INSIGHTS INTO HUMAN FATIGUE: STATISTICAL ANALYSIS IN AIRCRAFT MAINTENANCE

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Abstract

The present study delves into the realm of human fatigue within the context of aircraft maintenance in both Portugal and Brazil. The intricate technologies inherent in modern aircraft render their maintenance a pivotal function, where errors carry the potential for significant damage. The work environment, marked by its diversity and dynamism, demands uninterrupted hours and constant attention, leading to inadequate sleep and excessive workloads for professionals and, consequently, contributing to fatigue. This fatigue, in turn, amplifies the likelihood of human errors, posing a direct threat to operational safety. To comprehend the impact of fatigue on professionals, including Aircraft Maintenance Technicians (AMTs), we conducted a survey involving 312 participants. Employing questionnaires and four culturally validated scales, we assessed fatigue levels, drowsiness, workload, and quality of life. Additionally, we explored correlations between sociodemographic factors, work-related aspects, and fatigue. The findings revealed that 52.90% of participants experienced fatigue. Fatigue exhibited a positive and significant correlation with both drowsiness and workload while displaying a significant negative correlation with quality of life. Further analysis identified statistically significant differences among participants aged 36-50 who worked in shifts, at night, or in unhealthy environments. In light of these findings, we recommend that regulatory bodies develop tailored regulations and practical measures to assess and manage the risks associated with fatigue in the specific context of aircraft maintenance environments. Such initiatives are crucial for ensuring the well-being of professionals and, consequently, the overall safety of aircraft operations.

Keywords: Fatigue, Aircraft Maintenance, Human Factors

1. Introduction

Human fatigue in aviation, particularly in aircraft maintenance and operations, represents a critical safety concern requiring a more profound understanding and effective management [1]. The genesis of aviation fatigue is multifaceted, encompassing factors such as workload, prolonged wakefulness, sleep deprivation, and disrupted circadian rhythms attributed to occupational and socio-economic conditions. The former pertains to internal organizational and human-related factors, while the latter is intertwined with individual lifestyle choices and the intrinsic economic and social status of each person [2, 3].

Tracing back to the early days of aviation, pioneers like Charles Lindbergh highlighted the risks associated with fatigue [4]. Over the past two decades, fatigue has been a significant factor in major aviation accidents, and despite concerted management efforts, it remains a persistent challenge in both civilian and military aviation sectors [5].

The manifestation of fatigue varies across aviation operations. Commercial airline pilots frequently report high fatigue levels during flights, exacerbated by factors such as international travel, which introduces additional complications like jet lag [6]. Notably, fatigue also has long-term health implications, which, although not explicitly mentioned in the International Civil Aviation Organization (ICAO) definitions, significantly impact a pilot's ability to operate safely, leading to diminished performance, energy levels, cognitive functions, and mental health [7].

In aircraft maintenance, human fatigue is a paramount safety issue, affecting the performance and safety of maintenance personnel. Aircraft Technicians are especially susceptible to it due to night shifts, demanding job responsibilities, long and often unpredictable working hours, and sleep deprivation. Signs of fatigue in this context include poor decision-making, decreased memory function, and emotional and motivational impairments [8]. Managing fatigue in aviation maintenance is a complex endeavor [9]. Strategies include addressing fatigue directly and mitigating error-related damages through measures like overtime management and leave policies, as well as implementing fatigue reduction strategies such as work hour limitations and schedule adjustments. The application of Fatigue Risk Management Systems (FRMS), initially designed for pilots, has gained increasing importance in operational monitoring [8, 9].

Organizations have unique opportunities to mitigate fatigue-related issues. Adjustments in workflow and error control measures, such as line checks, can be implemented. Moreover, the impact of jet lag and circadian rhythm disruptions, significant for flight crews, is less pronounced in maintenance roles that do not involve time zone crossings [5]. Fatigue risk management strategies have gained widespread adoption in the aviation and aerospace industries. The aviation sector has evolved to incorporate or modify traditional service models in favor of FRMS, receiving support from recognized aviation authorities like the European Union Aviation Safety Agency (EASA), the U.S. Federal Aviation Administration (FAA), and the ICAO [8].

