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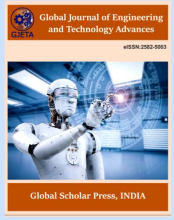

(Research Article)

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Human factors in aviation maintenance: understanding errors, management, and technological trends

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Abstract

Aircraft maintenance and inspection are complex systems that work on a time-based schedule and require teamwork of different professionals to maintain the airworthiness of aircraft. Errors in maintenance and inspection processes cause in-flight engine shutdowns, flight delays, flight cancellation, sometimes resulting in accidents and incidents that cause significant economic consequences. Due to the substantial impact on both safety and financial aspects of an air carrier, this paper focuses on hangar maintenance as the work is carried out across several shifts by different technicians, addressing various human factor issues that contribute to errors. The paper will also briefly discuss shift work and the health problems of maintenance technicians, human factor issues affecting maintenance, the significance of understanding human factor models, and the impact of maintenance and inspection errors with case studies, particularly aircraft accidents predominantly caused by human factor issues. Additionally, the paper also explores recent advances and trends in aircraft maintenance technologies, highlighting their transformative potential through predictive maintenance, robotics, augmented and virtual reality, big data analytics, blockchain, and additive manufacturing. These technologies promise enhanced efficiency, safety, and effectiveness for maintenance practices. The paper concludes by presenting insights into error management methods and providing recommendations for future research. By integrating traditional insights with cutting-edge technological considerations, this comprehensive analysis aims to significantly contribute to the evolution of safety protocols and practices within the aviation maintenance domain.

Keywords*:* Human Factors; Human Error; Shift Turn Over; Maintenance Error; Inspections Error; Error management

1. Introduction

Within the dynamic environment of global aviation, where globalization and technological advances continue to shape its development, aircraft maintenance plays a crucial role in maintaining airworthiness. This complex system operates on a precise schedule with collaboration from diverse professionals to ensure the airworthiness of aircraft. This aspect holds immense significance both in terms of safety and financial impact for air carriers, contributing to 15% of accidents between 1982 and 1991 [1]. Rankin et al. (2000) have examined the economic impacts of maintenance errors, emphasizing their dramatic consequences [2]. Engine shutdowns incur costs of approximately $500,000 each time, while flights delayed due to engine maintenance errors result in losses of roughly $10,000 per hour of delay. Cancellations caused by similar issues cost around $50,000 per cancellation [2].

Human factors in aviation traditionally focused primarily on aircrew and air traffic control (ATC) errors; however, there has been an awareness regarding their importance in maintenance and inspection errors. Under its National Plan for Aviation Human Factors, the Federal Aviation Administration (FAA) acknowledged the crucial role of humans in maintaining safe air transportation systems by researching aircraft inspectors and maintenance technicians. Over 75%

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of the time, accidents and incidents are related to pilot or human errors [3]. However, an earlier study conducted in the United States in the early 1990s found that maintenance factors are the contributing factors in 18% of accidents [3]. The Air Midwest incident in 2003 involving a Beech 1900D aircraft highlighted the tragic consequences of improper rigging of the elevator control system, leading to a loss of control during flight and a subsequent crash [4]. Similarly, Southwest Airlines Flight 1380 in 2018 experienced an engine failure caused by a maintenance error—a fractured fan blade due to metal fatigue resulted in debris damaging the aircraft, leading to the loss of engine power and a passenger's life [5]. These incidents highlight the need for improved inter-airline communications, adherence to maintenance procedures, and increased diligence during maintenance, repair, and final inspection procedures. Such events have also raised public awareness, prompting civil aviation industry players and regulatory bodies to implement safety enhancement programs, including initiatives like the FAA's Aging Aircraft Program and human factors initiatives by international bodies such as Transport Canada or the European Joint Aviation Authorities.

