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Analysis of the Dependability of Position Lights of Aircraft

Marcel ŠTĚPÁNEK[1*], Kamila HASILOVÁ[2], Milan PŠENIČKA[3]

[1]Department of Aviation Technology, Faculty of Military Technology, University of Defence, Kounicova 65, 66210, Brno, Czech Republic
[2]Department of Quantitative Methods, Faculty of Military Leadership, University of Defence, Kounicova 65, 66210, Brno, Czech Republic
[3]AERO Vodochody AEROSPACE a.s., U Letiště 374, 25070 Odolena Voda, Czech Republic

*Correspondence: *marcel.stepanek@unob.cz*

Abstract

This article focuses on position lights on the subsonic advanced light combat and trainer aircraft Aero L-159 Alca with an emphasis on the dependability of the position lights. Through long-term operation of the L-159 aircraft and continuous recording and reporting of faults, we are able to perform a comprehensive reliability analysis of lighting elements. Based on such observations, it is possible to create a reliability predictive model for lighting and signalling components, with the Poisson process being employed in this study. In addition, analysis and comparing failure rates can deal with the degree of criticality of the influence of position light failures on air traffic safety. The results of this study are crucial for enhancing understanding and safety measures in the area of dependability of lighting and signalling systems on modern military aircraft.

KEY WORDS: *aircraft, avionic, position light, dependability, reliability, failure rate, fault, prediction, Poisson process.*

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1.Introduction

Prediction of the technical condition of aircraft and its equipment is a significant requirement to ensure a high level of reliability of aviation technology and flight safety. The essential condition for dealing with the problem of the failure prediction is either the collection of data from the operation of the given component, or from the values of specific diagnostic parameters. Since data collection systems are common part of modern avionics systems, it is possible to use the principle of analytical estimation of errors based on the evaluation of output parameters. If it is not possible to find a suitable parameter (mileage or time until oil change, visual condition of a tire until its replacement, etc.) for the estimation of failure, the technical condition of the aircraft system or entity is evaluated only based on statistical prediction methods. [1]

Position lights are a mandatory part of any modern aircraft. Their purpose is to ensure visibility and safety during all phases of flight. In second section, we will focus on the importance of position lights and, related norms and standards. In addition, a brief description of the position lights on the selected aircraft type follows. A technological comparison of lighting elements will be conducted with focusing on design changes and innovations implemented on the new generation aircraft. [1] [2]

The most avionics faults on an aircraft are diagnosed and recorded by on-board monitoring systems. In the case of position lights, the failure is reported during an operational inspection (one-time, pre-flight, mid-flight, post-flight inspection) or during prescribed maintenance according to technical documentation of an aircraft. These inspections are carried out by the aircraft avionics engineers. It is therefore their responsibility to find and describe the fault and its cause, mission related consequences and fault mitigation. Recorded faults and failures their descriptions are collected in an integrated logistics system. Part of this registration system is the "aircraft maintenance" functionality, with specific agenda for "failure forms". All defects of lighting elements are listed here, together with all other faults and failures for all aircraft components. The collected data are analysed and process by the operator as well as provided to the aircraft manufactured for further analysis to allow them constantly improve safety and reliability parameters of each aircraft system in time.

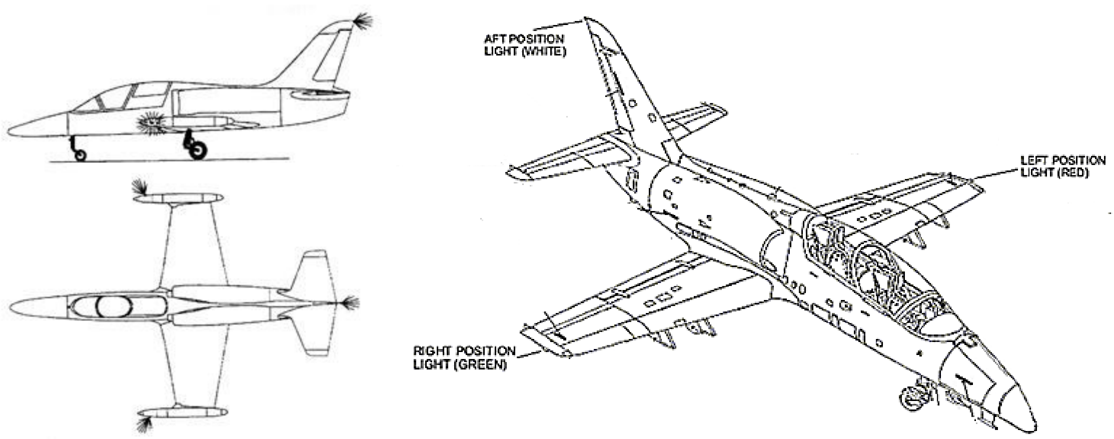
To achieve a comprehensive dependability analysis of the position lights on the L-159 aircraft, we employed a robust methodology that involves the systematic collection, analysis, and processing of operational data. We consulted data entry and record keeping experts for data collection, which allowed us to minimize information bias in the data set. This collaboration ensured that data were accurately recorded and systematically stored, increasing their validity and reliability for subsequent analyses. As a result, the risk of misinterpretation is greatly reduced. [3] As a result we achieve more precisely focuses on evaluating the probability of failure of these lighting components, considering the technological design of the aircraft's lighting systems. The analysis is grounded on empirical data derived from the operational use and maintenance records of the L-159 aircraft by the Czech Air Force.

