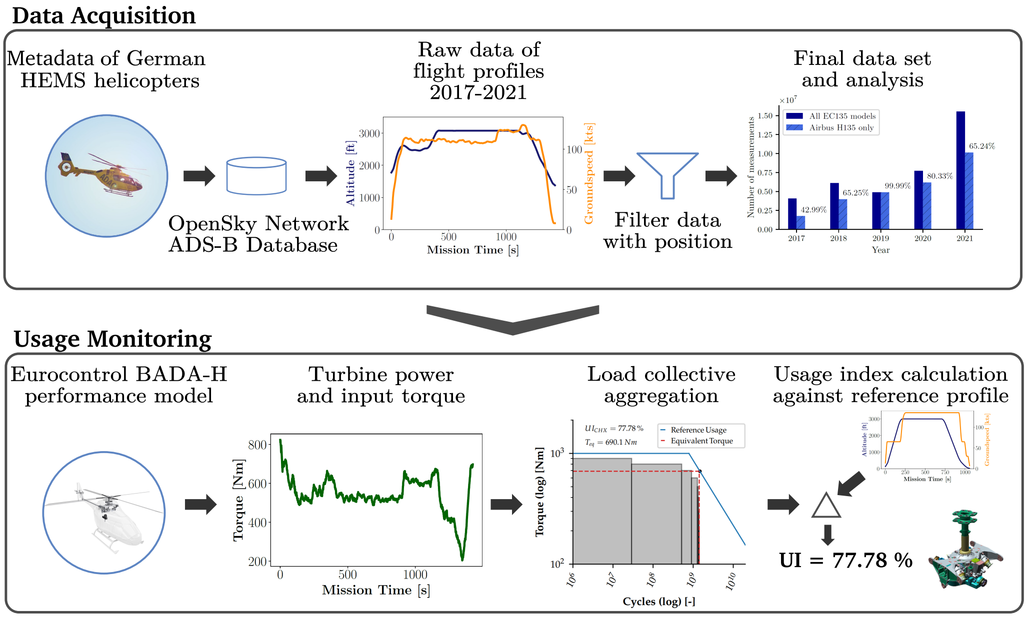


Figure 2. Overview of the acquisition of the ADS-B data set and the usage monitoring methodology.

The objective of the data acquisition is to collect real flight profiles of helicopters to gain insights into their operations. Subsequently, the specific gearbox usage information is extracted from the data using the usage monitoring methodology.

2.1. ADS-B Flight Data

Since the end of 2020, aircraft operating in European airspace with a maximum certified take-off mass exceeding 5700 kg or a maximum cruising true airspeed (TAS) greater than 250 kts are mandated to be equipped with Mode S transponders [21]. These transponders have a unique 24-bit aircraft address (ICAO24 identifier) and can thereby be selectively interrogated by air traffic control to provide flight information. In addition to the selective interrogation, Mode S transponders can be equipped with the ADS-B surveillance technology, which periodically sends flight information data to ground and airborne receivers [22]. ADS-B messages typically contain the following information provided by the aircraft's avionic system [23]: unique ICAO24 identifier, GNSS position, altitude (either pressure or GNSS altitude), groundspeed and barometric vertical rate. Sometimes, other information such as the flight's callsign or an *on-ground* indication are sent as well [22]. The *OpenSky Network* is an open data ADS-B receiver network with the goal of providing live and historic ADS-B records to researchers [22,23]. Although most helicopters are operated under visual flight rules (VFR) and are not mandated to be equipped with ADS-B, a first analysis of the data from the *OpenSky Network* has shown that many operators equip their helicopter fleet with this capability. Therefore, the data can be used to analyse specific flight missions of the *visible* helicopters via ADS-B. A typical flight profile that can be extracted from the sent data of a helicopter can be seen in Figure 2, which shows groundspeed and altitude as the main parameters to understand specific mission types of helicopters.

2.2. Performance Model

For the monitoring of specific subsystems, the flight profiles need to be transformed into usage information in the domain of interest (e.g., structural monitoring, gearbox, etc.). In the context of helicopter MGBs, the usage is defined here as the duration and amplitude of the received input load/torque, which directly relates to the turbine power output. An aircraft performance model (APM) calculates the required turbine power output for the specific flight path of an aircraft. APMs for helicopters can be developed at different levels of depths depending on the known parameters of the specific helicopter type, available data for validation, and the requirements for the level of detail. In the presented approach, we focus on a generic model capable of processing large ADS-B data sets from different helicopter types to analyse and compare the usage between various fleets. For this purpose, the *Eurocontrol BADA-H* helicopter performance model was implemented and used [24]. *BADA-H* was developed to support trajectory and fuel consumption prediction in air traffic management and for environmental analysis. It is based on a mass-varying kinetic approach with three degrees of freedom that assumes the helicopter as a point mass. At each timestamp, the underlying forces acting on the helicopter (aerodynamic, propulsive, gravitational) and the change in total energy are calculated to derive the power output by the turbine engines. Each helicopter is described by a set of technical specifications and empirically fit coefficients.

Assumptions were made to create a generic model for a multitude of helicopters—for example, the rotor tilt angle is assumed to be constant, and there is no ground effect. With these simplifications, the model is available for 20 helicopter types with maximum take-off weights ranging from 1500 kg to 30,000 kg. The performance has been validated by *Eurocontrol* to be in acceptable limits for most use cases in operational analysis. Because of its generic approach and validation, it is suitable for our computation of performance from large scale ADS-B data sets. More information on the model structure can be found in [24].