Interventions to prevent operational fatigue include limiting work hours, employing scientifically backed schedules considering circadian rhythms, promoting healthy eating habits, and educating employees about fatigue. Moreover, self-assessment strategies for fatigue, treatment of sleep disorders, and detection methods are integral to comprehensive fatigue management [7]. While environmental factors like temperature may induce fatigue, lighting and air quality improvements help alleviate it [10].

One way to address that companies have to investigate this topic is by taking into account the recent developments in machine learning techniques [11, 12]. Making algorithms to learn about each performance and socio-economic conditions will give valuable insights about each individual, being a maintenance technician, pilot, air traffic controller, or any other.

Wearable technology presents an efficient method for real-time fatigue monitoring [13, 14]. Equipped with sensors these devices can track physiological indicators such as activity levels, sleep patterns, and heart rate variability [13]. The data analysis from wearables facilitates proactive fatigue risk management, particularly in high-stakes settings like aircraft maintenance [14]. However, this approach raises concerns regarding the handling of personal data. Regulators, aviation stakeholders, and professionals must deliberate on the optimal approach to address fatigue in the maintenance environment, applying wearable technology to preemptively identify conditions that may elevate the risk of errors, compromise safety, and diminish productivity. The implementation of such technology could mark a significant advancement in real-time fatigue management, contributing to a safer maintenance environment.

2. Methodology

The approach adopted in this study employs an explanatory research strategy grounded in quantitative analysis, relying on numerical data and statistical tools to examine the relationship between variables, quantify group differences, and validate theoretical constructs within a structured empirical framework as noted by Kerlinger [15]. Authors like Fortin [16] and Loehlin [17] describe this correlational explanatory approach as a common quantitative framework, especially when the goal is to assess variables and their interrelations without interference, thus allowing an unaltered observation of natural attributes, patterns, and connections.

The study's central inquiry, which probes into the extent of fatigue among aircraft maintenance workers and its correlation with key influencing factors, seeks to understand maintenance staff's perceptions of fatigue within their professional sphere and its causative elements. It involves mapping out variable interactions and interpreting these connections through an established theoretical lens. Data will be sourced via surveys administered to these maintenance professionals, situating the study within a quantitative, descriptive, and correlational research model. As for the temporal aspect, the

research is categorized as a cross-sectional analysis because all data points will be collected simultaneously, without accounting for prior or subsequent conditions.
Human fatigue falls under the category of latent variables, requiring indirect measures for its assessment, such as fatigue, workload, and life quality.

- Fatigue as the dependent variable to be forecasted or elucidated;
- Sleep and Workload as predictive variables presumed to impact the dependent variable, aiding in its prediction or elucidation;
- Life quality, sociodemographic details, and job-related factors as moderating variables that alter the influence of predictive variables on the dependent one, clarifying the variance in their interrelation. Information related to gender, age, marital status, parenthood, and educational level are seen as sociodemographic moderators, while factors like maintenance tenure, job function, shift patterns, and work environment are categorized under job-related moderators. To effectively employ these variables in research, their conceptualization must be operationalized, setting up the data for accurate gathering, analysis, and interpretation, meaning the measurement methods for each variable need to be defined.

Consequently, a conceptual framework addressed in Figure 1 illustrates the interplay among these variables for this study's purposes.

