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The Impact of Human Factors and Maintenance Documentation on Aviation Safety: An Analysis of 15 Years of Accident Data Through the PEAR Framework

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Regardless of the type of maintenance performed on aircraft, instructions are to be used to provide the aviation technicians completing the maintenance activities with guidance on, and an outline of, the maintenance items to be performed and completed. However, the use of instructions does not guarantee the correct and proper completion of the maintenance activities as the instructions may be erroneous and/or maintenance personnel can misunderstand, misinterpret, or improperly follow the procedures outlined. Resulting maintenance errors can potentially result in aircraft accidents, as illustrated by Air Midwest Flight 5481. With the purpose of understanding how human factors associated with written maintenance instructions have contributed to aircraft accidents, the researchers qualitatively analyzed, using the people (P), environment (E), actions (A), resources (R) – PEAR – framework, 12 aircraft accidents that occurred from January 1, 2003, through December 31, 2017, under Part 121 or Part 135 operations in the United States that had maintenance instruction-related errors as contributing or causal factors. The detailed accident information, including causal factors, were retrieved from the aircraft accident reports provided by the National Transportation Safety Board (NTSB). The findings indicated that maintenance activities, specifically in terms of the adequacy and proper use of maintenance instructions, are largely impacted by human factor elements, such as the overall organizational environment and the resources available.

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As mandated by the United States Code of Federal Regulations (C.F.R.), virtually every U.S. registered aircraft operating in the United States airspace is subjected to periodic maintenance activities (Title 14 C.F.R. § 91.405, 2011). However, the extent of the mandated maintenance activities is dependent upon the exact type of operations of each aircraft. On one hand, general aviation (GA) aircraft operating under Title 14 C.F.R. Part 91 are commonly subject to maintenance activities as part of annual inspections and 100-hour inspections. On the other hand, aircraft operating under Title 14 C.F.R. Part 121 and Title 14 C.F.R. Part 135 are subjected to maintenance activities per continuous airworthiness inspection programs (Title 14 C.F.R. § 91.409, 2011). Despite the different types of aircraft inspections and maintenance activities that are to be performed, all have one aspect in common, namely the requirement to use a form of documentation or instruction, such as maintenance manuals, checklists, and/or job cards that outline the details of the task at hand (Title 14 C.F.R. § 43.13, 2011). However, these maintenance instructions have the potential to negatively impact aviation safety. For instance, when poorly prepared, maintenance instructions could be a contributing factor to aircraft accidents (Hobbs, 2008). The maintenance instructions and documentation, amongst others, can present technical errors, be hard to follow, describe procedures in an unclear manner, or provide awkward instructions, which can result in procedural errors – when procedures are not executed as intended – and/or violations – when procedures are deliberately and intentionally not followed (International Civil Aviation Organization [ICAO], 2002). Thus, the risk of improperly performing maintenance activities, even with the guidance of technical documentation, is still present. In situations where maintenance activities are performed erroneously, a so-called maintenance error is said to have occurred (Dhillon & Liu, 2006). A listing of maintenance-related aircraft accidents prepared by the Federal Aviation Administration (FAA) illustrates that maintenance errors, regardless of how minor or insignificant a specific maintenance item might seem, can have serious effects and consequences, with the potential of creating major safety issues and result in fatal accidents, as was observed during the accident of Air Midwest Flight 5481 (FAA, 2018; National Transportation Safety Board [NTSB], 2004).

Literature Review

Impact of Aviation Maintenance on Aviation Safety

A prime example of the importance and impact of maintenance documentation on aviation safety, especially of misunderstanding maintenance instructions, is provided by the accident of Air Midwest Flight 5481.

Air Midwest Flight 5481. On January 8, 2008, a Beechcraft 1900D operated by Air Midwest as US Airways Express crashed shortly after takeoff from Charlotte-Douglas International Airport (CLT) in North Carolina, killing 21 people aboard, including two flight crewmembers. The National Transportation Safety Board (NTSB) (NTSB, 2004, p. x) identified the "airplane's loss of pitch control during takeoff" as the probable cause of the mishap, further elaborating that the loss of pitch control was due to the improper rigging of the elevator control system and a Center of Gravity (C.G.) too far aft of the certified limit. Two days prior to the accident, the elevator system control cables of the affected aircraft were examined during a maintenance check, and the tension of these control cables was found to be too low. In order to adjust the tension, the entire elevator rigging procedure was supposed to be followed as there was no individual job card specifically focusing on adjusting the tension of the control cables. However, both the mechanic and the supervisor misunderstood the procedures, and believed that only the steps in the elevator rigging procedure that focused on the tension adjustment had to be followed (NTSB, 2004). During the post-accident review the mechanics stated that "steps c, f, g, h, i, j, n, and s were not required because those steps were only necessary for cable replacement and not for cable tensioning" (NTSB, 2004, p. 23). However, skipping these steps resulted in an inadequate restriction of the aircraft's nose down travel, and thus contributed to the accident (Hobbs, 2008; NTSB, 2004). Through the example given by Air Midwest Flight 5481, the impact that maintenance instructions have on the proper completion of maintenance activities, especially when not properly understood, are illustrated, and the risks associated therewith are highlighted.

Aviation Maintenance and Safety

The human element, including flight personnel as well as personnel on the ground, such as aircraft technicians, has a great impact on safety in the aviation industry (FAA, 2018; Hobbs, 2004; Oster, Strong, & Zorn, 2013). Human error has been cited as a causal factor for between 75% to 80% of all aviation accidents, and around 12% of this proportion of aircraft accidents are linked to aircraft maintenance activities (FAA, 2018). As the aircraft maintenance system and environment are very complex and intricate, human errors should be expected (Latorella & Prabhu, 2000). According to Hobbs (2008), even if improper maintenance activities are not identified as the primary cause of an accident, they may still have played an important role therein.