The *BADA-H* model was implemented in *Matlab R2020b* [25], and further assumptions were made to work with the ADS-B flight data:

- Since only groundspeed can be extracted from the available flight data, we assume that it is equivalent to TAS, neglecting wind, etc.
- As we focus on HEMS flights, the helicopter mass is assumed to be close to its maximum allowed takeoff mass (MTOM) due to the amount of equipment and a standard crew of three persons (pilot, emergency doctor and paramedic). It is not possible to infer from the ADS-B data whether a patient is on board. We thus assume the mass to be 150 kg less than its MTOM, which results to 2830 kg for an *Airbus H135*.
- We assume a standard barometer pressure setting of 1013 hPa to calculate the ambient pressure from the ADS-B altitude.
- Since the vertical rate within ADS-B is relatively coarse (intervals of 64 ft/min) and has a high variance due to momentarily extreme peaks, it is calculated with the forward differential coefficient of altitude.
- The flight profile data are smoothed with a moving average. For this, we used the Matlab function *smoothdata* with a *SmoothingFactor* of 0.05.

Otherwise, the implementation follows the *Eurocontrol* equations, uses the same module structure, and has been validated with reference data available in the *BADA-H* files. From the calculation, the power provided by the turbine engines is extracted to further calculate the gearbox input torque, as shown in Figure 2. In the general framework of the proposed approach, the APM can also be exchanged if a more detailed model is needed and more data on the helicopter type is available.

2.3. Derivation of the UM Indicator

Most helicopter types have a constant or minimal varying rotor speed [26,27]. In the example of the twin-engine medium-size helicopter *Airbus EC*135, the rotor speed is varied only in startup phases and at higher altitudes by the full authority digital engine control (FADEC) in between 98% to 104% of the nominal speed [9]. The rotor speed is therefore assumed to be constant. While the rotor speed is kept constant, the turbine power output and load on the gearbox vary according to the flight dynamics and required lift [26]. These loads, which depend on the specific flight profiles, build the basis for the usage profiles that we extract from the data. The input torque of the gearbox is calculated with the basic equation $P = T \times \omega$ where the input speed of the gearbox ω and the power output of the turbines P is known. As a result, the torque profile is depicted as a green curve in Figure 2. The curve directly represents the gearbox usage of one flight but is difficult to analyze and compare to other torque profiles without expert knowledge. For the analysis of multiple flights of a helicopter fleet, the information is further aggregated and set in relation to a reference design usage of the gearbox.

The approach to the derivation of a meaningful usage indicator (UI) follows the main aspects of the standard *ISO 6336* Parts 1 and 6 for spur and helical gears [28,29]. In a first step, the torque profiles are aggregated into load spectra as a combination from both turbine power outputs (in a twin-engine helicopter). Since the ADS-B data from the *OpenSky Network* are available at a frequency of 1 Hz, the power and torque calculations are also based on this interval. With constant input speed and assuming constant input torque within the one-second interval, the revolutions within the torque class can be counted. One revolution corresponds to one load cycle of the input gear. This is the basis for the usage monitoring methodology since it implies a respective life consumption. More detailed information about the load variations within this interval is not available from the ADS-B data and cannot be generically applied to different gearboxes.

In contrast to *ISO 6336*, the torque spectra are not further converted into the gear tooth stresses for the specific failure modes, as would be necessary during the design phase of the gearbox. If the gearbox geometry and parameters are fully known, the conversion could be performed with parts 1 through 5 of the *ISO 6336* standard [28]. In addition, the torque spectrum could be calculated for all individual components if required.

After aggregating the flight profiles into torque spectra, a damage accumulation theory based on the traditional Palmgren–Miner rule is applied to convert torque into a usage indication [29]. As a linear damage accumulation method, the Palmgren–Miner rule states that each cycle n within a stress class i (or torque class in this case) damages the gear equally [29]. The stress spectrum of a system is related to its design profile, which is an S-N curve for the specific material. The S-N curve indicates the maximum number of cycles N_i of each stress class, at which a failure occurs. The existing damage D of the system is then calculated with Equation (1):

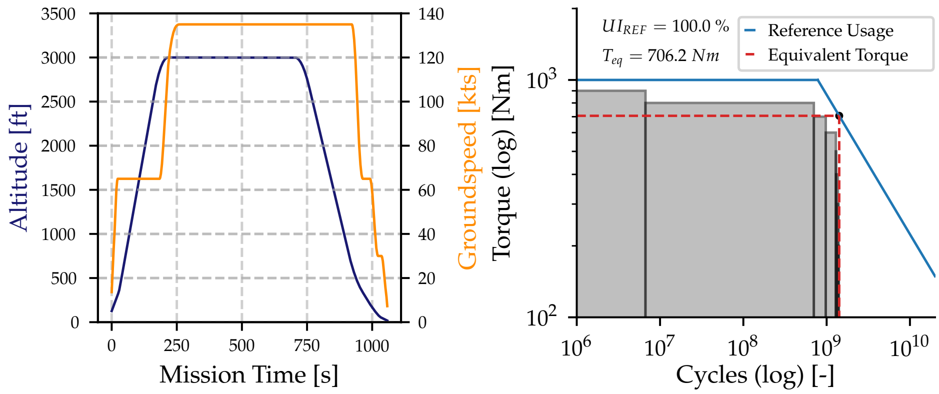
$$D = \sum_i \frac{n_i}{N_i} = UI \tag{1}$$

A failure of the system is expected when the damage reaches $D = 1$. We calculate the usage in the same way and state that $UI = D$. Unlike the original specifications in *ISO 6336*, the exact S-N curves of the gearbox components are not known, and the objective is instead to compare the specific usage of the entire gearbox to a reference usage. The reference usage is defined mathematically with the characteristic S-N curve hyperbola [30]:

$$T = \left(\frac{C}{N}\right)^{\frac{1}{a}} \tag{2}$$

N is the designed number of cycles at a torque T from the artificial reference flight profile. The constant C and the exponent a define the curve in the range of finite life endurance. If $a \to \infty$, then there is no cycle limit, which is the case for very low torque classes in the original Miner rule. For the definition of the usage reference curve, the parameters are defined with a default flight profile based on the default helicopter procedure in the *BADA-H* user manual [31]. The created reference profile has a flight time of approximately 17 min and is shown in Figure 3a.