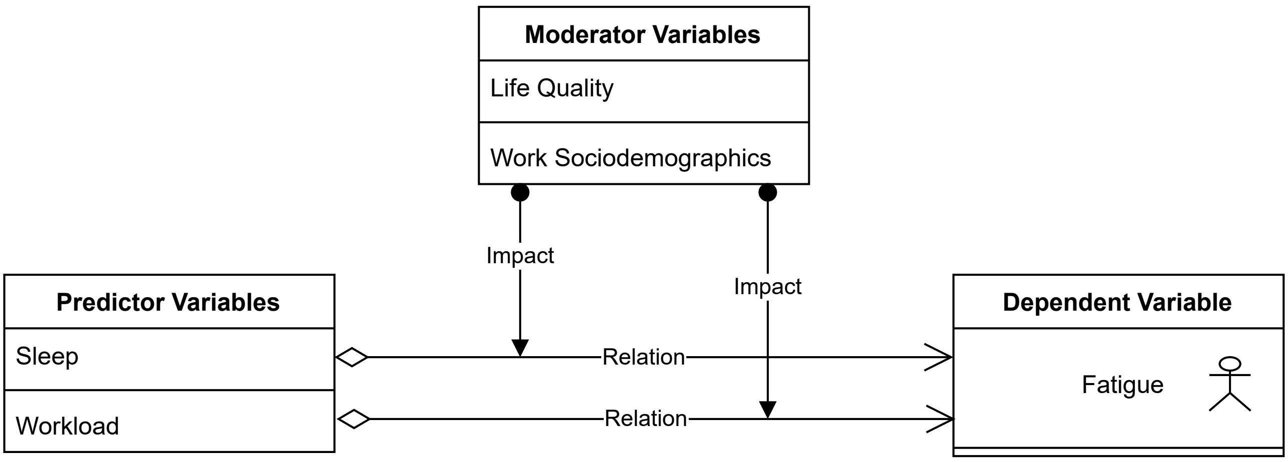

Figure 1 – Relation between the studied variables.

This study unfolds within the aircraft maintenance sphere across Brazil and Portugal, engaging professionals who operate in these environments. Data collection is a pivotal phase that entails crafting and deploying an instrument suited to the research problem, phenomena, target population, and objectives, thereby enabling investigation. A meticulously planned data collection process enhances the quality of any social research study. Quantitative research methods are employed to measure certain social phenomena, like opinions or behaviors, within a target audience, via a statistically representative sample. A survey serves here as a tool for querying a significant number of subjects about a specific social phenomenon, allowing for the quantification and analysis of the data collected. To measure individual concepts or traits, scales are utilized. Researchers often opt for instruments that are meticulously constructed or culturally adapted and statistically demonstrate good reliability (internal consistency) and item validity, ensuring the quality of study results. Cultural adaptation and validation of instruments are recurring topics across knowledge domains that utilize them, presenting complex challenges for professionals and researchers.
The subsequent analysis of survey results was conducted using SPSS (Statistical Package for Social Sciences) V27. SPSS Statistics, a robust statistical software suite developed by IBM, is renowned for its efficacy in data management, advanced analytics, multivariate analysis, and business intelligence. A critical aspect of the methodological approach was the application of Cronbach's alpha, a widely recognized measure for estimating the reliability of items and scales within research. It is defined by

equation (1), where N is the number of items, $\overline{cov}$ is the mean covariance between the different items and S represents all the matrix elements.

$$\alpha = \frac{N^2\overline{cov}}{\sum S_{Item}^2 + \sum cov_{Item}} \tag{1}$$

Cronbach's alpha is essential for determining the internal consistency of the tools used, with a reliability coefficient of 0.70 or above indicative of satisfactory internal consistency. Furthermore, the study paid close attention to the number of response alternatives on the survey items, adhering to the psychometric principle that the optimal range of response options on a scale should be between 4 and 7 to maintain robust reliability and validity; a range narrower than this may compromise these crucial psychometric properties.
The instruments selected for this study were chosen for their relevance and established reliability in measuring the constructs of interest. These included:

- The Fatigue Assessment Scale (FAS) evaluates symptoms of chronic fatigue. Uniquely, it does not differentiate between fatigue types, thereby capturing a comprehensive picture of physical and mental fatigue symptoms.
- The Epworth Sleepiness Scale (ESS) is instrumental in gauging the probability of dozing off during the day across different scenarios. This scale is valuable, providing insights into daily sleepiness levels.
- The Need for Recovery Scale (NFR) assesses the necessity for rest following work activities. It offers critical insights into work-induced fatigue and the quality of recovery periods, which is essential in understanding the overall well-being of the workforce.
- The World Health Organization Quality of Life (WHOQOL-Bref) instrument provides a broad life quality evaluation. It encompasses various domains, including physical health, psychological state, social relationships, and environmental factors, allowing for a multidimensional life quality assessment.