1.1. Types of Aircraft Maintenance

Aircraft maintenance can be categorized into two distinct types: line maintenance (LM) and hangar maintenance (HM). Line maintenance refers to routine, day-to-day tasks performed on an aircraft between flights while it is on the ground. These tasks are essential for maintaining the aircraft's airworthiness and ensuring its safe and timely departure for the next flight. Line maintenance is typically conducted at the airport gate or on the ramp and includes inspections, minor repairs, and troubleshooting. Examples of LM tasks include pre-flight checks, addressing minor repairs, and troubleshooting reported issues. When an issue exceeds their capabilities, hangar maintenance takes over.

Hangar Maintenance (HM) involves more extensive and complex tasks that cannot be performed on the airport ramp. Aircraft are taken to hangars for scheduled maintenance, repairs, and modifications that require specialized equipment and facilities. HM activities often include heavy maintenance checks, overhauls, structural repairs, and modifications/upgrades, presenting its own set of challenges. Medium and heavy tasks may occur simultaneously, depending on complexity, spanning multiple hours, and heavy maintenance may extend over days. These tasks are executed under time pressures and sometimes in challenging ambient conditions, including lighting, temperature, tight spaces, or noise restrictions. Mechanics who work at the hanger maintenance are subjected to stress as they must complete the work to meet the due date and deliver the aircraft on time. So, this paper will discuss about the hanger maintenance and related human factor issues.

2. Research Method

To determine the effect of human error in aircraft maintenance and inspection, and to evaluate the impact of human factor issues in aircraft maintenance organizations an online literature search was carried out using Google Scholar, Science direct, PubMed, and Web of Science. The search was limited to articles that are published between 1980 and 2024 using a predefined set of keywords related to human error, human factor issues, sleep, circadian rhythm disturbance, maintenance errors, inspection errors, accidents, error management strategies and countermeasures. Documents collected for analysis included manuals, regulations, advisory circulars, industry research reports, peer-reviewed articles, conference papers and books. This extensive and systematic approach ensured the robustness and comprehensiveness of the study's foundation.

Based on the reviewed literature, this paper focuses on hangar maintenance, which involves tasks extending across various shifts and the participation of different technicians. Due to its complexity, numerous human factor issues arise, leading to errors, incidents, and ultimately, accidents in aircraft. This paper will also briefly discuss the shift work and health problems of the maintenance technicians, human factor issues that affect maintenance, the significance of understanding the human factor models, and the impact of maintenance and inspection errors with some case studies i.e., aircraft accidents that occurred predominantly due to human factor issues. The paper thoroughly investigates recent advancements and trends within aircraft maintenance technologies. It emphasizes their transformative potential, particularly in the areas of predictive maintenance, robotics, augmented and virtual reality, big data analytics, blockchain, and additive manufacturing. This paper concludes by discussing the error management methods with special reference to error reporting systems both reactive and proactive error detection methods, recent trends and advancements in aircraft maintenance technologies and conclude by providing a few recommendations for future research in this field.

3. Shift Work, Health Problems, and Related Human Factor Issues in Aircraft Maintenance

Hanger maintenance task takes more than 24 hours to be completed and maintenance organizations schedule the work in shifts to be competitive in the industry. Organizations adopt either 8-hour or 12-hour shifts. On 8-hour shifts system, the shifts are referred to as morning shift, afternoon, and night shifts and on 12-hour shift system, it is referred to as day or night shift [6].