From the reference flight profile, the reference input torque for a specific helicopter MGB is calculated as described in Section 2.2. The usage of gearboxes is only comparable if the same amount of operating time is considered. The reference flight is therefore scaled up to the time of gearbox overhaul, as this would be the preferred time for a gearbox maintenance organization to assess gearbox usage. The scaling does not depend on the number of flights considered for the torque spectrum, but more flights would represent the typical usage of the MGB more accurately. Therefore, extracted flights from the ADS-B data can be combined and then scaled up to the total time between overhaul (TBO).



(**a**) (**b**)

Figure 3. (**a**) Reference flight profile. (**b**) The derived usage reference curve (blue) with associated load spectrum (grey).

The accumulated torque spectrum of the reference flight is shown in Figure 3b for an *Airbus EC135* MGB with a gearbox input speed $\omega_{MGB,EC135} = 5898 \frac{1}{\text{min}}$ [32]. The TBO of this gearbox is set at 4000 FH. At constant input speed, this accumulates to $N_{total} = \sum_i n_i \approx 1.415 \times 10^9$ cycles, where n_i is the number of cycles in torque class i. The spectrum is presented on a double logarithmic scale with the endured cycles in the respective torque class. The parameters of the reference curve were adjusted to fulfill $UI \stackrel{!}{=} 1$ for the reference spectrum, with $a = 1.702067$ and $C = 10^{14}$. With the defined reference curve, the Palmgren–Miner rule can be applied to accumulated flight torque spectra from ADS-B flight data to evaluate the usage. Another measure of overall usage is the equivalent torque T_{eq}, which is given by the Equation (3) [29]:

$$T_{eq} = \left(\frac{\sum\limits_i n_i T_i^a}{\sum\limits_i n_i} \right)^{\frac{1}{a}} \tag{3}$$

The usage calculated only with the equivalent torque and the total endured cycles with Equation (1) are equal to the spectrum usage. In the case of the reference profile torque spectrum in Figure 3b, the red dashed line of the equivalent torque meets the reference usage curve at the total amount of cycles N_{total} at the time of overhaul, as its usage index is $UI_{REF} = 100\%$.

3. Long-Term Flight Data Set

For the application of the described usage monitoring methodology, ADS-B data were extracted from the *OpenSky Network* database [23]. To narrow the possible data, we assumed that the usage of helicopters is different, even if the general mission tasks are the same. One of the most prominent and visible civil helicopter mission tasks is to provide emergency medical assistance and transport (HEMS), which is why we focus on them. The final extracted data set has been published and can be accessed online [33].

3.1. HEMS in Germany

Due to the early establishment of HEMS in Germany, it has evolved into a large network of more than 70 HEMS stations [34,35]. At each station, one or more helicopters are operated with a reserved callsign *Christoph*. The stationed helicopters are used either as primary rescue transport helicopters (Rettungshubschrauber—RTH) with smaller aircraft (*Airbus EC*135/*H*135) or as intensive care transport helicopters (Intensiv-Transporthubschrauber—ITH) with larger capacity and equipment (*Airbus EC*145/*H*145) [34]. In some cases, the helicopters are used as dual-use helicopters (Dual-Use-Helicopter—DUH). RTHs in Germany are operated by three main operators: *ADAC Luftrettung* (ADAC), *DRF Luftrettung* (DRF) and the *Federal Ministry of the Interior* (Bundesministerium des Inneren—BMI). A HEMS flight in a specific environment is therefore characterized by its specific helicopter (ICAO24), the operating station (e.g., *Christoph 1*) and the station location (e.g., Berlin).

3.2. Data Acquisition and Filtering

To query ADS-B flight data from the OpenSky Network database, the python package *traffic 2.7.0* was used [36]. An initial analysis indicated that the HEMS helicopters could not be reliably identified with the callsign *Christoph*. Instead, it was found that the ICAO24 identifier could be reliably tracked within the ADS-B data. To filter all relevant HEMS helicopters, public sources of the ICAO24 identifiers were researched, along with information on the model type and other specifications (e.g., registration). The complete HEMS fleet has to be larger than the number of operating stations to account for maintenance, repair and overhaul (MRO) and to ensure a continuous availability.

In addition, information on the operating stations and locations of the three main operators were collected, including: station callsigns (multiple callsigns if multiple helicopters were stationed at the same location), city, facility name (e.g., *Campus Benjamin Franklin of the Charité in Berlin*), HEMS category (RTH/ITH/DUH), coordinates, elevation, type of station (airport/heliport/hospital), operator, helicopter type and special equipment (24-h operations, etc.). In total, information of 79 operating stations at 70 locations were collected, neglecting stations only operating during the COVID-19 pandemic or from other operators. A summary of the HEMS stations is given in Table 1.

Table 1. German HEMS station overview.

HEMS Type	*EC*135/*H*135	*EC*145/*H*145
RTH	49	6
ITH	1	12
DUH	1	10
Total	51	28

Continuing to focus only on *Airbus EC*135/*H*135 helicopters as the largest HEMS sub-fleet, aircraft information was retrieved on 76 helicopters operating the 51 stations. The HEMS helicopters belong to four different generations (1, 2, 2+, 3) of the *Airbus EC*135 type. Each generation has two engine options, marked as P (Pratt and Whitney) or T (Turboméca—now Safran). The newest generation is the *EC*135 *T3/P3* (*H*135). With the corresponding ICAO24 identifiers, the *OpenSky* database was queried for the five-year period from 1 January 2017 to 31 December 2021. The data were queried for each calendar week within the total period of time, resulting in 265 data files.