In the five-year span between 1996 and 2001, 1,016 aviation mishaps with maintenance issues cited as causal factors were registered in the Maintenance Error Information Management System (MEIMS), a database which combines FAA, National Aeronautics and Space Administration (NASA), and U.S. Navy maintenance error data (Krulak, 2004). Similarly, in the Aviation Safety Review for 2016, the United Kingdom (UK) Civil Aviation Authority (CAA) highlighted aircraft maintenance as a prominent primary cause for airplane and helicopter accidents, serious incidents, and high severity occurrences (Civil Aviation Authority [CAA], 2017). The significance of maintenance on the safety of the aviation industry is further highlighted by the records of NASA's Aviation Safety Reporting System (ASRS) database. From the 54,318 incidents reported in the database for the time period between 2010 and 2020, 1,661 reports reference maintenance-related procedural violations (ASRS, n.d.).

One important aspect of maintenance-related errors is that they can exist without being visible or discovered for a prolonged period of time, and consequently are more latent and less obvious than other error-types (FAA, 2018). In the past, the search for a root cause frequently stopped when the last person that was in touch with, or worked on, the damaged component is found, instead of continuing the search deeper into the causes for the failure (Hibit & Marx, 1994). However, with the introduction of the continuing analysis and surveillance system (CASS) – an approach now required for airlines in the United States to prevent maintenance errors – performing a root cause analysis is a mandatory component of airlines' maintenance programs (McFadden & Worrells, 2012). While it is useful to know what the actual error-condition was, it is more crucial to understand the reason why a specific error occurred, as it allows to understand and analyze the root causes of the error (Hobbs, 2008).

Maintenance documentation is a critical aspect for the proper completion of aircraft maintenance activities. After reviewing 2,360 incidents listed in the ASRS database that occurred between 1996 and 2003, Hobbs and Kanki (2008) indicated that maintenance manuals were a common factor among the reports analyzed. Additionally, the maintenance error history (MEH) model presented by Rashid, Place, & Braithwaite (2013) illustrates that information, as provided in aircraft documents and manuals, technical compact discs (CDs), or bulletins, could be an error-trigger during the aircraft maintenance process. These trends were further reflected by Hobbs (2008), where elements related to maintenance documentation, such as poor designs or procedures, were identified to be contributing factors to maintenance errors and incidents. The organization of these sources of information is crucial and can result in an error-producing condition, as errors can occur when attempting to retrieve information from "confusing, misleading or excessively cluttered documentation and charts" (ICAO, 2002, p. 2-6).

The importance of aircraft maintenance activities and their impact on aviation safety is further highlighted by the FAA (2018) and Hobbs (2008) through a listing of aircraft accidents and incidents whose causes are related to maintenance issues and errors. The FAA (2018) and Hobbs (2008) incident and accident listings are combined in Table 1.

Human Factors in Aviation

Most of the aircraft accident literature has focused on the analysis and modeling of human factors (Wiegmann & Shappell, 2001), their impact on aircraft accidents (Australian Bureau of Air Safety Investigation (BASI), 1996; Dambier & Hinkelbein, 2006; Daramola, 2014; Kelly & Efthymiou, 2019; Kharoufah, Murray, Baxter, & Wild, 2018; Li & Harris, 2006; Li, Harris, & Yu, 2008; Liu, Chi, & Li, 2013; Mendonca, Huang, & Keller, 2017; Shappell & Wiegmann, 2004; Shappell, Detwiler, Holcomb, Hackworth, & Boquet, 2006), and accident prevention methods (Taneja, 2002). More specifically, the literature is mostly centered on the aircrew-aspects of human factors. Examples include a report by the [Australian] Bureau of Air Safety Investigation (BASI) focused on pilot-related human factors as causes of aircraft accidents (BASI, 1996) and Taneja's (2002) review of methods to investigate and prevent of human factors as they relate to aircraft accidents. Furthermore, Wiegmann and Shappell (2001) studied the effectiveness of using the Human Factors Analysis and Classification System (HFACS) framework, placing special emphasis on the identification of human factors in aircraft accidents and incidents.

Table 1
Aircraft Accidents and Incidents Due to Maintenance Related Issues

Flight Identifier	Year	Mishap Type	Maintenance Related Cause
Eastern Airlines 855	1983	Incident	Installation of chip detectors without O-rings
Japan Airlines 123	1985	Accident	Improperly performed repair on rear pressure bulkhead
Aloha Airlines 243	1988	Accident	Unidentified disbonding and fatigue damage during inspection
British Airways 5390	1990	Accident	Improper bolts used during windscreen installation
Excalibur Airways, G-KMAM	1993	Incident	Lack of knowledge of Airbus flap change procedures
Emery Worldwide 228	2001	Incident	Improperly installed landing gear extension components, and failure to detect mistake
China Airlines 611	2002	Accident	Metal fatigue resulting from improper maintenance
Air Midwest 5481	2003	Accident	Improper rigging of the elevator control system during maintenance
Colgan Air 9446	2003	Accident	Improper replacement of cable and inadequate functional check
American Airlines 1400	2007	Accident	Improper engine manual engine start-up procedure used by maintenance personnel

Note: Adapted from "An Overview of Human Factors in Aviation Maintenance" by A. Hobbs, 2008, pp. 3-8 (https://www.atsb.gov.au/media/27818/hf_ar-2008-055.pdf). Copyright 2008 by the Australian Transport Safety Bureau; "Aviation Maintenance Technician Handbook – General" by Federal Aviation Administration, 2018, p.14-33 (https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/media/amt_general_handbook.pdf). Copyright 2018 by the Federal Aviation Administration.