3.1. Shift Work and Health Problems

The aircraft maintenance technicians (ATM) who work at abnormal hours during the shift work (shift rotation) experience both physiological and psychological stress due to the disruptions of their biological functions like sleep and social life [7]. This shift rotation disrupts the circadian rhythms and due to the lack of quality sleep, ATMs experience fatigue and as a result, they experience memory difficulties and make mistakes that lead to errors and accidents [8]. Over time, the severe disturbances of sleep lead to chronic fatigue, nervousness, and depression [9]. These effects are intensified if ATMs work more than 35 to 40 hours per week. If not taken care of this will ultimately lead to serious medical conditions [10]. The three major risks associated with shift work are the mismatch between sleeping time and circadian rhythm, poor eating habits, high consumption of alcohol and the issues related to social life [11]. Costa reported that shiftwork causes stress which in turn increases the heartbeat, blood pressure and cholesterol level, and alters the metabolism of shift workers [7]. Costa et al. reported that 20 to 75 % of shift workers especially who work in night shift have gastrointestinal disorders such as heartburn, gas, irregular bowel movement, and constipation [9]. The research work based on fifty years data carried out by Costa revealed that gastrointestinal disorders are two to five times more prevalent in workers who carry out the task in night shift than who work in day shift [7]. Shift workers also go through psychological and emotional distress [12].

3.2. Human Factor Issues that Affect Maintenance

As hanger maintenance takes several hours to be completed it is carried out over multiple shifts. Parke & Kanki reported that depending on the complexity of the problem sometimes it even takes twelve to fifteen shifts to complete the repair on an aircraft [13]. If it takes more shifts to complete the work, then different ATMs will be working together to complete the task. So, when the ATMs in one shift leave, it is their responsibility to hand over the tasks to the ATMs of next shift by providing the essential information to carry out the task. This exchange of information requires interpersonal skills and is one of the important phases in maintenance organizations and must be performed correctly [14]. There are no regulations regarding shift turnover practices and FAR Part 121.369 only requires an organization to complete any maintenance task they begin and does not provide any structured shift turnover briefing. It states that procedures are to be followed to ensure that inspections, preventative maintenance, and other required maintenance are completed properly before an aircraft is released for service because of shift changes or similar work interruptions [14]. Shift turnover usually occurs in two ways namely written shift turnover and face-to-face shift turnovers. The written shift turnover is practiced mainly in the aviation industry when multiple shifts are involved. The vague briefing leads to errors. The ineffective communication and coordination lead to unworthy aircraft [13].

Maintenance personnel also face stress related to shift work (night shift) such as fatigue, gastrointestinal disorders, cardiovascular disorders, psychological and emotional stress which ultimately affect their performance and pose risk to aviation safety [14]. ATMs also work in an environment with time pressures, and rarely in difficult ambient conditions of lighting, temperature, confined space, and noise. Apart from this the inadequate training, unskilled personnel, poor equipment design, unavailability of proper tools, and unclear equipment maintenance and operating procedures also contribute to human error. All these interfere with the judgment ability of maintenance personnel in making decisions about their maintenance work and lead to error which ultimately causes mishaps and accidents [15].

The twelve most common causes that interferes with the maintenance personnel's judgment skills are "lack of communication, lack of knowledge, lack of teamwork, lack of resources, lack of assertiveness, lack of awareness, complacency, distraction, fatigue, time pressure, stress, and organizational norms" [14]. In 1993 Boeing investigated the human factor issues that contributed to 122 incidences and classified the maintenance error into four categories namely omissions, improper installations, wrong parts, and others [16]. The analysis of more than 1000 incidents from Aviation Safety Reporting System (ASRS) revealed that the major cause for maintenance error is the omission of a vital procedure, abnormalities in documentation procedures, and installing wrong parts [15].

4. Human Error Models

As the study examines aviation human factors, it becomes evident that its development was driven by fatal accidents such as the Aloha Airlines incident in 1980 and the BAC 1-11 windscreen accident in 1990. These incidents highlight the crucial importance of incorporating human factors into aviation, leading to an enhanced understanding of human capabilities and limitations within workplace environments.