By employing the Poisson process, we aim to develop a predictive model for the reliability of lighting and signalling components. This study is novel in its approach as it combines extensive real-world data with advanced statistical modelling techniques to enhance the understanding of the dependability of aviation lighting systems. The significance of this research lies in its potential to improve maintenance practices, spare parts planning and safety protocols for military aircraft. Through detailed analysis and comparison of failure rates, we can assess the criticality of position light failures and their impact on air traffic safety. The results of this study can be used for both the academic community and practitioners in the field of aviation safety and reliability.

2. Aircraft and Description of its Position Lights

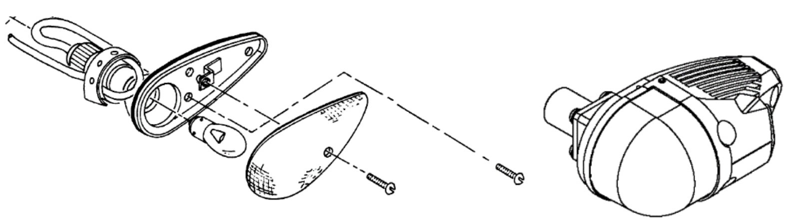
Position lights are crucial for ensuring the visibility and safety of aircraft during flight. In the past, incandescent lamps and low-pressure fluorescent lamps were commonly used in aircraft. However, recent advancements have led to the adoption of more advanced technologies such as electroluminescent lighting and liquid crystal displays. The development is increasingly focusing on the use of LEDs for lighting and signalling on aircraft due to their high visibility, reliability, and low energy consumption. [4]

The primary function of position lights is to indicate the presence of an aircraft and to determine its position and shape (Fig. 1). The L-159 aircraft (light, subsonic, fighter aircraft, single or double-seat aircraft with a wide range of missions) has three position lights on the outer surface of the aircraft. The white light is located in the highest part of the trailing edge of the rudder (vertical stabilizer or tail fin - Fig. 3). Another pair is located on the outer edge of the fuel tanks (Fig. 2). The right light is green, the left light is red. [5] The L-39NG aircraft (new generation double-seat turbofan- powered military trainer and light combat aircraft) has position lights located on each trailing edge of the wing and on the trailing edge tip of the vertical stabilizer. The colour distribution is identical to L-159, both following the standards of International Civil Aviation Organization (ICAO). [6]



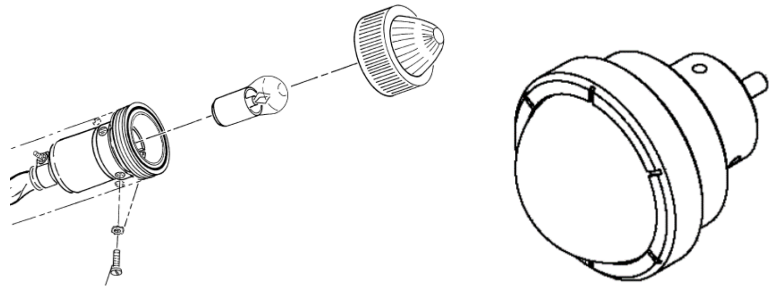
(a) (b)

Fig. 1. Placement of position lights [6] [7]: a) on the left L-159; b) on the right L-39NG)



(a) (b)

Fig. 2. Wing position light (red, green) [7]: a) old type on the left L-159; b) new type on the right L-39NG.



(a) (b)

Fig. 3. Rear position light (white) [7]: a) old type on the left L-159; b) new type on the right L-39NG).