The HFACS model has since been applied in a variety of studies to understand the human factor elements associated with aircraft accidents, in both, civil and military operations. Through the application of the HFACS framework, the criticality of the human element in aviation is further emphasized, as skill-based errors, perception errors, decision errors, violations, and crew resource management are quoted as frequent aircraft accident causal factors (Dambier & Hinkelbein, 2006; Daramola, 2014; Kelly & Efthymiou, 2019; Li & Harris, 2006; Liu et al., 2013; Shappell & Wiegmann, 2001; Shappell et al., 2006; Wiegmann & Shappell, 2001). Overall, in general aviation (GA) and commercial aviation, skill-based errors dominate, causing approximately 80% and 70% of unsafe acts, respectively. On the military side, however, the contribution of skill-based errors is approximately equal to that of decision errors (Shappell & Wiegmann, 2004). By combining the HFACS framework with statistical methods, Li et al. (2008) determined that for safety interventions to be impactful, they are to be implemented at the Level three and Level four of the HFACS framework, relating to supervisory and organizational processes, respectively. Specifically, unsafe supervision (Level three) refers to latent failures resulting from inadequate acts of the supervisory echelons, while organizational influences (Level four) is tied to managerial and upper-level decisions and actions (Wiegmann & Shappell, 2001).

Additional human factors models with applications to aviation have also been developed and applied. Yang and Fan (2016) introduced a novel human factors model, namely the PEART (people, environment, actions, resources, and time) model. This model is based on the PEAR model, but with an additional element – time, as it is critical to also consider how time impacts an operation and the human factors associated therewith (Yang & Fan, 2016). Further, Zhang, Wang, Luo, & Tang (2013) created a statistical model based on Bayesian network theory to represent causality via conditional probability of the impact of human factors on civil aviation incidents.

Research on the human factors of the aircraft maintenance industry includes studies focusing on their impact on ergonomics and the maintainability of aircraft (Bernard, Zare, Sagot, & Paquin, 2020), relationship to errors (Padil, Said, & Azizan, 2018), influential factors (Jaiswal, Dalkilic, Verma, & Singh, 2019; Santos & Melicio, 2019), incorporation into safety management system (SMS) practices (Miller & Mrusek, 2019), and approaches to map the risks thereof (Kucuk, 2019). Only few reports usually issued by government-related agencies like the FAA in the United States and the Australian Transport Safety Bureau (ATSB) in Australia have focused on further analyzing and researching aircraft accidents with regards to their relationship to maintenance activities, as presented by the FAA (2018) and Hobbs (2008). However, in these reports, the accidents are overviewed in a general and broad manner or the focus thereof is not explicit to accidents caused by, or related to, maintenance instruction-related issues. Goldman, Fiedler, & King (2002) obtained reports of maintenance-related GA accidents that occurred between 1988 and 1997 from the NTSB. The associated data were analyzed, and the accidents were classified into categories by type of aircraft involved, installation error (i.e. what was the type of maintenance error), aircraft system affected, certification of the mechanics, and operational impact (Goldman et al., 2002). While this research provides an understanding of the frequencies of the relative categories, it does not present details on the causes of the maintenance errors analyzed or an analysis of the human factors involved.

The PEAR Model

The PEAR model provides a framework to characterize human factors – the relationship between people, their capabilities, and their environment and activities (FAA, 2018; ICAO, 2002). Specifically, the PEAR model considers four elements that impact human factors in the area of aviation maintenance, namely *people* (P), *environment* (E), *actions* (A), and *resources* (R) (FAA, 2018).

The people element of the PEAR model refers to the individuals that perform the maintenance activities (FAA, 2018). As not every individual involved in the maintenance activities presents the same characteristics, maintenance operations and activities have to respect each individual's limitations (ICAO, 2002). The PEAR model considers physical characteristics, physiological, psychological, as well as psychosocial characteristics (FAA, 2018; ICAO, 2002; Johnson & Maddox, 2007). By extension, as a critical element to human capability and performance, and a fundamental component of human factor analysis, fatigue – both from a physical as well as mental perspective – is further highlighted and studied under the *people* element of the PEAR model (Johnson & Maddox, 2007). The complete list of human factors characteristics considered under the people element of the PEAR model is outlined in Table 2.

Table 2
PEAR Elements Classification

P - People			
Physical Elements	Psychological Elements	Physiological Elements	Psychosocial Elements
Physical size Gender Age Strength Sensory limitations	Workload Experience Knowledge Training Attitude Mental/emotional state	Nutritional factors Health Lifestyle Fatigue Chemical dependency	Interpersonal conflicts Financial hardships Personal loss

E – Environment	
Physical Environment	Organizational Environment
Weather Location of activities Shift Workspace Safety Sound level Lightning characteristics	Personnel Corporate culture Morale Supervision Company size Profitability Crew structure Labor-management relations Pressures

A - Actions		
Steps required to perform and complete a task The number of people involved to complete a task Sequence of activities		
Requirements		
Communication Attitude Certification	Information control Knowledge	Skill Inspection

R – Resources	
Manuals Tools Work stands and lifts Other people Materials Quality systems Procedures and work cards	Computer software systems Test equipment Fixtures Task lightning Ground handling equipment Training Paperwork and associated signoffs

Note: Adapted from “Aviation Maintenance Technician Handbook – General” by Federal Aviation Administration, 2018, pp.14-10 – 14-12 (https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/media/amt_general_handbook.pdf). Copyright 2018 by the Federal Aviation Administration; “A PEAR shaped model for better human factors” by W.B. Johnson and M.E. Maddox, 2007, pp. 20-21 (https://www.faa.gov/about/initiatives/maintenance_hf/library/documents/media/reports_publications/pear_civil_aviation_training_magazine_4-07.pdf).