To prevent the errors from happening, it is necessary to understand why the event occurred and identify the factors that led to it, as different strategies are required to prevent different types of errors. One of the most accepted models of human error is the skill-rule-knowledge framework and it was proposed by Rasmussen in 1983 [15]. Rasmussen classified the actions of the maintenance personnel as skill-based behavior (tasks performed routinely and does not require any conscious effort), rule-based behavior (perform the tasks based on rules or procedures), and knowledge-based behavior (required during a critical situation to perform a task). Rasmussen (1983) classified the human errors based on these behavior types' namely skill-based errors, rule-based errors, and knowledge-based errors. Skill-based errors occur when ATMs accidentally perform the incorrect step due to a lapse (failure to carry out the planned task) or slip (accidentally does another well-learned procedure). Rule-based errors occur when ATMs apply a wrong rule and knowledge-based errors occur due to the lack of knowledge, or training [15, 16]. Hobbs reported that approximately 48 % of the accidents and incidents in the aircraft maintenance organizations occur due to skill-based errors [15]. A research study conducted by Australian Transportation Safety Board (ATSB) on human factors in airline maintenance classified the errors based on SRK model and the percentage contribution of the error types are illustrated in Fig.1 [17].

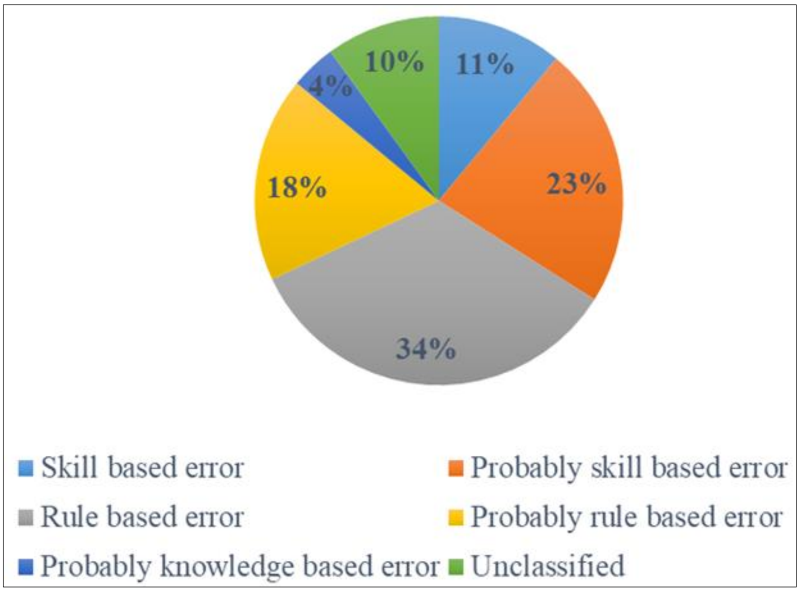

Figure 1 Human error types based on Skill Rule Knowledge based model

Based on this SRK model, James Reason proposed another model known as "Swiss Cheese" model [18]. Reason stated that though system failures are mainly caused by ATMs action, it occurs due to the combination of both latent and active failures along with other environmental forces. All these individual actions risk control, and environmental forces are influenced by the organizational deficiencies. To prevent these incidents and accidents, it is important to trace and identify all the factors that caused it and due to this, it is also referred to as root cause analysis [18].

The "Shell" (Software, Hardware, Environment, and Livewire) model which was proposed by Edwards in 1970 is now recommended by the International Civil Aviation Organisation [16]. This model divides human factors into different areas such as the interaction between people and software, people and hardware, people and environment, and interactions between people in the system. This model is most valuable in analyzing the human factor issues in the aircraft maintenance environment [17].

In addition to the SHELL model, models such as the Human Factors Analysis and Classification System (HFACS), and James Reason's "Dirty Dozen" identify and categorize human errors, contributing valuable insights to the multifaceted nature of human factors in aviation safety [16]. This holistic approach allows for a thorough examination of the complex interplay between human performance and system vulnerabilities, facilitating the development of strategies to mitigate potential threats to aviation safety.