By integrating these diverse yet complementary scales, the study was able to paint a detailed and nuanced picture of the factors contributing to human fatigue, particularly in the context of work and lifestyle. This comprehensive approach ensures the findings are reliable and reflect the complex interplay of factors influencing human fatigue.
In statistical analysis, particularly when evaluating a normal variable distribution, the Kolmogorov-Smirnov test stands as a pivotal tool. This test is instrumental in assessing the distribution characteristics of the variables under study, indicating a rejection of the null hypothesis (the variable conforms to a normal distribution), as evidenced by a p-value less than 0.05. It suggests that the Fatigue Assessment Scale (FAS) data do not adhere to a normal distribution.
The Spearman correlation coefficient, r_S, is evaluated through equation (2), where n is the number of data points of the two variables and d_i is the difference in ranks of the "ith" element, and it is used to obtain the correlation coefficients between two variables.

$$r_s = 1 - \frac{6}{n(n^2-1)} \sum_{i=1}^{n} d_i^2, \quad -1 \leq r_s \leq 1 \tag{2}$$

Given these insights, this research pivoted towards applying non-parametric tests to analyze fatigue-related data. Non-parametric tests are particularly advantageous in scenarios where the data do not conform to the assumption of normal distribution, as they do not rely on specific distributional requirements. Within the study's scope, two non-parametric tests were employed: the Mann-Whitney and the Kruskal-Wallis test. These tests are instrumental in evaluating assumptions regarding the distribution of data samples. The Mann-Whitney test is a non-parametric method for comparing distributions between two independent groups. It assesses the degree of similarity between two samples

drawn from the same population, thereby evaluating the congruence of their distributions, being valuable in analyzing small sample sizes or in instances where the data do not meet the prerequisites for conventional statistical analysis, such as normal distribution.
The Mann-Whitney test is given following equation (3) where R_1 is the sum of the sample realizations of the small sample and n is the total number of realizations.

$$Z = \frac{R_1 - \frac{n_2(n+1)}{2}}{\sqrt{\frac{n_1 n_2(n+1)}{12}}} \tag{3}$$

Conversely, the Kruskal-Wallis test extends the functionality of the Mann-Whitney test by facilitating the comparison of more than two groups, assuming that there are no differences between them, at to perform that, it tests the null hypothesis. On the other hand, the alternative hypothesis suggests the samples possess differing values. If the P-value is less than 0.05, it leads to a rejection of the null hypothesis, indicating a significant difference between the groups. So, it can be affirmed that the Kolmogorov-Smirnov test is generally preferred for larger datasets ($n > 50$) and serves as a method to verify the normality of the distribution model. Its application is crucial in determining the appropriate analytical approach, be it parametric or non-parametric, based on the data distribution.
The Kruskal-Wallis test is given in equation (4), where k is the number of groups, n_i is the number of realizations within the group and R_i is the sum of realizations within sample i.