3.3. Filtering and Overview of the Data

Each week in the raw data contains flights from a subset of all possible 76 *EC*135/*H*135 helicopters. The median of this weekly operational subset is 55, and the maximum is 64, which corresponds well to the number of 51 operated *EC*135/*H*135 stations. Only a fraction of the tracked helicopters are represented by ADS-B flight information, but only by Mode S interrogations. In order to analyze flight routes and environments, helicopters that did not transmit a position in 95% of the measurements in each weekly data file were filtered out. With this filter, the remaining measurements include all important data for the usage monitoring: registration, ICAO24 identifier, operator, timestamp, groundspeed, altitude and position (latitude/longitude). Then, measurements without a callsign were assigned a unique artificial callsign with the corresponding ICAO24 identifier. The remaining flights were structured into flight segments with unique IDs using the *traffic* function *assign_id* [36]. The cleaned five-year data set contains a total of 38,332,562 measurements, structured into 165,595 assigned flight segments. Each week of the filtered data set contains measurements from 2 to 20 tracked EC135 helicopters. For an overview of the locations of the HEMS flights included in the data, the map in Figure 4 illustrates the number of measurements per district in Germany.

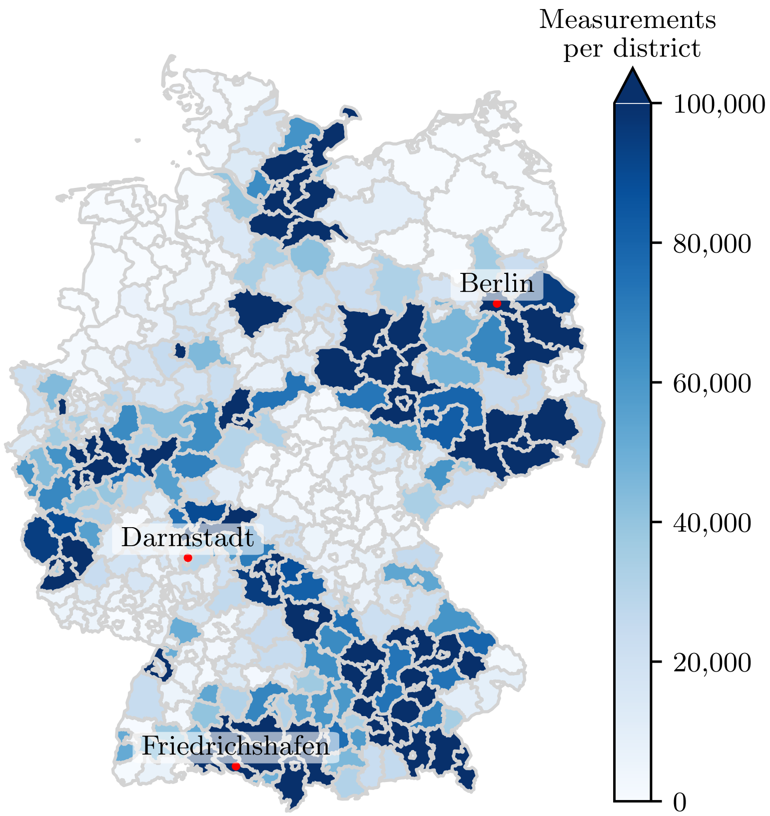


Figure 4. Map of Germany with the intensity of the color representing the amount of measurements per district.

The data clearly do not cover all of Germany and show large areas without HEMS data from the *EC*135 fleet. Nevertheless, there are some areas that are represented well, such as in the Berlin district or around Friedrichshafen. Figure 5 shows the number of measurements per week from the filtered data set.

The data show an annual periodicity, indicating a seasonality of operated HEMS flights, with fewer missions flown during the winter. Beginning in early 2020, an upward trend in measurements per week is evident. Especially during 2021, the number of measurements per week increase by a factor of two compared with the years 2017–2020. Several causes may be responsible for the rising trend: the overall ADS-B coverage of the *OpenSky Network* may have increased in the regions with HEMS activities, or there may have been more HEMS helicopters sending ADS-B data.

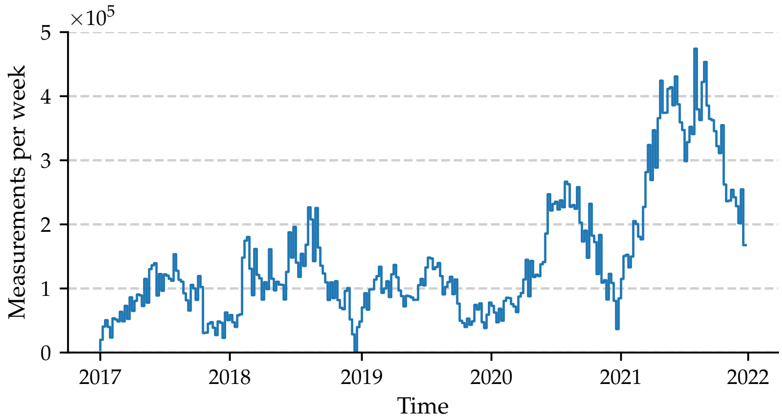


Figure 5. Weekly ADS-B measurements in the filtered data set.