4.1. Impact of Human Factor Errors in Aircraft Maintenance and Safety

Human error that occurs during the aircraft maintenance and inspections are attributable either to the actions or non-actions of the ATMs. Generally, the human error results in a specific discrepancy that does not exist before the maintenance work was started in that exact aircraft or results in an unsafe condition that goes undetected during the scheduled or unscheduled maintenance [16]. Human error occurring during the maintenance and inspection has contributed to numerous accidents that have happened in the aviation industry.

The unapproved procedure adopted by the maintenance personnel was the cause for American Airlines DC-10 accident (1979). The manufacturer, McDonnell Douglas (DC), recommended to remove the pylon and engine separately, but the maintenance team removed both as a single unit to save time and cost. This unapproved procedure was the cause for the accident. The worst accident in aviation history is the crash of Boeing 747, a Japanese Airlines aircraft, which claimed the life of 520 people on board in 1985. Boeing accepted that it made a faulty air cabin repair in 1978. Though it performed the regular flight checks it failed to do the checks where the repairs were done [19]. In 1988, Aloha Airlines aircraft, Boeing 737, met with an accident which was attributed to improper maintenance and inspection [15]. The cause for the Continental Express flight 2574 that crashed in 1991 was the improper communication between the ATMs during the shift turn over, i.e., the outgoing maintenance team didn't communicate to the incoming shift personnel about the importance of replacing the fasteners for the de-ice boot on the horizontal stabilizer [20]. Accidents and mishaps also occur due to the incorrect installation of components, lack of proper inspection, and quality control [16]. The Eastern Airlines aircraft, Lockheed L-1011 accident that occurred in 1983 was attributed to the improper installation. The investigation team found that all the three magnetic chip detectors were installed without the O-ring seals. The airlines have experienced twelve incidents involving the in-flight engine shutdowns and unscheduled landings due to O-ring seal problems over a period of twenty months prior to this accident [21]. The British Airways flight 5390 met with an accident in June 1990. While climbing to its cruising altitude through 17,300 feet the left windscreen of the cockpit was blown out and the pilot was partially ejected through the open window [22]. Out of the 90 bolts that secured the windscreen 84 were smaller in diameter. While the aircraft was in maintenance, there were an insufficient number of staffs, and the shift maintenance manager tried to help by fixing it himself. He failed to check the maintenance manual and didn't confirm whether it is the right type of bolt required to fix the windscreen. The investigation team also emphasized the other related risk factors such as storage of parts, issues related to the night shift, and working environment that contributed to the accident [22]. Both the Eastern Airlines and British Airways accidents highlighted how a single maintenance error could compromise the aircraft safety.

5. Error Management to Reduce the Human Errors in Maintenance

The Federal Aviation Administration (FAA) stated at the National Safety Conference, which was held in 1995, that it is essential to establish a database at the national level for human factors research in the aviation industry, especially, to develop a maintenance error analysis tool and maintenance resource management training based on crew resource management principles [14]. This section briefly discusses the efforts made in detecting and managing the human error in aircraft maintenance and inspection. There are two approaches which are widely adopted in detecting maintenance and inspection errors. The reactive method is based on error reporting systems, which help to develop error management strategies to prevent a recurring error, and the proactive detection method helps to identify the error causing events and prevent it before it occurs [23].

5.1. Error Reporting Systems Based on the Reactive Approach

This system first classifies the errors into different categories and then identifies how the human error contributed to those errors and identifies the underlying problems. So, it is a reactive approach. There are different error reporting systems. Latorella & Drury explained that these error reporting systems have certain common characteristics: All the error reporting systems are based on the events, reporting is primarily classified based on the type and structure of the aircraft, and then classified again based on the criticality of the error [24]. The reports of these systems usually bring about changes in the general procedures of inspection and maintenance.