$$X^2 = \frac{12}{n\,(n+1)} \sum_{1=1}^{k} \frac{R_i^2}{n_i} - 3(n+1) \tag{4}$$

3. Results

In total, 312 participants who completed the questionnaires had their responses validated. The FAS scale scores, illustrated in Table 1, revealed that 147 (47.10%) participants exhibited a normal state (without fatigue), 127 (40.70%) had moderate fatigue, and 38 (12.20%) experienced extreme fatigue. Considering only the fatigued individuals, 165 (52.90%) participants were fatigued. Regarding the fatigue frequency quantified in Table 2, the results indicate cause for community concern, as only 21.4% never experienced fatigue.
The ESS scale scores, reflected in Table 3, show that 146 (46.80%) participants experienced abnormal sleepiness. Table 4 indicates the results from the NFR scale scores. It shows that 133 (42.60%) participants had higher scores, indicating a greater need for recovery concerning their workload. Table 5 represents the WHOQOL-Bref scale scores, which revealed that 88 (28.20%) participants needed to improve their quality of life, while 171 (54.80%) had a regular life quality.
To discern the relationship between the dependent variable (fatigue) and the independent sociodemographic and work-related variables, we conducted a comprehensive statistical analysis for each categorical independent variable outlined in the study, leveraging the data obtained from questionnaire responses. Regarding sociodemographic variables, out of the 312 participants, 276 (88.50%) were male, and 36 (11.50%) were female. Additionally, 35 (11.20%) were Portuguese, and 277 (88.80%) were Brazilian. Among the participants, 232 (74.40%) were married, 231 (74%) had children, and the majority, 180 (57.70%), had completed education up to the bachelor's level. Regarding the "work-related aspects" variables, out of the 312 participants, 170 (54.50%) held the position of AMT, 174

Table 1 – Fatigue levels.

Level	Frequency	Percentage
not fatigued	147	47.1
moderated fatigue	127	40.7
extreme fatigue	38	12.2
total fatigued	165	52.9
total	312	100

Table 2 – Fatigue Frequency.

		Answers	
		Number	Percentage
Fatigue	1 - never	669	21.40
	2 - sometimes	1375	44.10
	3 - regularly	508	16.30
	4 - often	428	13.70
	5 - always	140	4.50
Total		3120	100.0

Table 3 – Sleepiness levels.

Level	Frequency	Percentage
normal	166	53.2
abnormal	146	46.8
total	312	100

Table 4 – Work Load.

Level	Frequency	Percentage
low	179	57.4
high	133	42.6
total	312	100

Table 5 – Life Quality.

Level	Frequency	Percentage
life quality needs to improve	88	28.2
regular life quality	171	54.8
good life quality	53	17.0
total	312	100

(55.80%) worked in shifts, 91 (29.20%) worked during nighttime hours, 230 (73.70%) worked in an environment subject to insalubrious and danger, and 36 (11.50%) had more than one job.
Crafting clear and precise hypotheses is paramount in any statistical study, serving as the cornerstone for designing measurement dimensions and shaping the research methodology. In the context of this study, and based on the sociodemographic and work-related variables in the study, the following hypotheses were tested:

- **Hypothesis 1**: There is a correlation between the sleepiness participants feel and their levels of fatigue. Participants with higher levels of sleepiness experience greater levels of fatigue.
- **Hypothesis 2**: There is a correlation between the workload participants are subjected to and their levels of fatigue. Participants who experience high levels of workload experience greater levels of fatigue.
- **Hypothesis 3**: There is a correlation between the quality of life of participants and their levels of fatigue. Participants with a better quality of life experience lower levels of fatigue.
- **Hypothesis 4**: There is a significant difference in the level of measured fatigue based on the gender of the participant.
- **Hypothesis 5**: There is a significant difference in the level of measured fatigue based on the nationality of the participant.
- **Hypothesis 6**: There is a significant difference in the level of measured fatigue based on the age group of the participants.
- **Hypothesis 7**: There is a significant difference in the level of measured fatigue based on the marital status of the participants.
- **Hypothesis 8**: There is a significant difference in the level of measured fatigue based on whether the participant has children.
- **Hypothesis 9**: There is a significant difference in the level of measured fatigue based on the educational level of the participants.
- **Hypothesis 10**: There is a significant difference in the level of measured fatigue based on the participants' experience in aircraft maintenance.
- **Hypothesis 11**: There is a significant difference in the level of measured fatigue based on whether the participant is involved in aircraft maintenance.
- **Hypothesis 12**: There is a significant difference in the level of measured fatigue based on the role the participant plays in aircraft maintenance.
- **Hypothesis 13**: There is a significant difference in the level of measured fatigue based on whether the participant works in shifts.
- **Hypothesis 14**: There is a significant difference in the level of measured fatigue based on whether the participant works night shifts.
- **Hypothesis 15**: There is a significant difference in the level of measured fatigue based on whether the participant works in an environment subject to unhealthiness and danger.
- **Hypothesis 16**: There is a significant difference in the level of measured fatigue based on whether the participant has more than one job.