Another analysis is shown in Figure 6. A trend in the amount of measurements sent per helicopter each week indicates better coverage or newer helicopter models sending location data more often. The bottom graph shows that more helicopters are included in each week of data starting in early 2020. This could indicate that newer helicopter models have been introduced, replacing older helicopters in the HEMS fleet and equipped with newer versions of Mode S transponders. Both trends contribute to the main finding, shown in Figure 5, that more measurements were received at the end of the data set period. The flight segment length (measurements per assigned flight ID) was analyzed and showed no clear trend during the period. The mean flight segment length is approximately 231 measurements, which is equivalent to 231 s of time. Based on the short flights, the received HEMS flights were likely conducted in urban areas.

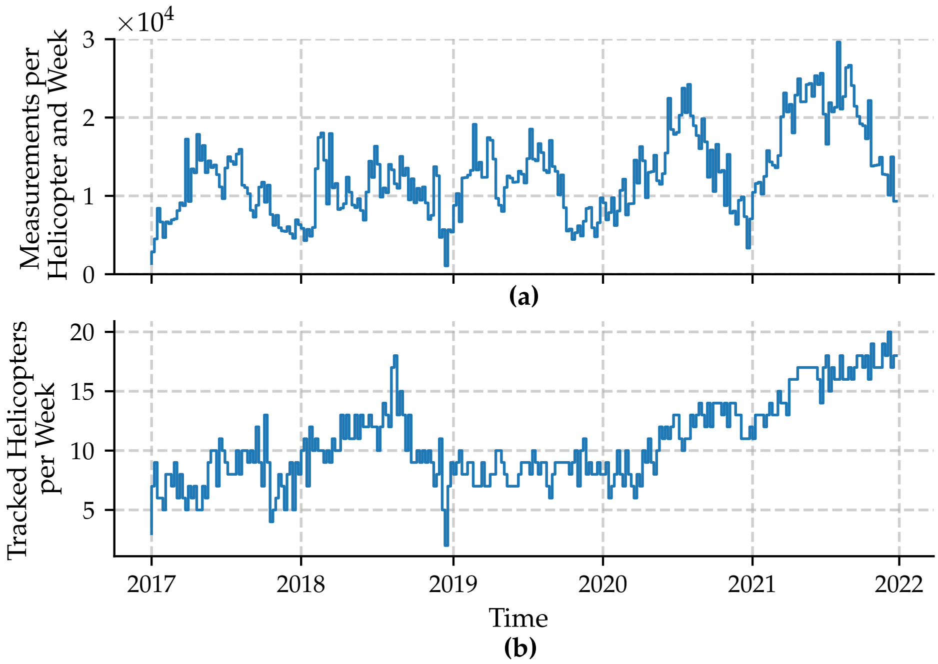


Figure 6. (**a**) Mean number of measurements per helicopter within the filtered data set. (**b**) Number of tracked helicopter registrations per week.

A total of 62 *EC*135 helicopter registrations are included in the filtered data set. Figure 7 shows the measurements per helicopter registration—the top 20 helicopters account for approximately 92% of all measurements. All operators are represented in the data, which may help in exploring differences between them.

Figure 8 shows that the majority of data are from the latest *EC*135 type, the *H*135 (*EC*135 *T3* and *P3*). It also shows the general trend that the data are increasing every year, and that this is not only due to newer helicopter models. A decrease in the total amount of received measurements per year was only recorded in 2019, where the *H*135 is almost the sole helicopter type represented in the data.

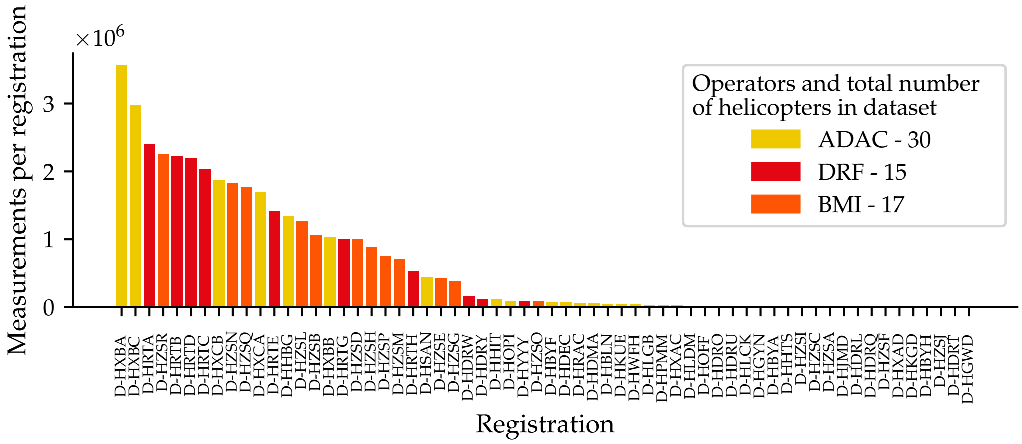


Figure 7. Number of measurements of each registration within the data set.

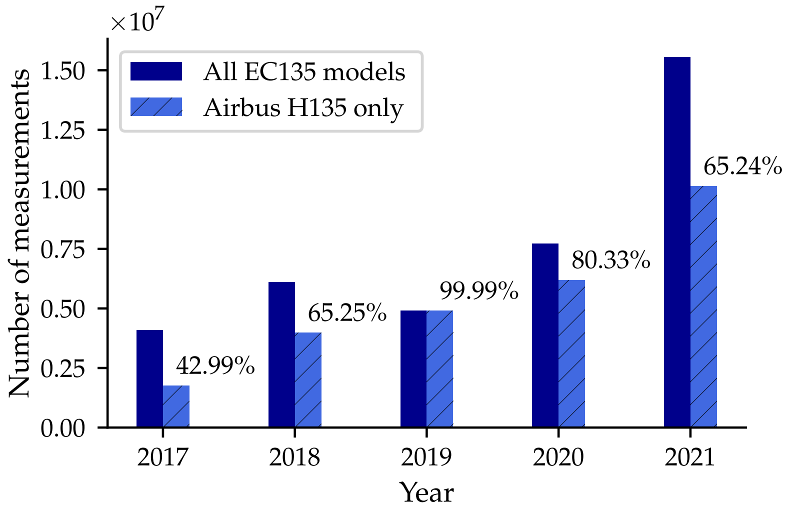


Figure 8. Number of measurements per year and share of the helicopter model *Airbus H*135.