Designing and implementing position lights (also known as navigation lights) on aircraft involves adhering to various international and national standards and regulations. These standards ensure that the lights provide the necessary visibility for the aircraft, aiding in the prevention of collisions by allowing pilots to determine the direction of other aircraft during night time and in conditions of reduced visibility. ICAO sets international civil aviation standards, including those for aircraft lights, through its Annexes to the Convention on International Civil Aviation (Chicago Convention). Specifically:

- Annex 6 (Operation of Aircraft): It includes general requirements for aircraft lights. [8]
- Annex 14 (Aerodromes): Although primarily focused on aerodromes, it also includes some standards that describe how aircraft lights should be visible from the ground. [9]

For civil aircraft operating within Europe, Europe Aviation Safety Agency (EASA) regulations also apply, which often mirror or adapt ICAO standards to the European context. In addition to international standards, individual countries may have their own specific regulations and requirements (NAA – National Aviation Authorities). Aircraft operators must ensure they comply with the regulations applicable in their country of registration and operation. While the specific requirements can vary depending on the aircraft type and jurisdiction, they generally include guidelines on:

- Colour: Position lights must be red on the left (port) wing, green on the right (starboard) wing, and white on the tail.
- Visibility Range: The lights must be visible from a certain distance, often several miles, and at specific angles to ensure they can be seen by other aircraft in the vicinity.
- Intensity and Flash Patterns: There are specific requirements for intensity and flash patterns to ensure they are conspicuous.
- Operation: Regulations specify when the lights must be operational, such as during night operations or when operating under Instrument Flight Rules (IFR).

All the above-mentioned requirements for the characteristics and conditions for civil aircraft position lights are incorporated into military defence standards with the help of individual military authorities. For Europe and the Czech Republic, these are bodies such as The European Defence Agency (EDA), the European Military Airworthiness Authorities Forum (MAWA) and the National Military Aviation Authority (NMAA). [10]

3. State of the Art

Current events on the defence and security scene of the Czech Republic are undoubtedly the ongoing modernization of the military technologies of the Air Force of the Czech Republic. Korecki et al. [11] discuss the importance of aircraft life cycle phase analysis and its relevance to financing and supply. Definition of the design and development phase, the production phase, the operation phase and the recycling and disposal phase. The Life Cycle Engineering (LCE) phases and the defining boundaries of the system are closely related to the following text.

Available scientific resources dealing with avionics data collection, reliability analysis of aircraft lights and display systems use traditional methods such as failure-free modelling and reliability prediction, but in addition, today's authors often use alternative models and methods to increase accuracy and applicability in real-world scenarios.

The importance of working with data in general and the methodology of this issue are described by Prakapienė and Prakapas. [3] Data accuracy is derived from a systematic process of data collection, analysis, interpretation and synthesis to provide timely and valid information for statistical and subsequent predictive models. Cheng et al. [12] introduced a novel fault diagnosis method for aviation general processing modules, utilizing prognostics and health management (PHM) technology to assess the health status of avionics systems, including lighting circuits. This approach integrates parameter acquisition, feature extraction, failure analysis, and system fault location to accurately diagnose faults. Gao, Li, and Dai [13] developed a fault prediction method based on an echo state network (ESN) for avionics, including lighting systems. Their approach, leveraging one-dimensional wavelet denoising and z- score standardization, significantly improves medium and long-term fault prediction accuracies. Tameh, Sawan, and Kashyap [14] proposed an optical, analogue, self-referencing, ratio-metric smart displacement sensor for avionics. Its design aims at enhancing the reliability of position sensing in lighting systems by mitigating power fluctuations. MacLean, Richman, and Richman [15] analysed the predictability of aircraft failures, including lighting systems, as they age. They applied a Poisson regression model to study unscheduled landings due to moderate mechanical failures, highlighting the impact of aging on system reliability. Samara et al. [16] introduced a statistical method for the independent monitoring of single sensors in aircraft, enhancing the reliability and safety of aircraft lighting systems. This approach addresses abrupt faults characterized by smaller time constants than those of the aircraft. Pandian et al. [17] critiqued traditional reliability prediction methods in avionics, suggesting that handbook-based prediction methods often lead to inaccurate results. They advocated for alternative approaches like physics-of-failure and data analytics for prognostics and systems health management. Furse and Safavi [18] demonstrated the feasibility of spread spectrum sensors for locating faults in aircraft wiring, including those affecting lighting loads. This technology promises significant advancements in identifying intermittent faults that impact lighting system dependability. Menu, Nicolai, and Zeller [19] discussed designing fail-safe architectures for aircraft electrical power systems, emphasizing the critical role of reliable power supply in ensuring the functionality of position lights and other safety-critical components. Mesgarzadeh, Söderquist, and Alvandpour [20] highlighted the challenges posed by silicon aging on the reliability of avionics systems, including lighting controls. As Complementary Metal–Oxide–Semiconductor (CMOS) technology scales down, aging accelerates, necessitating considerations for longevity in design.