Concerning the normality of the dependent variable under study distribution (statistical adequacy), the results of the Kolmogorov-Smirnov test suggest that we should reject the null hypothesis (the variable follows a normal distribution) and conclude that the FAS scale data are not normally distributed. Therefore, non-parametric tests were used for analyses related to the fatigue variable. To

analyze the reliability of the study scale, Cronbach's alpha was calculated for all items, resulting in a value of 0.89, which indicates very good internal consistency, and therefore, the results are valid within the statistical sample n. The provided information regarding variables and statistics, such as the Median Score (Mdn), Standardized Test Statistic (z), Mann-Whitney test (U), Correlation Coefficient (r), Statistical Significance (ρ), and the Total Number of Cases (N), collectively are crucial for the statistical analysis and interpretation of the study's findings. Mdn offers information about the central tendencies of variables, aiding in understanding typical values within the dataset. Meanwhile, z, derived from statistical tests like Mann-Whitney, quantifies the significance of differences or associations, highlighting the practical relevance of research outcomes.
The Mann-Whitney test (U) itself serves as a robust tool for comparing groups or conditions when assumptions for traditional parametric tests are not met. The Correlation Coefficient (r) gauges the strength and direction of relationships, shedding light on the degree of association between variables. Regarding the Statistical Significance (ρ), this discerns whether findings are likely due to real effects or chance, ensuring the reliability of results. Lastly, the Total Number of Cases (N) determines the sample size and consequently influences the reliability of the study outcomes.

- **Hypothesis 1 - Results**: A moderate positive correlation, $r = 0.513$, $n = 312$, ρ<0.001, was identified between participants' drowsiness and fatigue levels, with higher drowsiness associated with greater perceived fatigue.
- **Hypothesis 2 - Results**: A strong positive correlation was found between workload and fatigue levels among participants, $r = 0.790$, $n = 312$, ρ<0.001, indicating higher workloads are associated with increased perceived fatigue.
- **Hypothesis 3 - Results**: The results show a strong negative correlation ($r = -0.731$, $n = 312$, ρ<0.001) was found between participants' quality of life and their fatigue levels, indicating that higher quality of life is associated with lower fatigue. Confirming Hypotheses 1 and 2, the research also established that increased sleepiness and workload correspond to higher fatigue levels. Regarding the sociodemographic analysis of the 312 participants, it revealed that the majority are male (88.50%) and Brazilian (88.80%), with most being married (74.40%) and holding up to a bachelor's degree (57.70%). These findings align with existing literature, emphasizing the impact of sleep, workload, and quality of life on fatigue in the aviation maintenance sector.
- **Hypothesis 4 - Results**: The Mann-Whitney test results show no significant difference in fatigue levels between male and female participants, with $U = 4703.5$, $z = -0.52$, ρ= 0.6. Even with the lack of statistical significance, the findings indicate that among female participants higher fatigue levels ($Mdn = 23$, $n = 36$) are found compared to males ($Mdn = 22$, $n = 276$). The results also suggest that aircraft maintenance is a field predominantly occupied by male individuals.
- **Hypothesis 5 - Results**: The Mann-Whitney test results indicated no significant difference in fatigue levels between Portuguese and Brazilian participants, with $U = 3949$, $z = -1.79$, ρ= 0.07. Despite this lack of significance, the data indicates higher fatigue levels in the Portuguese participants ($Mdn = 24$, $n = 35$) compared to their Brazilian counterparts ($Mdn = 22$, $n = 277$).
- **Hypothesis 6 - Results**: The Kruskal-Wallis test showed a statistically significant difference in fatigue levels across three age groups (Group 1, $n = 70$: 21-35 years; Group 2, $n = 156$: 36-50 years; Group 3, $n = 86$: 51-80 years), with X2 (2, $n = 312$) = 6.78, ρ = 0.034. The data also revealed that the middle age group (36-50) had a significantly higher median score ($Mdn = 23$) compared to the oldest age group (51-80 years, ρ = 0.015) with a median value of 20.5. Regarding participants aged 36-50 years, the results suggest that workload ($r = 0.790$, ρ= <0.001, $n = 156$) has a greater influence on fatigue levels than sleep ($r = 0.507$, ρ= <0.001, $n = 156$).
- **Hypothesis 7 - Results**: The Kruskal-Wallis test showed that there is no statistically significant difference in fatigue levels based on the marital status of participants, with X2 (3, $n = 312$) = 2.34, ρ = 0.504.