Usually, accidents that occur in the aviation industry are investigated by the National Transportation Safety Board (NTSB). During the investigation, NTSB determines whether the maintenance was conducted appropriately and accurately as per the schedule, or whether the maintenance staff could have identified or repaired an issue that caused the accident. If they identify a maintenance or inspection problem existed, then the board considers the airline's quality control system and safety management system. NTSB investigates further to confirm whether the airlines comply with FAA regulations and manufacturers recommendations in scheduling the maintenance and inspections tasks. After the investigation, NTSB provides recommendations to FAA, airlines, and manufacturers. In case of the Continental Express accident, NTSB recommended making changes regarding shift change over at the operator's level, quality assurance programs to be adopted at the airline level and insisted FAA to oversee the quality assurance programs [20].

The incidents that occur in the aviation industry are allowed to be reported anonymously to NASA's Aviation Safety Reporting System (ASRS). This system is used mainly by the pilots; aircraft mechanics can also enter the reports to the system. Though it provides valuable database there are a few limitations: reports may be biased as they are based on the personal perspective of the reporting personnel, provides sample reports based on search terms used, and mainly used by pilots. But ASRS reports provide more detailed information than NTSB reports [2].

Airlines also have their own internal error reporting systems. They maintain the records separately based on the personal injuries, aircraft damages, equipment damages, and delays that occur due to maintenance and inspection errors. Departments within the airlines maintain these records individually and generally do not share the details with each other. This individual record keeping does not provide any quality information, and the recurring error cannot be recognized properly [25]. Due to the limitations of the internal error reporting systems, Wenner and Drury proposed a system called Unified Incident Reporting System (UIRS). It has two forms - a common reporting form which collects the data for all incidents irrespective of its origin, and the second form directs the user to one of the outcome-specific forms based on the hazard patterns [25].

The accident and incident reporting systems fail to identify the situational factor that caused the event and often ends by blaming personnel within the system. The recommended error control methods based on these two systems include providing further training to the operator and implementing additional inspection checks. However, this approach is considered ineffective because an effective method should identify the situational factors that contributed to the accident. An alternative method, Maintenance Error Decision Aid (MEDA), was developed by Boeing to identify the factors that contribute to the maintenance and inspection errors and to reduce and ultimately eradicate the probability of error occurrences in future. The main objective of MEDA is to improve the understanding of human factor issues at the maintenance organizations, identify the deficiency, and provide trend analysis for the errors that occur in commercial airline maintenance to take corrective measures [2]. The effectiveness of Boeing's Maintenance Error Decision Aid (MEDA) was evaluated by Rankin et al. [2]. They reported that MEDA has different categories for reporting an error, such as general data, operational event data, error classification, analysis of contributing factors, and corrective actions [2]. MEDA captures the situational factors more effectively and is possible to integrate the error reporting systems among airlines and with the manufacturer. Evaluation reports and technician surveys proved that MEDA process is an effective tool for maintenance organizations. In Europe, the Aircraft Dispatch and Maintenance Safety System (ADAMS) was developed which is like MEDA. It includes a range of maintenance errors and helps to describe the psychological form of the error based on habit capture and memory failure [17].

Through the voluntary disclosure and service difficulty reports, the outcomes from the internal error reporting system are conveyed to the FAA, which analyzes the data and trends regarding the specific problem. Based on the severity of the maintenance issue, FAA issues either Advisory Circulars (non-mandatory) or Airworthiness Directives (mandatory). Airworthiness Directives are issued when there is solid evidence for the problem. Aircraft manufacturers also issue service newsletter and magazines with the relevant information about the human factor issues which caused the accident or incident.