This review underscores a multidisciplinary approach to enhancing the dependability of aircraft position lights, incorporating fault diagnosis, predictive maintenance, and innovative sensor technologies. The integration of advanced diagnostics and probabilistic modelling offers promising pathways for improving not only the reliability and safety of aviation lighting systems but improves the general safety of aircraft operation overall.

4. Data and Methods

The information system of the Air Force of the Army of the Czech Republic is used as a data source. It collects and stores all records of faults and failures and other operational data of the fleet. The collection and processing of data is therefore carried out thanks to this monitoring platform. We use this data source for our statistical analysis and predictive methods. The mentioned system for operational data acquisition is a military information logistics system used for official purposes of the Czech Army, for this reason the data are not published in their entirety, but only partial samples are demonstrated (see Table 1).

Table 1.

Partial data sample from operation of L-159 aircraft

A/C	Date of failure	Flight hours	Flight hours between failures	Flight hours between failures	Colour of position light	Type of position light
No.1	13.06.2013	225:19:34	225:19:34	225.33	WHITE	incandescent lamp
No.1	14.02.2014	264:26:26	39:06:52	39.11	WHITE	incandescent lamp
No.1	17.01.2017	431:45:13	167:18:47	167.31	WHITE	incandescent lamp
No.1	15.02.2017	437:20:13	5:35:00	5.58	WHITE	incandescent lamp
No.2	20.03.2012	267:33:43	267:33:43	267.56	WHITE	incandescent lamp
No.2	21.07.2015	483:52:47	216:19:04	216.32	WHITE	incandescent lamp
No.2	23.07.2015	491:30:39	7:37:52	7.63	WHITE	incandescent lamp
No.2	20.08.2015	516:26:08	24:55:29	24.92	GREEN	incandescent lamp
No.2	01.09.2015	526:25:15	9:59:07	9.99	WHITE	incandescent lamp
No.2	03.11.2015	535:04:02	8:38:47	8.65	WHITE	incandescent lamp

First, we use standard methods of descriptive statistics to describe the main characteristics of the data. Then, we use a Poisson process to develop probabilistic model based on operational data statistics in order to model failure rates of the position lights on the aircraft. If we have information about failure rates (e.g., how many times a position light fails per one flight hour), we can use this process to model and predict reliability parameters of individual components. However, it is important to consider the specifics of the given system and to prepare and filter appropriate data. R software is used for our data processing. [21] [22]

A Poisson process is a model used to describe events that occur independently at a constant average rate over time. In the context of our data, where the number of failures and the time between failures are known, we can use a Poisson process to model the number of failures over time, more precisely the probability of occurrence of failures.

$$p(x) = \lambda e^{-\lambda x}$$

Assuming that λ denotes the average aircraft failure rate per determined time, we obtain its estimate using the maximum likelihood method. [23] [24]

$$\hat{\lambda} = \frac{n\ (total\ number\ of\ failures)}{t\ (total\ operating\ time)}$$

In order to calculate the failure truncated two-sided confidence interval for λ, we use the Pearson χ^2 distribution, where n is the total number of failures and t is the total operating time. [25]

$$\left(\frac{1}{2t}\chi^2_{\frac{\alpha}{2}}(2n);\ \frac{1}{2t}\chi^2_{1-\frac{\alpha}{2}}(2n+2)\right)$$

Mean Time Between Failures (MTBF) is a key reliability metric that encapsulates the average interval during which position lights operate without failure. It is a key metric for maintenance planning, providing an aggregated view of component durability and functional availability. To explore the statistical spread and assess the consistency of MTBF across the fleet, the variance was examined. This measure of spread reveals the heterogeneity within the dataset, highlighting potential variability due to a variety of operational factors such as different usage patterns, maintenance practices or even different environmental conditions that the fleet may encounter. Other basic statistical data and results are also presented. [25]

In conjunction with these indicators and the exponential distribution, the chi-squared and goodness-of-fit test were employed to test the hypothesis that the observed frequencies of failure intervals conformed to a theoretical distribution, often assumed to be an exponential distribution in reliability studies for components such as position lights. This parametric test compares the empirical distribution against an expected frequency distribution and yields a p-value. It is the probability of observing the computed test statistic, or a more extreme value, under the null hypothesis, assuming the null hypothesis is true. A high p-value suggests that the observed distribution is not significantly different from the expected one, indicating the empirical data consistency with the assumed theoretical model. [26]

The main statistical methods and tools used to analyse data from fleet operation and position light failure rates include: Boxplot, which provides a visual representation of the distribution of time between failures for individual aircraft, highlighting the median, quartiles, and outliers, thus enabling quick identification of data deviations and variance. The analytical tool ANOVA (analysis of variance) was utilized to compare mean values across different groups of aircraft, aiding in identifying statistically significant differences in light failure rates between aircraft types. The step function of cumulative count of failures and the cumulative step distribution function allowed us to visualize the accumulation of failures over time and assess the frequency of occurrence of failures, which is crucial for maintenance planning and operational optimization. Finally, a histogram with the probability density function of the exponential distribution was applied to verify the assumption that the time between failures follows an exponential distribution, which is common in reliability theory and enables modelling and prediction of failures based on stochastic processes. Together, these methods provide a comprehensive view of the dynamics of failures, and their utilization is essential for ensuring a high level of operational reliability of the individual aircrafts as well as the whole fleet availability. [27]

5. Results and Discussion

As a first step, we will present the results of basic statistical data for the entire fleet and also for one selected aircraft from the fleet as an example.