- **Hypothesis 8 - Results**: The Mann-Whitney test results showed no significant difference in fatigue levels between participants with and without children, with $U = 9114.5$, $z = -0.34$, ρ = 0.7.

- **Hypothesis 9 - Results**: The Kruskal-Wallis test showed no significant difference in fatigue levels based on participants' educational levels with X2 (3, $n = 312$) = 2.21, ρ = 0.529. Significant differences in fatigue were only noted among participants aged 36-50 years, suggesting higher fatigue perception in this age group among aircraft maintenance professionals. Regarding work aspects, out of 312 participants, 54.50% are Technical Maintenance Engineers, 55.80% work in shifts, and 29.20% have night schedules. The data also shows the average experience is 19.14 years, ranging from 1 to 58 years.

- **Hypothesis 10 - Results**: The Kruskal-Wallis test indicates no statistically significant difference in fatigue levels based on the participants' experience in aircraft maintenance, with X2 (2, $n = 312$) = 3.64, ρ = 0.162. Although not statistically significant, the findings suggest higher fatigue levels in participants with lower experience (1-15 years, $Mdn = 23$; 16-30, $Mdn = 22$; 31-60, $Mdn = 20$).

- **Hypothesis 11 - Results**: The Mann-Whitney test results show a significant difference in fatigue levels between participants who perform maintenance tasks and those who do not, with $U = 7209$, $z = -2.88$, ρ = 0.004, $r = 0.1$. According to the data, higher fatigue levels were observed in participants engaged in maintenance ($Mdn = 23$, $n = 233$) compared to those not involved in maintenance activities ($Mdn = 20$, $n = 79$). For maintenance workers, data also suggests that workload ($r = 0.808$, ρ<0.001, $n = 233$) has a greater impact on fatigue levels than sleep ($r = 0.527$, ρ<0.001, $n = 233$).

- **Hypothesis 12 - Results**: The Kruskal-Wallis test indicates a statistically significant difference in fatigue levels based on job functions, with X2 (6, $n = 312$) = 15.97, ρ = 0.014. The roles of "Aircraft Maintenance Technician" and "Maintenance Supervisor/Inspector" (maintenance performers) recorded significantly higher median scores ($Mdn = 23$) compared to the "Maintenance Management" role (non-performers of maintenance), with ρ <0.001 and ρ = 0.03 respectively, and a median value of 19. Regarding the roles of AMT and supervisor/inspector, the data suggests that workload ($r = 0.782$, ρ<0.001, $n = 170$ / $r = 0.870$, ρ<0.001, $n = 63$, respectively) has a greater influence on fatigue levels than sleep ($r = 0.579$, ρ<0.001, $n = 170$ / $r = 0.359$, ρ= 0.004, $n = 63$ respectively).

- **Hypothesis 13 - Results**: The Mann-Whitney test results show a significant difference in fatigue levels between participants who work in shifts and those who do not, with $U = 7887$, $z = -5.21$, ρ < 0.001. Higher fatigue levels were found in shift workers ($Mdn = 24$, $n = 174$) compared to non-shift workers ($Mdn = 20$, $n = 138$). Regarding shift workers, the data indicates that workload ($r = 0.842$, ρ<0.001, $n = 174$) has a greater impact on fatigue levels than sleep ($r = 0.562$, ρ<0.001, $n = 174$).