As shown in Table 2, the *environment* in the area of maintenance activities includes both the physical as well as the organizational environment (Johnson & Maddox, 2007). The *physical environment* refers to a series of physical conditions that can impact the maintenance activities, while the *organizational environment* refers to organizational characteristics that define a company, and thus, the workplace (FAA, 2018). From an organizational perspective, as highlighted by the HFACS model, decisions taken in the upper levels of management – such as the allocation of resources or implemented policies and procedures – have an impact on the frontline actions, and consequently impact safety (Wiegmann & Shappell, 2001).

The *actions* element of the PEAR model refers to all actions and activities that are performed and/or completed as part of the aviation maintenance operations. *Actions* range from the requirements needed to complete the maintenance activities, to the actual steps performed during the maintenance activities (FAA, 2018; Johnson & Maddox, 2007). Within the context of the HFACS framework, the actual steps performed, if leading to an accident, can be classified as unsafe acts of operator, in the form of errors and/or violations (Wiegmann & Shappell, 2001), following the definitions afore-provided. Table 2 highlights the human factors characteristics considered under the actions element of the PEAR model.

In the most basic sense, *resources* refers to any element that is required to complete maintenance activities, as shown in Table 2. This includes both tangible as intangible elements, such as tools and training, respectively (FAA, 2018). Under the HFACS model, resource management is classified as a subset of organizational influences, the fourth level of failure (Wiegmann & Shappell, 2001). When analyzing the *resources* element of the PEAR model, however, it is important to identify additional resources that are required, rather than merely characterizing existing resources (FAA, 2018). The allocation of resources is dictated by safety and cost-effectiveness objectives (Wiegmann & Shappell, 2001).

Significance of the Study

Often times, safety hazards that can lead to future aircraft accidents can be eliminated or mitigated after an accident when they are properly understood and proactive action is taken (ICAO, 2016; Sumwalt & Dalton, 2014). As presented in the literature review, aviation maintenance and its impact on safety is a known and frequently studied discipline, simultaneously highlighting maintenance documentation as a risk factor. However, the studies presented do not focus on specific accidents and incidents in which maintenance documentation, as a sub-element of maintenance activities, has impacted and threatened aviation safety. Consequently, researching aircraft accidents that were caused by, or related to maintenance instructions, and understanding recurring themes amongst the characteristics of the maintenance activities performed is expected to allow the industry to recognize and more effectively address the risks and factors associated with aircraft maintenance instructions. Through the expected increased understanding obtained through this research, proactive action can be taken to improve the area of maintenance instructions, with the objective of improving the overall safety of the aviation industry.

Research Questions

This study was an attempt to understand the underlying factors of aircraft accidents which occurred under Part 121 and Part 135 operations from 2003 to 2017 and were caused by maintenance errors related to, or induced by, written maintenance instructions, through the application of the PEAR model. Specifically, the following research questions were addressed:

1. What are the characteristics of the maintenance activities that could be improperly performed due to issues presented and caused by written maintenance instructions?
2. What are the underlying human factor-related causes of the maintenance errors induced by written maintenance instructions issues?

Methodology

To answer the research questions, data from aircraft accidents that occurred between January 1, 2003 and December 31, 2017 under Part 121 and Part 135 operations, and that were caused by, or related to, issues with written aircraft maintenance instructions and documentation were obtained from the NTSB aviation accidents databases (NTSB, n.d.-a; NTSB, n.d.-b). The gathered data were used to study the human factors elements that were related to the maintenance documentation issues through the application of the PEAR model.

Data Collection

Similar to Goldman et al. (2002), the aircraft accident data from 15 years were obtained through the online aviation accidents database (NTSB, n.d.-a). To query only the accidents of interests, the search filters on the NTSB website were adjusted to include accidents classified by the NTSB as "airplane" accidents occurring in the United States under Part 121 and Part 135 operations from January 1, 2003 to December 31, 2017. A key word search for "maintenance" was conducted to obtain only the reports from accidents in which the maintenance activities were investigated.

Data Analysis

The list resulting from the NTSB search included the accidents that occurred within the specified time range, under Part 121 and Part 135 operations, and whose reports have the keyword "maintenance" included. This included any mention of maintenance within the accident reports, and consequently did not specifically sort out accidents related to issues with maintenance instructions and documentation. To sort out the accidents that were related to, or caused by, maintenance instructions issues, the final or preliminary accident reports, depending on availability, were read and analyzed. After manually filtering out the accidents that were caused by maintenance documentation-related issues, the strategy used by Goldman et al. (2002) was followed. The selected accidents were coded in different categories in order to obtain accident demographic information. In this study, the accidents were coded in the categories described below.

The accidents were coded with respect to the number and types of injuries, as provided by the NTSB report. The types of injuries are fatal, serious, minor, and none (NTSB, 2013; Title 49 C.F.R. § 830.2, 2011). The accidents were further coded in terms of the level of damage to the aircraft, as provided by the NTSB accident report. Aircraft damage can be coded into four categories, as provided and defined by the NTSB (2006): destroyed, substantial, minor, and none.

The *Aircraft System Affected* category identifies and classifies the aircraft system that the improper maintenance activity was taking place on. The aircraft system categories are adopted from Goldman et al. (2002), and are: flight controls, powerplant, landing gear, flight/navigation instruments, electrical system, fuselage, rotor system, wing (vertical and horizontal), fire warning system, air conditioning/heat/pressurization/oxygen, and anti-/de-ice systems.