Entire fleet:

- Average time between failures (MTBF): 223.85 hours
- Median time between failures: 141.49 hours
- Variance: 55.444.53 hours²
- First quartile (Q1): 28.93 hours
- Third quartile (Q3): 341.50 hours

Aircraft No.1:

- Average time between failures (MTBF): 109.33 hours
- Median time between failures: 103.21 hours
- Variance: 10.837.53 hours²
- First quartile (Q1): 30.73 hours
- Third quartile (Q3): 181.82 hours

Figure 1 presents a boxplot displaying the time between failures of position lights for individual aircraft. Each box represents a single aircraft, and the height of the box indicates the interquartile range of time between failures, excluding extreme values.

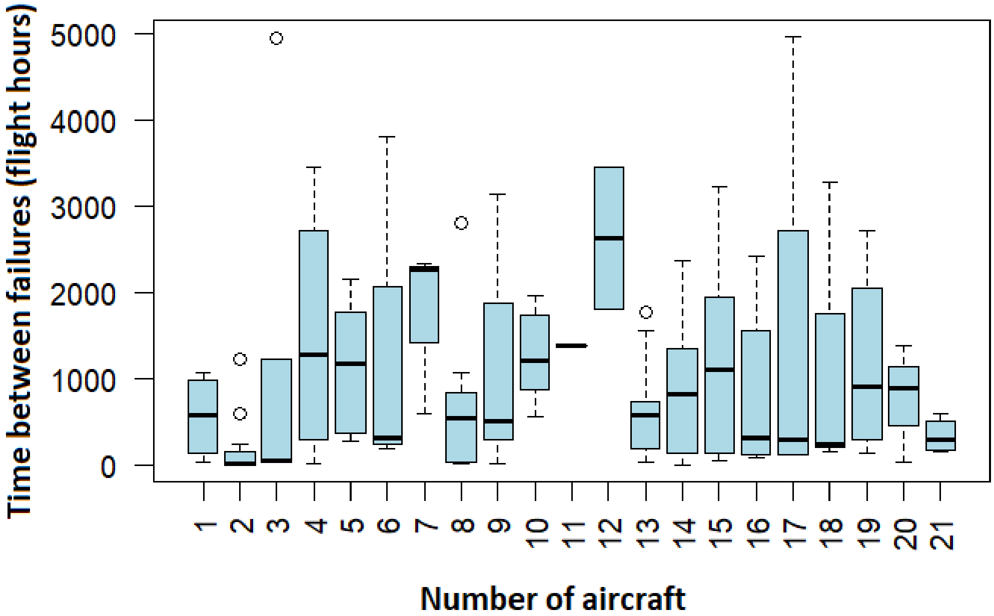


Fig. 4. Boxplot for time between failures of position lights

From the Figure 4, it is evident that some aircraft exhibit a very wide range of times between failures, which may indicate inconsistent reliability. There are notable extreme values for some aircraft that could require further investigation (why there was such a long or short interval between failures). The medians vary, suggesting that the average time between failures differs among aircraft. A boxplot graphically displayed the distribution of data points in groups based on quartiles and outliers, which are key pieces of information that can be formally tested using ANOVA. The results of the ANOVA test are summarized in Table 2.

Table 2.

ANOVA table with aircraft (A/C) being a factor (df stands for degrees of freedom)

Source	**df**	**Sum of Squares**	**Mean Squares**	**F-statistic**	**p-value**
Factor (A/C)	20	2.30×10^{7}	1149899	0.935	0.546
Residuals	87	1.07×10^{8}	1230306		

The F-statistic value of 0.935, accompanied by a p-value of 0.546, suggests that the observed variation in time between failures across the different aircraft in our fleet does not significantly deviate from the presumed equality of means. It can be concluded that there are no significant differences between groups of aircraft in the times between failures.