4. Application and Results

The described UM approach is applied to a small subset of the HEMS data set to compare the usage of helicopters of the same type and mission objectives. The data analysis of different station areas indicated that the quality of the ADS-B data, in terms of the completeness of the flight profiles, varies significantly. Urban areas with few obstructions and terrain tended to have better coverage, although this is not universally valid. Data quantity and quality depends not only on the terrain and the ADS-B receiver coverage but also on the individual helicopters operating the station for only a certain period of time.

4.1. Description of the Example Use Case

Two helicopters based at two different station locations, Berlin and Friedrichshafen, each with five representative flights, were selected for the further application of the UM methodology. Table 2 summarizes the characteristics of the selected helicopters.

Table 2. Overview of the selected helicopters.

Registration	Operator	Station	Location	Model Type	Entry into Service
D-HXCB	ADAC	*Christoph 31 (CHX31)*	Berlin	*Airbus EC135 T3*	2020
D-HRTA	DRF	*Christoph 45 (CHX45)*	Friedrichshafen	*Airbus EC135 T3*	2017

Since the entry into service of the new H135 helicopter *D-HXCB* at the Berlin *Christoph 31* station, the number of ADS-B data and complete flights in the data set have increased significantly. *Christoph 31* is the German HEMS station with the most HEMS missions per year [34,37]. In contrast to the German capital, the Friedrichshafen station is located in a more rural environment in southern Germany, close to the Alps (see the map in Figure 4). Both stations predominantly serve the main RTH mission type with the same helicopter model. Therefore, a difference in usage is mainly influenced by the differences in the environment and the specific characteristics of the missions. From each station, five complete flights were extracted from the data set with the flight profiles shown in Figure 9.

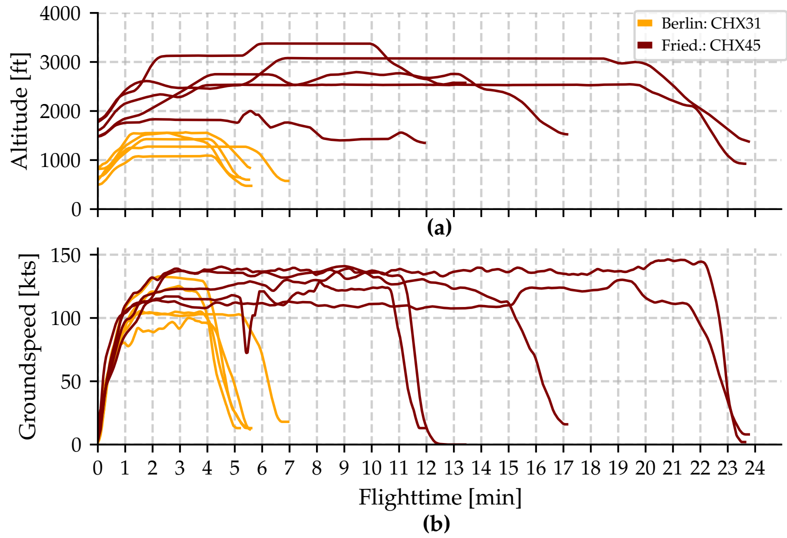


Figure 9. (**a**) Altitude profiles of the five selected flights from station *CHX31* and *CHX45*. (**b**) The corresponding groundspeed profiles.

The flight profiles show significant differences between the two helicopters. While the Berlin flights represent the urban HEMS flights with short duration and a typical climb, cruise and descent profile, the Friedrichshafen flights show more variance in terms of duration, step climbs and groundspeed deviations. The Friedrichshafen flights are of longer duration, and the destinations are mainly other hospitals at a greater distance. This could indicate that patients had to be transferred to specialized care not available at the smaller hospitals in Friedrichshafen. It can also be seen that the station location in Friedrichshafen is situated at a higher elevation, and the destinations are at a higher altitude when compared to the Berlin flights.

The differences in the flight profiles are summarized in Figure 10. For the Friedrichshafen helicopter, the median groundspeed of 122.8 kts is significantly higher than for the Berlin flights, which can be attributed to the longer cruise phases of *CHX45*. Most groundspeed values (50% within the interquartile range) of the Berlin flights are between 65 kts to 105 kts, which is a larger spread compared to the Friedrichshafen flights. Comparing the boxplot of the altitude profiles, the Berlin flights show lower variability and a lower station elevation. The differences in these statistical metrics of the flight profiles indicate a difference in usage, which is quantified and aggregated further with the usage monitoring approach.

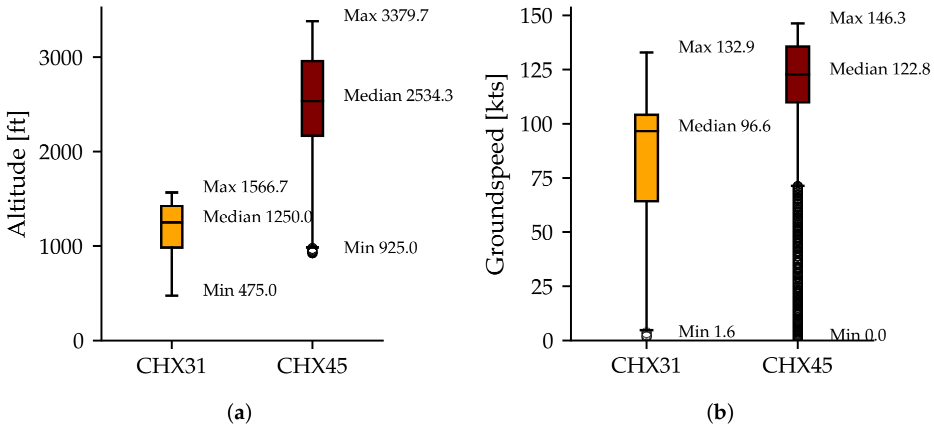


Figure 10. Boxplots and statistic of the chosen subset of flights for (**a**) altitude and (**b**) groundspeed.