The *Physical Description of Errors* category allows the classification of the aircraft accident in terms of the physical maintenance action that was performed incorrectly. The categories used were adopted from Hobbs (2008) and are: omission, commission, and timing and precision. According to Hobbs (2008), an omission refers to not performing a required action, as for example not safety wiring two bolts together, or omitting a series of steps in a procedure. Commission, on the other hand, refers to "[when] an action is performed that should not have been performed" (Hobbs, 2008, p. 10), as for example improperly connecting the end terminals of an electrical device. Lastly, timing and precision refers to actions that were "performed at the wrong time, in the wrong order, or without the necessary level of precision" (Hobbs, 2008, p. 19). Using the definitions provided by Hobbs (2008), examples of timing and precision errors could include connecting the negative lead of a battery first or inflating a tire to the wrong pressure.

The *Maintenance Activity* category identifies the type of maintenance that has been performed on the aircraft. The coding used was adapted from the NTSB Aviation Coding Manual (NTSB, 1998) and from Goldman et al. (2002). The categories used in the analysis are: adjustment, alignment, annual inspection, 100-hour inspection, balancing, calibration, compliance with an Airworthiness Directive (AD), design change, installation, inspection, lubrication, modification, major repair, major alternation, overhaul, pressurizing, rebuild/remanufacture, replacement, service bulletin (SB)/letter, and service aircraft/equipment (Goldman et al, 2002; NTSB, 1998).

Accidents that fit into more than one sub-category within the five categories provided above were counted in both sub-categories. For example, if two aircraft systems were affected in an accident, both of the systems were counted as systems affected. The frequency of the type of operation, type of injuries, aircraft damage, system affected, physical description of errors, and maintenance activity was then computed. Following the example provided by Goldman et al. (2002), the frequencies of each category were used to obtain an overall understanding of the demographic of the accidents that were caused by, or related to, maintenance instruction and documentation issues.

PEAR Model

The human factors that resulted in, or affected, the maintenance instructions-related issues were analyzed through the application of the PEAR model. Researchers utilized the PEAR model to identify the individual factors that affected the maintenance activities, focusing on the maintenance documentation issues that were improperly completed. More precisely, the NTSB reports of the selected accidents were carefully reviewed by the researchers to identify the frequency of the themes and categories of the PEAR model. The themes identified under the Results section reflect the human factors categories from the PEAR model, as outlined in the above-presented Table 2. The researchers aimed to identify said categories and themes in the selected NTSB reports to obtain a count of the human factors present in the accident reports analyzed. To reduce the potential impact of bias, the methodology implemented was based on the methods presented in previous studies focusing on aviation human factors and maintenance errors, as introduced in the Literature Review. Furthermore, the classification was guided by the researchers' previous experience in the field of aviation safety and human factors.

Research Questions

To answer Research Question 1, the information obtained from the demographic analysis was used as it provides data regarding the characteristics of these accidents. Specifically, a frequency analysis of the different sub-categories previously identified for the system affected, physical description of errors, and maintenance activity categories was performed. Through this analysis, recurring themes in terms of maintenance activity characteristics can be identified and discussed.

Research Question 2 was answered through the results from the PEAR analysis. Specifically, a frequency analysis was performed on the various PEAR elements and recurring themes amongst the people, environment, action, and resources human factor elements that were identified. The results from the frequency analysis and the recurring themes were used as the basis for the underlying maintenance human factor-related causes of the selected accidents.

Results

Eighty-five Part 121 accidents and 196 Part 135 accidents from the NTSB databases initially matched the aforementioned search criteria. Using the manual selection process, five Part 121 and seven Part 135 accidents were identified to have maintenance instruction-related issues as a causal factor. Table 3 provides an overview of the selected accidents.

Table 3
Selected Part 121 and Part 135 Accidents Overview

Accident	Date	Operation	Cause Related to Instructions
DCA03MA022	01/08/2003	Part 121	Improper understanding of instructions
DEN04LA023	11/18/2003	Part 135	Improper maintenance instructions
LAX05LA244	07/22/2005	Part 135	Failure to follow maintenance instructions
NYC06FA128	05/30/2006	Part 121	Inadequate maintenance instructions
DCA06FA058	07/28/2006	Part 121	Inadequate maintenance instructions
CHI07LA043	12/17/2006	Part 135	Improper maintenance instructions
DCA07MA310	09/28/2007	Part 121	Improper use of maintenance instructions
CHI08LA071	01/09/2008	Part 121	Failure to follow maintenance instructions
MIA08LA079	03/15/2008	Part 135	Failure to follow maintenance instructions
CEN10LA389	07/08/2010	Part 135	Failure to follow maintenance instructions
WPR12FA332	07/28/2012	Part 135	Failure to follow maintenance instructions
WPR14FA068	12/11/2013	Part 135	Improper understanding of instructions

An overview of the selected Part 121 and Part 135 accidents including the accident number, operation type, aircraft damage, aircraft system affected, physical description of the error, and maintenance activity are provided in Table 4. Both, the Part 121 and Part 135 accident detailed descriptive statistics based on the outlined parameters were calculated and are presented in Table 5. The analyzed accidents resulted in a total of 22 fatalities – one fatality was reported in a Part 135 accident (NTSB, n.d.-f) and 21 fatalities were reported in a Part 121 accident (NTSB, 2004). In approximately 80% of all selected accidents, the aircraft received substantial damage, while in the remaining cases the aircraft were found to be destroyed. The three individual systems most frequently affected by the improper maintenance in Part 121 and Part 135 accidents were the landing gear – accounting for 50% of accidents, powerplant – accounting for approximately 33% of the accidents, and flight controls – accounting for approximately 16% of the accidents. The majority of the accidents, specifically 60% and 75% of the Part 121 and Part 135 accidents, respectively, were caused by acts of omission, where a required maintenance activity or item was not completed. The improper maintenance actions were completed as part of seven different maintenance activities: adjustment, airworthiness directive (AD) compliance, inspections, service bulletin/letter implementations, overhaul, replacement, and service of aircraft and equipment. Three of the maintenance actions categories – adjustment, replacement, and service of aircraft and equipment – overlap between both, Part 121 and Part 135 accidents.