5.2. Pro-active Error Detection Methods

The safety of the aviation industry would greatly improve if the factors that cause the errors are identified at an early stage, even before the event occurs. The methods used to identify the errors are described briefly in this section. The FAA performs audits on a regular basis to inspect the airlines' maintenance and inspection programs. In addition to these regular audits, errors can be identified through human factors (HF) audit. In an HF audit, the performance of operators is observed and recorded directly by a human factor expert, and this helps to assess the likelihood of the errors. There are certain limitations to this methodology as it interferes with the typical work environment, and it is difficult to obtain an optimal sample size [26]. A computer-based HF audit was developed by the Galaxy Scientific Corporation for the aviation maintenance and inspection known as ERgoNomic Assessment Program (ERNAP). The audit results obtained from ERGNAP help designers and manufacturers to build ergonomically efficient systems [27]. Some error identification methods utilize subjective evaluation to determine whether the work environment is susceptible to errors or not. Reason developed a tool for British Airways known as Managing Engineering Safety Health (MESH) [17]. It aids in assessing the maintenance personnel's perspective about the local and organizational factors that contribute to errors. This computer-based survey is conducted regularly and anonymously with randomly selected personnel. This tool collects the data and summarizes the factors that might contribute to the accidents. The quality control team of the airline identify the issues and take necessary actions to rectify them [24]. Based on Reason's model, a maintenance extension of Human Factors Analysis and Classification System (HFACS-ME) was developed to assist in identifying the errors in maintenance actions. It is effective in identifying the relationship between the latent conditions and active failures [17]. Apart from these direct observations, recently simulation methods are also adapted to predict the human errors. The simulation method allows the HF expert to observe the performance of maintenance personnel in a virtual environment, including simulations of ambient conditions [24].

The requirement for a training based on Crew Resource Management (CRM) principles for ATMs was obviously felt as a requirement after the Aloha Airlines accident in 1988. In this accident, the blame was made on the entire operating system. The FAA developed the Maintenance Resource Management training (MRM) based on crew resource management principles [14]. The first-generation MRM focussed on the communication skills and awareness between ATMs. The second-generation programs primarily focused on direct communication, reduced the paperwork, and logbook errors. But it was not proactive and didn't train the ATMs about how to avoid key issues. The third generation MRM focused on situational awareness and individual issues that affected safety and encouraged organizational change. Different strategies such as training, equipment design, job design, and selection of equipment have been adopted to reduce the human errors.

6. Recent Trends and Advancements in Aircraft Maintenance Technologies

Recently, aircraft maintenance technology has seen significant advancements and trends. Innovative technologies are driving these advancements and trends. Predictive maintenance has quickly become an industry buzzword, with airlines adopting solutions utilizing data analytics, machine learning, and sensor technologies for predictive maintenance purposes. Predictive maintenance in aviation can increase reliability and operational efficiencies by using big data analysis and advanced algorithms to monitor and analyze machine data [28]. This approach enables proactive prediction of potential failures while simultaneously minimizing unscheduled downtime and increasing operational efficiency.

Aircraft maintenance, repair, and overhaul (MRO) companies encounter significant challenges in inspecting aircraft exteriors, particularly in assessing maintenance needs. Traditional inspection methods involve complex and time-consuming processes, often posing safety risks for engineers. To overcome these challenges, the industry is increasingly turning to robotics and automation solutions tailored for hangar maintenance. One notable advancement is the utilization of flying drones for efficient and rapid aircraft inspections. MRO Drone, a collaboration between Blue Bear Systems Research and Irish aircraft engineering software specialists Output 42, has developed the RAPID (Remote Automated Plane Inspection & Dissemination) system [29]. This system, requiring minimal operator training, can significantly reduce aircraft inspection times by up to 90%. EasyJet has already implemented Blue Bear drones for aircraft inspections, reporting substantial time savings [29]. Airbus has also entered the arena with its Advanced Inspection Drone designed for hangar use. Fitted with a visual camera, obstacle detection sensor, and specialized software, this automated drone can inspect the upper parts of an aircraft fuselage. The system allows for a thorough inspection of an entire A320 family aircraft in just 30 minutes, operated by individuals without drone flying qualifications [29].