4.2. Application of the UM Methodology and Discussion

As a use case, the maintenance organization of the two selected helicopters would analyze the specific gearbox usage at the time of the overhaul. A TBO of 4000 FH is assumed for the *EC*135 helicopters as described in Section 2.3. The selected flights of each helicopter is then scaled up to the TBO, resulting in approximately 2685 flights of *CHX45* and 8314 flights of *CHX31*. The specifications of the MGB of *EC*135 helicopters are summarized in a paper by Doleschel and Emmerling with the input speed of the MGB assumed to be constant at $\omega_{MGB,EC135} = 5898\,\frac{1}{\text{min}}$ [32]. Figure 11 shows the histogram of the calculated torque for both scaled flight data sets.

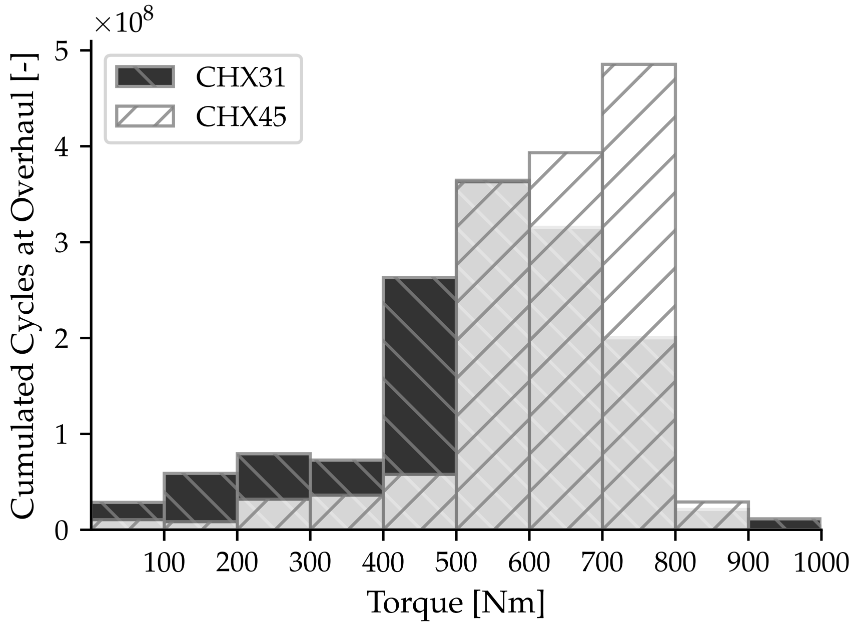


Figure 11. Torque histogram of the scaled flights of *CHX31* and *CHX45*.

As can be seen in the histogram, the MGB of *CHX45* experienced more cycles at higher torque classes compared to *CHX31* in Berlin. For *CHX31*, most cycles were counted in the 500 NM to 600 NM torque class, while the maximum number of cycles of the *CHX45* MGB are counted in the 700 NM to 800 NM class. Applying the presented UM methodology, the resulting spectra are shown in Figure 12, representing the usage of the two helicopters.

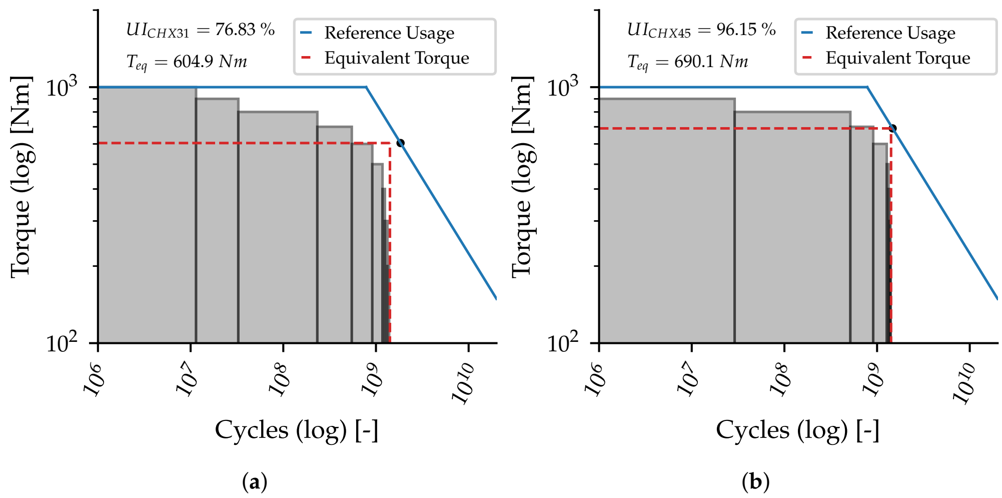


Figure 12. The result of the usage analysis summarized as summed torque collective with UI and T_{eq} for (**a**) *CHX31* and (**b**) *CHX45*.

Differences in the flight profiles and torque spectra are reflected in the calculated usage indicators. For Berlin, the calculated UI is 76.83%, and for Friedrichshafen, the calculated UI is 96.15%. The equivalent torque as another usage indication of *CHX45* is higher as well. As a visual aid, the red dashed line of the equivalent torque and the distance of its corner to the reference usage represents the usage of the MGBs as well.