Analysis of the Accidents Applying the PEAR Framework

Table 6 lists the PEAR elements that were identified for each accident based on the information provided in the NTSB aircraft accident reports. All but two PEAR items were selected from the previously provided PEAR item list. The PEAR items listed in Table 6 as "Maintenance action improperly completed" and "Maintenance action not completed" under the *Action* PEAR column were not provided in the list created based on the FAA (2018) documentation nor Johnson and Maddox (2007). These elements were added by the researchers to more accurately reflect the accident information outlined in the NTSB aircraft accident reports. Some of the reports did not provide additional details on the accident causal factors other than outlining that the maintenance items provided in the maintenance documentation were not completed or completed improperly. Thus, these two categories account for the lack of detail in the NTSB accident reports while still providing an indication of the causal accident factors related to maintenance instructions.

The PEAR analysis results are synthesized in Table 7 to reflect the frequency of the PEAR items identified and their occurrence (Part 121 vs. Part 135 accidents). The most frequent PEAR element amongst Part 121 accidents as well as amongst both operation types together is *Resources*, with 10 and 16 occurrences, respectively. The most frequent PEAR element amongst Part 135 accidents is "Action", with seven occurrences. The least occurring PEAR element is *Environment* with a single occurrence from a Part 121 accident. Additionally, no *People* or *Environment* PEAR element items were identified for Part 135 accidents. The most frequent individual PEAR element item is the *Resources* item "Procedures and work cards", with eight occurrences total - four occurrences from each, Part 121 and Part 135 accidents. The *Action* item "Maintenance action not completed" is the only other individual PEAR element item with four occurrences from one accident category, in this case from Part 135 accidents. All remaining PEAR element items occur once or twice per operation type.

Table 4
Selected Part 121 and Part 135 Accidents Descriptive Information

Accident	Operation	Injuries	Fatalities	Level of Damage	Aircraft System Affected	Physical Description of Error	Maintenance Activity
	Part 121 Accidents						
CHI08LA071	Part 121	-	-	Substantial	Powerplant	Omission	Replacement
DCA07MA310	Part 121	-	-	Substantial	Powerplant	Commission	Service
DCA06FA058	Part 121	-	-	Substantial	Landing Gear	Omission	Overhaul
NYC06FA128	Part 121	1 – Serious	-	Substantial	Landing Gear	Timing & Precision	Service
DCA03MA022	Part 121	1 – Minor	21	Destroyed	Flight Controls	Omission	Adjustment
	Part 135 Accidents						
WPR14FA068	Part 135	3 – Serious; 5 – Minor	1	Destroyed	Powerplant	Omission	Service Bulletin; Inspection
WPR12FA332	Part 135	-	-	Substantial	Flight Controls	Timing & Precision	Airworthiness Directive
CEN10LA389	Part 135	-	-	Substantial	Landing Gear	Omission	Replacement
MIA08LA079	Part 135	-	-	Substantial	Landing Gear	Timing & Precision; Omission	Adjustment
CHI07LA043	Part 135	-	-	Substantial	Landing Gear	Omission	Inspection; Adjustment; Replacement
LAX05LA244	Part 135	-	-	Substantial	Powerplant	Omission	Inspection
DEN04LA023	Part 135	-	-	Substantial	Landing Gear	Omission	Service

Table 5
Distribution of Accident Descriptive Criteria by Operation Category

Categories	Sub-Categories	Part 121	Part 135	All Accidents Combined
Fatalities & Injuries	Fatal	6.954%	4.166%	6.748%
	Serious	0.331%	12.500%	1.227%
	Minor	0.331%	25%	2.147%
	None	92.384%	58.333%	89.877%
Level of Damage	Destroyed	20%	14.286 %	16.666%
	Substantial	80%	85.714%	83.333%
	Minor	-	-	-
	None	-	-	-
Aircraft System Affected	Flight Controls	20%	14.286%	16.666%
	Powerplant	40%	28.571%	33.333%
	Landing Gear	40%	57.143%	50%
Physical Description of Error	Omission	60%	75%	69.231%
	Commission	20%	-	7.692%
	Timing & Precision	20%	25%	23.077%
Maintenance Activity	Airworthiness Directive	-	10%	6.666%
	Inspection	-	30%	20%
	Service Bulletin/Letter	-	10%	6.666%
	Overhaul	20%	-	6.666%
	Replacement	20%	20%	20%
	Service Aircraft/Equipment	40%	10%	20%

Discussion

The characteristics of the improperly performed maintenance activities are determined based on the affected aircraft systems, the physical description of the errors, and the maintenance activity itself, as summarized in Table 5. Relating to aircraft systems, the landing gear is the system most susceptible to be involved in instruction-related inadequate maintenance activities. The spread of affected aircraft systems, however, is narrow, as only two other systems presented maintenance-related issues caused by the maintenance instructions, namely the powerplant and flight control systems. While the specific relative frequency of the systems involved differs, the powerplant, flight controls, and landing gear were similarly ranked amongst the most frequent aircraft systems involved in accidents by Goldman et al. (2002). The results obtained, nevertheless, need to be considered in relation to the framework of the analysis, and are not indicative of other systems not being subjected to instruction-induced faulty maintenance. Specifically, the analysis performed only considers maintenance issues related to aircraft accidents. Consequently, the system failure needs to be significant to trigger an accident-causing fault. Therefore, in context, the criticality of adequate maintenance for, and the importance of maintenance instructions of, the flight control, powerplant, and landing gear systems are illustrated by highlighting the severity of a fault thereof – namely, an aircraft accident. Furthermore, in a study conducted by Goldman et al. (2002) the aircraft systems involved in accidents were statistically related to the fatalities and injuries occurring, highlighting the importance of inadequate maintenance of specific aircraft systems.