Therefore, we can continue in our analysis. Assuming that the occurrence of the failures follows the homogeneous Poisson process, we employed the Maximum Likelihood Estimate (MLE) method to estimate the parameter λ, representing the average rate of failures per unit of time (i.e., per one hour of flight). To determine the confidence interval for λ, we utilized the Pearson χ^2 distribution allowing us to better understand the variability of the λ estimate. The point estimate of the failure rate is.

$$\hat{\lambda} = \frac{108}{24176.25} = 0{,}004467$$

Calculated the confidence interval for λ with 95% confidence level is following: (0.003664526; 0.005393422).

In our analysis, we also generated a step cumulative plot based on the data obtained from the fleet of the aircraft. Result can be seen on the left panel of Figure 5. The shape of the counting process function is more or less linear with one exception at the beginning, which is cause by one of the aircrafts. Aircraft No.2 had a very unusual occurrence of position light failures during service (see the right panel of Figure 5). However, this anomaly does not influence the overall behaviour of the failure occurrence in the entire fleet.

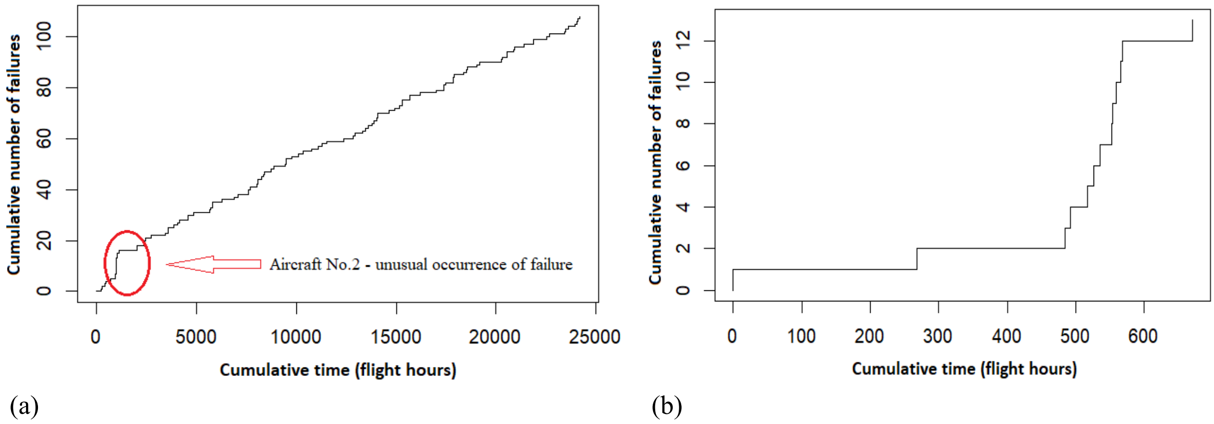


Fig. 5. Position light failures during service: a) step cumulative graph of the number of failures over time of the fleet; b) step cumulative graph of the number of failures over time of nonstandard occurrence aircraft No.2.

Testing the homogeneous Poisson process, we take a look at the inter-arrival times of the failures, which should follow the exponential distribution with parameter λ estimated earlier. Graph of an empirical cumulative distribution function (Fig. 6) provides a key perspective on the distribution of intervals between failures within our aircraft fleet. The red curve of the estimated exponential distribution function aids in understanding that the idea of homogeneous Poisson process is correct.

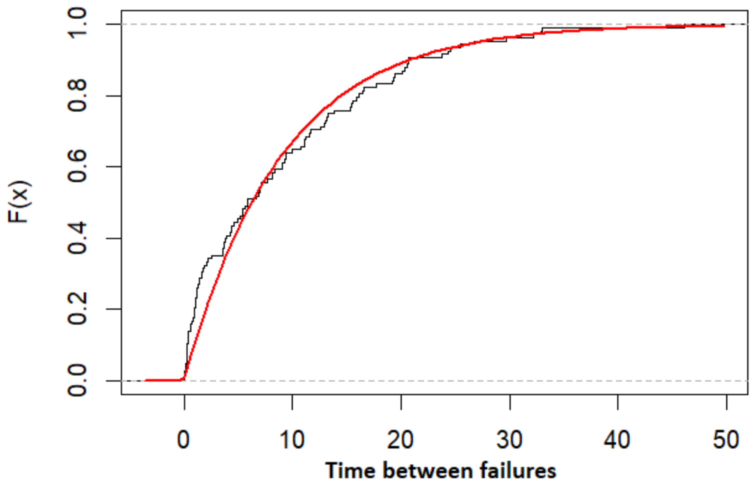


Fig. 6. Empirical cumulative distribution function (black curve) for time between failures for whole fleet and distribution function of the estimated exponential distribution (red curve).