- **Hypothesis 14 - Results**: The Mann-Whitney test identified a significant difference in fatigue levels between participants who work night shifts and those who do not, with $U = 5894.5$, $z = -5.75$, ρ < 0.001, $r = 0.3$. The findings show higher fatigue levels in night shift workers ($Mdn = 27$, $n = 91$) compared to non-night shift workers ($Mdn = 21$, $n = 221$). Regarding those working night shifts, the data indicates that workload (r= 0.788, ρ<0.001, n=91) has a greater impact on fatigue levels than sleep ($r = 0.335$, ρ<0.001, $n = 91$).

- **Hypothesis 15 - Results**: The Mann-Whitney test results show a significant difference in fatigue levels between participants working in unhealthy and hazardous environments and those who do not, with $U = 6264.5$, $z = -4.51$, ρ < 0.001, $r = 0.3$. The data indicates higher fatigue levels in workers in such environments ($Mdn = 23$, $n = 230$) compared to those not working in these conditions ($Mdn = 20$, $n = 82$). The data also suggests that workload ($r = 0.778$, ρ<0.001, $n = 230$) has a greater impact on fatigue than sleep ($r = 0.481$, ρ<0.001, $n = 230$).

- **Hypothesis 16 - Results**: The Mann-Whitney test results show no significant difference in fatigue levels between participants with multiple jobs compared to those with just one, $U = 4881.5$, $z = -0.17$, ρ = 0.86.

The study's findings reveal a complex interplay of factors influencing fatigue levels among aircraft maintenance professionals. Notably, a strong positive correlation exists between workload and fatigue, emphasizing the critical role of work demands in perceived fatigue. The AMTs age also plays a significant role, with individuals from the age group 36-50 years experiencing higher fatigue levels. Maintenance workers and those working in night shifts and unhealthy environments consistently report elevated fatigue, with workload exerting a more significant impact than sleep in these contexts. Conversely, gender, nationality, marital status, having children, educational levels, and years of experience in aircraft maintenance showed no substantial influence on fatigue. This comprehensive analysis underscores the multifaceted nature of fatigue in the aviation maintenance sector, providing valuable insights for addressing and mitigating its impact on professionals in this critical field. With this information, individuals, organizations, and regulators can start to mitigate fatigue in aviation maintenance.

4. Conclusions

This study focused on human fatigue in aircraft maintenance, specifically in the current period and within Portugal and Brazil, analyzing human factors and operational safety. The primary goal was to measure fatigue levels among professionals in this field and correlate these levels with influencing factors, including sociodemographic and work aspects. Data analysis was conducted using surveys. Key findings include that 52.90% of aircraft maintenance professionals experience fatigue, with 12.20% suffering from extreme fatigue. This highlights the need for effective fatigue risk management to ensure operational safety. The study revealed a positive correlation between sleepiness, workload, and fatigue levels, with higher sleepiness and workload associated with increased fatigue. Furthermore, 46.80% of the participants reported abnormal sleepiness, while 42.60% had high workload scores, suggesting these factors significantly influence fatigue levels. Life quality emerged as a moderating factor, with a negative correlation to fatigue - higher quality of life equates to lower fatigue levels. Sociodemographic aspects showed that participants aged 36-50 were significantly more affected by fatigue. Work aspects indicated that those in hands-on maintenance roles, working shifts or night hours, or in unhealthy environments experienced higher fatigue levels. The most influential factor across all significant aspects was workload, even surpassing sleep in night shift workers, which could be attributed to increased workload in recent years, especially post-COVID-19.
The study suggests that aviation authorities should develop regulations specifically for fatigue management in aircraft maintenance, as current regulations focus more on flight crew environments. The research indicates that maintenance professionals are increasingly exposed to higher workloads, potentially leading to maintenance errors and catastrophic outcomes. Finally, the study acknowledges limitations due to the reluctance of airlines and maintenance companies to distribute surveys internally, possibly due to fears of negative feedback, litigation, and the need for changes. Future studies are recommended to develop a unified, concise fatigue assessment scale with items specific to aircraft maintenance environments, created with input from professionals in the field.

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6. Copyright Statement

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