Most of the improperly performed maintenance activities were in the form of acts of omission. For both, Part 121 and Part 135 accidents, acts of omission were responsible for 60% and 75% of the inadequately performed maintenance activities, respectively. The most prominent example of an act of omission relates to the afore-quoted Air Midwest Flight 5481, where a misunderstanding of the maintenance instructions resulted in a technician not performing all the required steps, creating the accident-causing condition (Hobbs, 2008; NTSB, 2004). Omissions include both situations where steps explicitly spelled out in the maintenance instructions are not completed (NTSB, n.d.-c), as well as situations where the maintenance program and instructions do not include the required and necessary items (NTSB, n.d.-f). The frequency of occurrence of acts of omissions highlights the importance of performing every maintenance step required and the need for maintenance instructions to explicitly outline all required maintenance steps. This includes eliminating any ambivalence in the maintenance instructions to avoid uncertainties regarding the need to complete specified steps, such as in the event of Air Midwest Flight 5481.

No individual maintenance activity stands out by itself, but rather four categories are observed to have a 20% occurrence: adjustment, inspections, replacement, and service of aircraft and equipment, while three categories had an approximately six percent occurrence: AD compliance, service bulletin/letter implementations, and overhaul. As a wide spread in terms of maintenance activities is observed, not a singular type of activity is distinguished for individual error-inducing maintenance instructions. When analyzing the maintenance instructions with respect to the maintenance activities performed, where the instructions originated from and whether they were adapted, for instance to meet specific aircraft constraints, their usability, relevance, and applicability are crucial factors to consider (Zafiharimalala, Robin, & Tricot, 2014). For example, in accident DEN04LA023 (NTSB, n.d.-d), the approved maintenance instructions adapted for inspections and used by the airline did not match the maintenance requirements and instructions provided by the manufacturer. A similar discrepancy was reported in accident NYC06FA128 (NTSB, n.d.-e), where the manufacturer-provided instructions were not accurately reflected in the job card adapted to the specific operator's activities, thus missing crucial maintenance steps. Furthermore, certain type of maintenance activities inherently contain more detailed instructions than others, causing instructions to be either insufficient in content or overly detailed, leading technicians to refrain from using the provided documentation systematically (Zafiharimalala et al., 2014).

The analysis of the accidents applying the PEAR framework provided insight related to the human factor elements associated to the use of maintenance instructions. As aforementioned, the most impactful category of the PEAR framework is the *Resources* category. Under the HFACS model (Wiegmann & Shappell, 2001), resource management is listed as an organizational influence, impacted by the upper managerial levels. Within the *Resources* category, the two most frequent items are procedures and work cards, as well as manuals. As the analysis performed solely focused on maintenance-related accidents in which the maintenance instructions are quoted as causal factors, the high frequency of these items can be expected. Similarly, the relative high frequency of "Maintenance action improperly completed" and "Maintenance action not completed" under the *Action* category can be explained by the narrow focus of the study. Nevertheless, the PEAR analysis highlights that maintenance instructions by themselves are not able to support the maintenance activities, and that other factors centered around the human element are required to support the maintenance effort.

Table 6

PEAR Analysis Results

Accident Number	Operation	PEAR Elements			
		People	**Environment**	**Action**	**Resources**
CHI08LA071	Part 121	- Psychological characteristics: Excessive workload	-	- Maintenance action not completed - Sequence of activities	- Other people
DCA07MA310	Part 121	-	-	-	- Procedures and work cards - Quality system
DCA06FA058	Part 121	-	-	-	- Procedures and work cards
NYC06FA128	Part 121	-	-	-	- Procedures and work cards - Manuals
DCA03MA022	Part 121	- Psychological characteristics: Experience, knowledge, and training	- Organizational environment: Supervision	- Steps required to perform and complete a task - Requirements: Knowledge	- Procedures and work cards - Manuals - Training - Quality systems
WPR14FA068	Part 135	-	-	- Maintenance action not completed	- Procedures and work cards - Manuals
WPR12FA332	Part 135	-	-	- Maintenance action improperly completed	-
CEN10LA389	Part 135	-	-	- Maintenance action not completed	-
MIA08LA079	Part 135	-	-	- Maintenance action improperly completed	-
CHI07LA043	Part 135	-	-	- Steps required to perform and complete a task	- Procedures and work cards - Manuals
LAX05LA244	Part 135	-	-	- Maintenance action not completed	- Procedures and work cards
DEN04LA023	Part 135	-	-	- Maintenance action not completed	- Procedures and work cards

Table 7
PEAR Analysis Summary

	PEAR Items	Part 121 Accidents	Part 135 Accidents	Total
People	- Psychological characteristics: Workload	1	-	1
	- Psychological characteristics: Experience	1	-	1
	- Psychological characteristics: Knowledge	1	-	1
	- Psychological characteristics: Training	1	-	1
	Total People Items	4	-	4
Environment	- Organizational environment: Supervision	1	-	1
	Total Environment Items	1	-	1
Action	- Maintenance action not completed	1	4	5
	- Sequence of activities	1	-	1
	- Steps required to perform and complete a task	1	1	2
	- Requirements: Knowledge	1	-	1
	- Maintenance action improperly completed	-	2	2
	Total Action Items	4	7	11
Resources	- Other people	1	-	1
	- Procedures and work cards	4	4	8
	- Quality system	2	-	2
	- Manuals	2	2	4
	- Training	1	-	1
	Total Resources Items	10	6	16