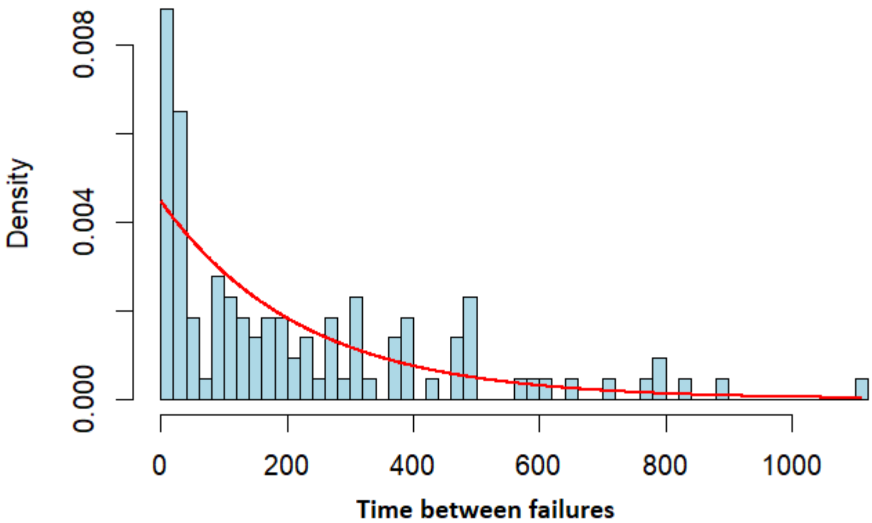


Fig. 7. Exponential distribution probability density histogram.

The exponential distribution probability density histogram (Fig. 7) provides evidence supporting the use of the exponential model to characterize the intervals between failures in our fleet. High agreement with the theoretical distribution indicates the random nature of failure occurrence, which is a key assumption for predictive maintenance and reliability planning.

Next, we support the visual result by testing the hypothesis that interval times between failures comes from the exponential distribution.

Chi-squared test:

- **X-squared (χ^2) = 25.309** (differences between expected and observed frequencies)
- **df = 18** (degrees of freedom)
- **p-value = 0.1166** (p-value greater than 0.05 implies that there is no reason to reject the null hypothesis)

Goodness-of-fit statistics

- **Kolmogorov-Smirnov statistic = 0.1452544** (lower values suggest a better fit), p-value = 0.02098
- **Cramer-von Mises statistic = 0.4335717** (lower values indicate a better fit), p-value = 0.05881
- **Anderson-Darling statistic = 3.6910957** (higher value suggests that the data in this area does not conform well to the expected distribution), p-value = 0.01241

In the context of our analysis, these tests suggest that the data have an acceptable level of agreement with the assumed theoretical distribution.

To find the probability of a given number of events in a period of time (MTBF = 223.85 hours), or the probability of waiting until the next event occurs, we need to analyse in detail the graphs of the Poisson probability function (Fig. 8) and the exponential distribution (Fig. 7), respectively.