4.3. Discussion

The results indicate more demanding usage of the *CHX45* gearbox with a possibly associated increase in damage and maintenance expense during the overhaul. Since the UI is calculated by relating it with the assumed reference flight profile and usage, it represents a relative measure of usage. Therefore, the interpretation of a single UI is not possible without knowledge of the reference profile or results from other helicopters. If the UI were calculated for each MGB, a comparison could be associated with the findings during overhaul and lead to an improved maintenance strategy or new service offers. The causes for the different torque loads cannot be derived with certainty from the flight profiles without further data analysis, parameter studies and expert knowledge. The various influences—station elevation, groundspeed, number of step climbs due to terrain, cruise time, mission time, etc.—each have an impact on the aggregated usage indication. With the described methodology, such an analysis could help redefine the design of the gearbox, adjust safety factors and analyze the impact of different usage scenarios on maintenance expenses. Our assumption that the helicopters' MGB usage varies for the same helicopter and mission type was confirmed by quantifying it with the described methodology. The relationship to actual gearbox damage needs to be analyzed further to confirm the usefulness of the approach.

In terms of the accuracy of the methodology, the *BADA-H* model has shown to be suitable for the efficient calculation of performance with large input data. Uncertainties in the computation are due to the underlying assumptions and the combination with ADS-B data. Unlike other mission types, short urban HEMS flights have a larger fraction of the flight time within ground effect and idle on the ground, which is not implemented in *BADA-H*. Since the coverage of ADS-B data rarely includes the time of the helicopter on the ground, this influence could not be quantified. A larger uncertainty arises from neglecting wind effects in the power calculation, since airspeed contributes to it in cubic form. The integration of wind information from open data sources could enrich ADS-B data without the need for a change in the model structure and further improve its reliability for industrial use cases. The helicopter mass assumption could be improved as well if the specific operational mass is known. For this, an analysis of the ADS-B data could reveal whether a patient is on board the helicopter.

5. Conclusions and Future Work

Usage monitoring is a basic approach within the PHM framework that is often neglected because it relies on the analysis of recorded usage parameters and its statistical analysis without more sophisticated algorithmic calculations. This is also the main advantage of UM, where observable parameters of the operations and operating conditions can be easily monitored and provide insights when analyzed together with design specifications and empirical evidence from day-to-day maintenance. In the presented work, we argue that the benefits of UM for helicopter gearboxes can be further exploited by integrating open-access ADS-B flight data. The described methodology uses flight data from the *OpenSky Network* in combination with the *Eurocontrol BADA-H* helicopter flight performance model to calculate the associated power output of the helicopter turbine engines. Converting the power to torque and applying a damage accumulation theory with a designed reference usage, a gearbox usage indicator is derived. For the application of the method and more detailed analysis of helicopter usage, a five-year-long ADS-B data set was extracted from the *OpenSky Network* database. The data set comprises 38 million measurements of German HEMS helicopters from 2017 to the end of 2021. As an example use case, selected flight profiles of two helicopters stationed in Berlin and Friedrichshafen in Germany were analyzed, and a significant difference in its usage was calculated.

The approach is generic and relies only on tools that are accessible to researchers, independently of access to or the installation of HUMS. With the methodology, various helicopter fleet usages can be compared to have an information gain for the overhaul process. Overall this supports potential improvements to maintenance strategies and a transition from scheduled maintenance to a usage-based maintenance. Due to the generic approach, improvements can be achieved when using more detailed flight performance models and integrating more information of the flights, such as wind or identified flight regimes. From a maintenance perspective, it might be beneficial to calculate the torque profiles for each individual component to manage the replacement of parts with their individual usage and operational time. The extracted and published data set can be of further use in providing insights into the specific usage of helicopters. Together with the metadata from HEMS stations and helicopters in Germany, HEMS operations can be analysed to gain a better understanding of today's and future urban air traffic.

Author Contributions: Conceptualization, D.H.; methodology, D.H.; software, D.H.; validation, D.H., J.L. and F.R.; formal analysis, D.H.; investigation, D.H.; resources, D.H., J.L. and F.R.; data curation, D.H.; writing—original draft preparation, D.H.; writing—review and editing, D.H., J.L. and F.R.; visualization, D.H.; supervision, D.H.; project administration, F.R.; funding acquisition, D.H., J.L. and F.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research is part of the *smartHUMS* research project funded by the Federal Aeronautical Research Programme of the German Federal Ministry for Economic Affairs and Climate Action (grant number 20D1918C). The APC was funded by the Technical University of Darmstadt.

Data Availability Statement: The data presented in this study are openly available in the TUdatalib repository at https://doi.org/10.48328/tudatalib-959 (accessed on 24 September 2022).

Acknowledgments: The authors thank the *OpenSky Network* for providing open access data to research and V. Mouillet from Eurocontrol for the provision of the *BADA-H* model. We acknowledge support by the Deutsche Forschungsgemeinschaft (DFG—German Research Foundation) and the Open Access Publishing Fund of the Technical University of Darmstadt.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

ADS-B	Automatic Dependent Surveillance-Broadcast
DUH	Dual-Use-Helicopter
FC	Flight Cycles
FH	Flight Hours
HEMS	Helicopter Emergency Medical Services
HM	Health Monitoring
HUMS	Health and Usage Monitoring System
ITH	Intensive Care Transport Helicopter
MGB	Main Gearbox
MRO	Maintenance Repair and Overhaul
RTH	Rescue Transport Helicopter
TBO	Time Between Overhaul
UI	Usage Indicator
UM	Usage Monitoring

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