In addition to flying drones, crawling robots have emerged as another innovative solution. Invert Robotics, based in New Zealand, has developed a robot featuring a patented suction mechanism enabling it to cling to an aircraft's exterior at any angle, including upside down. This versatile robot can operate on both dry and wet surfaces, providing high-definition video images for engineers to assess and record the aircraft's condition. Trials with Air New Zealand and partnerships with MRO service providers like SR Technics demonstrate the growing interest in these robotic inspection solutions [29]. Engine inspections are also benefiting from robotic solutions. Rolls-Royce and GE Aviation have undertaken research projects to employ robots in inspecting and servicing challenging-to-reach parts of engines.

Beyond inspections, robotic solutions are applied to various tasks in MRO operations. Pratt & Whitney Automation's Automated Robotic Maintenance System (ARMS) stands out for its ability to clean jet engine components swiftly and environmentally friendly. Similarly, Lufthansa Technik's CAIRE (Composite Adaptable Inspection and Repair) robot specializes in repairing carbon-fiber-reinforced polymers on aircraft wings and fuselages, showcasing the diverse applications of robotic systems in the maintenance domain [29]. Thus, the integration of robotics and automation in aircraft maintenance is transforming traditional inspection processes, enhancing efficiency, and ensuring safer operations.

Big Data analytics have revolutionized decision-making within maintenance by providing insights into strategies, component lifespan and fleet health as well as optimizing resource allocation. Blockchain technology is being explored as a solution to ensure secure and transparent maintenance records, protecting activities while mitigating risks from errors or discrepancies [30]. Meanwhile, additive manufacturing, or 3D printing, is making inroads in aircraft maintenance by offering on-demand production of spare parts at reduced lead times and costs savings. All these trends represent ongoing transformation of aircraft maintenance practices by emphasizing efficiency, safety, and the seamless incorporation of cutting-edge technologies into both line and hangar maintenance operations.

7. Conclusion

The aviation industry is highly complex, requiring collaborative teamwork under time constraints, limited performance feedback, and challenging working conditions. It is evident that the industry cannot function smoothly without the involvement of maintenance organizations. However, errors within these organizations pose a continuous threat to aviation safety. Historically, maintenance errors were perceived as individual failures, leading to investigations that concluded with punitive measures or training interventions. The global perspective has shifted, recognizing maintenance and inspection errors as reflections of interpersonal skills, workplace conditions, and organizational factors. Managing errors has evolved into a systemic response at the organizational level.

Organizations and regulatory authorities have adopted two approaches to address errors. The first involves minimizing the probability of maintenance errors by identifying and responding to underlying conditions. This includes initiatives such as maintenance resource management, fatigue management, training, and providing appropriate tools and equipment related to maintenance errors. The second approach acknowledges that errors can only be reduced, not eliminated entirely. Airlines must be vigilant in managing the inevitable threat of maintenance errors by implementing appropriate risk control measures to identify, minimize consequences, and rectify errors promptly.

In Europe, human factors training has been a mandatory requirement for aviation maintenance personnel since 1999, resulting in an 11% reduction in incidents related to maintenance errors [31]. Conversely, in the US, where the Federal Aviation Administration (FAA) has not mandated human factors training for Aircraft Maintenance Professionals (AMPs), incidents related to maintenance and inspection errors have increased significantly [31]. A recommendation is made for the FAA to mandate human factors training for AMPs, aligning with the successful European model, and ensuring comprehensive training across the industry. Further research is essential to determine the relationship between human factor issues and maintenance and inspection errors, aiming to reduce accidents and incidents caused by human error and minimize economic impact.

As technology rapidly evolves, advances such as predictive maintenance, robotics, augmented and virtual reality, big data analytics, blockchain, and additive manufacturing hold promise for improving efficiency, safety, and overall effectiveness in aircraft maintenance practices. Aviation's future resilience hinges on adopting cutting-edge technologies while continually updating safety protocols to maintain high standards of air travel.

Compliance with ethical standards

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Disclosure of conflict of interest

There are no conflicts of interest.

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