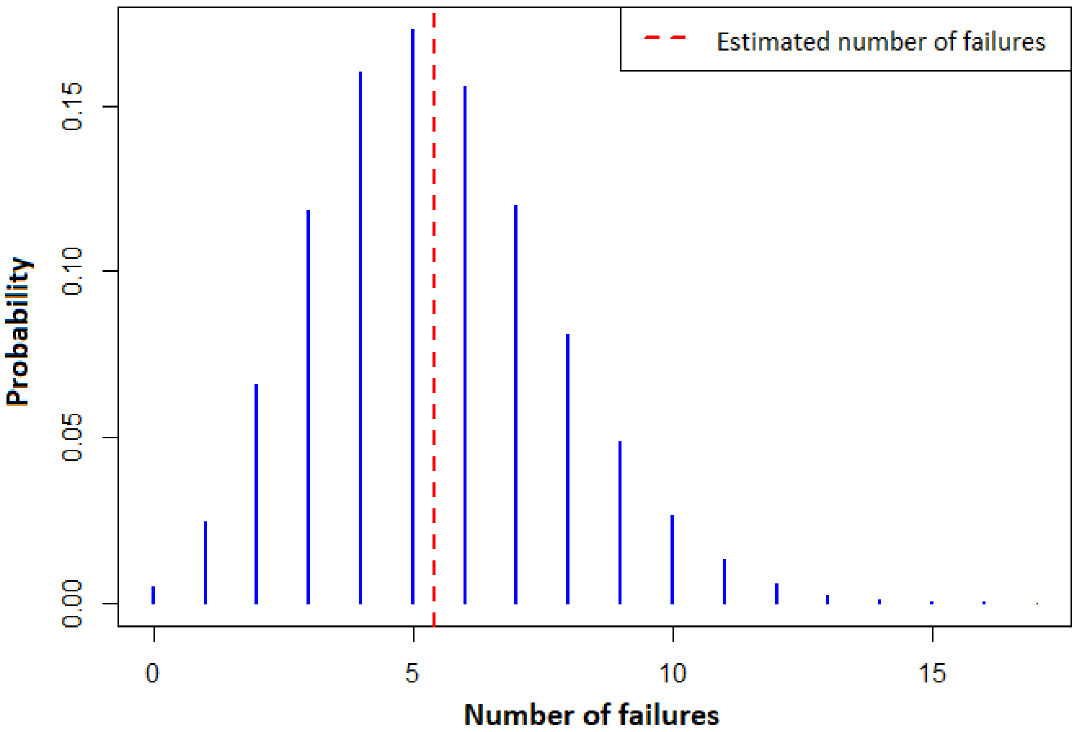


Fig. 8. Poisson process for probability of the number of failures in 1 year.

From the long-term observation of the annual raids of the fleet, an average raid in 1 year equal to 1647 flight hours was calculated. The probability function of the Poisson distribution plotted in Figure 8 shows that for our fleet the most likely number of failures in a year of operation is around the number 5, here the probability is 0.17282 (17.28%). This suggests that most of our aircraft have a relatively low number of failures, which is a positive indicator of operational reliability and maintenance efficiency. The dashed red line serves as an indicator of the number of failures with the highest probability of occurrence (5.4 failures per year). This is an approximated value based on the Poisson process calculated in software RStudio. However, this is only an approximation, as the discrete function does not allow us to use numbers other than integers. The occurrence of higher numbers of failures is significantly less likely, indicating that extreme events are not typical of the operation of our fleet. For example, the probability of 10 or more failures occur below the threshold of 0.02624 (2.624%) and less.

6. Conclusions

This article addresses the reliability of position lights on training and light combat aircraft L-159 Alca and attempts to statistically predict their future failure rates. Readiness of aviation technology is an area of critical interest in both civil and military aviation contexts. In civil aviation, discussions primarily focus on economic and safety aspects, whereas in military aviation, the emphasis extends to the continuity of pilot training and the associated security of the national airspace. Position lights play a vital role in aviation as they ensure the visibility of the aircraft and define its shape during flight. A malfunction in these lights would not comply with the aviation safety regulations, thereby compromising the safety of air traffic. Furthermore, since position lights remain illuminated throughout the flight, they are suitable for analysis based on flight hours, which eliminates the need to adjust the operation time of the diagnosed object over the flight duration.

In addition to processing and statistical analysis of data over the long operational period of this aircraft type, a cornerstone of this scientific article is the prediction of the number of failures per year. It was therefore necessary to determine the average flight hours of the fleet per training year from long-term operational data. Although options for predicting failures per month of operation, per average time of a single flight, or using the number of operational days instead of flight hours were considered, these measures would not have been sufficiently informative or relevant for appropriate prediction using the Poisson process. Statistical insignificance was also evident in examining the failure-free operations of individual aircraft separately, due to the small number of failures per aircraft. These numbers of failure are in the order of single digits.

It is also worth noting that the transition from incandescent bulbs to LEDs was carried out gradually as part of the modernization of this type of aircraft. The possible aim was to compare the reliability of both types of lighting and to confirm the expected higher reliability of LEDs. Unfortunately, the modernization took place only in recent years, and the period of LED usage did not provide enough diagnosed failures to be statistically utilized. In the future, based on observations of LED position lights and the results achieved, it may be possible to model a predictive reliability plan or determine the level of risk associated with this component failure. As part of a long-term initiative, experimental testing and measurement using highly accelerated life testing are being considered, and the evaluated results will be compared with incandescent lighting. [28] Future research may also explore predicting the location of faults based on empirical observation. The information system from which data is obtained offers not only the timing of fault detection but also the location. It could therefore be estimated whether it is better to focus on inspections (one-time, pre-flight, mid-flight, post- flight), or prescribed maintenance after certain flight hours or periodic maintenance after certain days of the equipment's life.

Even though the research is focused on relatively old but proven production technology and maintainability, the achieved results can serve as a benchmark or guide for evaluating modern, optimized types of aircraft lighting. In general aircraft operators can use research results to determine fleet maintainability or to identify potential operational problems. These results can help determine whether certain aircraft require improvements or changes in maintenance and whether some failures are too frequent and require additional attention. Based on the findings, the operator or manufacturer can optimize the intervals for prescribed maintenance of the aircraft or set an appropriate frequency for inspections focused on position lights. It is also possible to prepare the logistical support of the fleet based on the expected number of failures to prevent undesirable logistical delays. All this leads to more precise predictive analysis of the safety and reliability of lighting and signalling components for effective planning of the relevant spare parts and maintenance tasks while maintaining a high level of operational availability of the fleet.

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