For instance, the workload, knowledge, experience, and training – all psychological characteristics outlined under the *People* category – are PEAR elements related to the selected accidents. In the United States, the FAA regulates the certification of aircraft maintenance technicians (AMTs) and dictates the skills (Title 14 C.F.R. § 65.79, 2001), knowledge (Title 14 C.F.R. § 65.75, 1966), and experience (Title 14 C.F.R. § 65.77, 1970) required to be certified to perform maintenance activities on aircraft. By extension, to work as an AMT, certain recency requirements are to be met (Title 14 C.F.R. § 65.83, 2014), adding to the knowledge, experience, and training components. Furthermore, in relation to maintenance instructions, the FAA stipulates that "a certificated mechanic may not exercise the privileges of his certificate and rating unless he understands the current instructions of the manufacturer, and the maintenance manuals, for the specific operation concerned" (Title 14 C.F.R. § 65.81, 1980, para. 2). This regulation ties training of AMTs to the use and understanding of maintenance instructions, outlining the importance and criticality of instructions in the realm of aircraft maintenance activities. However, as presented by the accidents analyzed, a technician's training, knowledge, and experience are not the only human-centered factors that affect the technicians' performance. On-the-job situational elements, such as the workload, are further crucial, and as such, are to be considered. Accident number CHI08LA071 (NTSB, n.d.-c) illustrates a scenario in which the workload influenced the maintenance activities. Specifically, the technicians performing the maintenance task on the accident aircraft were called to help another technician and did not return to the original task, consequently failing to complete outstanding steps of the outlined maintenance task (NTSB, n.d.-c).

Nevertheless, the front-line technicians are supported by supervisors and quality systems, which, as shown by the PEAR analysis, can also fail to provide the required safety barriers, resulting in accident-causing conditions. In the analyzed accidents, one incident of a supervision failure was recorded under the *Environment* category of the PEAR framework, while two instances of quality system deficiencies were noted under the *Resources* category of the framework. Both, a quality system and adequate supervision are essential requirements for aircraft maintenance activities (Shanmugam & Robert, 2015). Per Shanmugam and Robert (2015), supervision can be classified into two main categories. First, relating to the required level of supervision, supervision is a managerial component. Second, relating to the supervision policy, supervision is an element associated with the certification of staff and technicians, thus tying back to the FAA-mandated AMT certification requirements afore-discussed. The quality system is its own category, and contains, amongst others, the following elements: quality and safety policy, quality review meetings, approval of document, and competency assessment (Shanmugam & Robert, 2015).

The accident of Air Midwest Flight 5481 provides a perfect example of a scenario in which both, supervision and quality system issues tied to maintenance instructions resulted in an accident-causing situation. Specifically, the supervisor of the technician performing the cable rigging operation – which resulted in the accident condition – was also in charge of quality assurance and further misunderstood the rigging instructions, agreeing to skip the steps in the instructions (NTSB, 2004). As aforementioned, skipping certain steps of the maintenance instructions during the rigging process ultimately restricted the aircraft’s pitch control, resulting in the accident of the aircraft (NTSB, 2004).

Limitations

The current study experienced some limitations. These factors ranged from the data sources used, the classification framework, and the scope of the analyzed accidents. First, the selection of accidents included a manual filtering process, in which accidents reports dated within the specified timeframe including the keyword “maintenance” were filtered. However, as a keyword search was employed, accident reports not meeting the keyword search criteria but still falling under the overall research framework may have been missed, and thus excluded from the analysis. Similarly, the data used for the classification of the causal factors of the accidents was retrieved from the accident reports provided by the NTSB. Consequently, the analysis was limited and restricted to the information provided by the NTSB reports. Furthermore, the detail provided by the NTSB reports varied across accidents, as certain accident reports included data from interviews and laboratory analyses, while others merely described the factual accident information. To expand and enhance the PEAR analysis performed, the information from the NTSB provided reports could be supplemented with further research into the accident causal factors, specifically with relation to maintenance documentation.

Due to the afore-described lack of detail in certain NTSB-provided reports, two additional PEAR categories were added to the PEAR analysis. As previously explained, the added categories accounted for the ambiguity and indefiniteness in the NTSB reports, but in return provided little detail in terms of human factor-related accident causal factors. By extension, the classification of the causal factors into the PEAR categories was based on the researchers' interpretation of the accident information provided, and thus includes a certain level of subjectivity. Furthermore, the scope of the accident reviewed is comparatively narrow, as it restricted to 15 years of accidents occurring under Part 121 and Part 135 operations in the United States. To expand the applicability and generalizability of the results obtained, the research framework could be applied to accidents occurring under Part 91 operations, outside of the United States, or in an expanded timeframe.

Conclusion

The analysis performed furthered the study and understanding of human factors in the field of aircraft maintenance, highlighting the impact and associated importance of maintenance documentation. Acts of omission – where a required maintenance step is not performed – were identified to be the most frequent error type, while the aircraft systems most subjected to instruction-related errors were the landing gear, powerplant, and flight control systems. Relating to human factors, trends identified by the applied PEAR model could be tied to FAA training requirements for aircraft technicians while simultaneously mirroring and furthering the results of previous human factors studies performed in the field of aviation. Specifically, the importance and relevance of factors supporting the aircraft maintenance efforts with a specific focus on the instructions used therein, such as available resources as well as the overall environment, were found to be crucial.

The findings support the idea that aviation safety is a combination of multiple elements working together. As stated in previous research, and highlighted through the results of the completed study, the existence of written maintenance instructions does not warrant the proper completion of the associated maintenance items. Instead, supporting elements such as technician training as well as adequate supervision and the overall working environment are key factors affecting the adequate maintenance of aircraft. The HFACS model discussed in literature as well as in the discussion of the results, reflects similar aspects. While the maintenance errors occur at the front line (the *Action* category of the PEAR framework), underlying factors – i.e. maintenance documentation in this study – often stem from managerial and regulatory levels. As aforementioned, people-related aspects such as training, experience, and knowledge, are primarily being addressed by FAA-regulated training for aviation maintenance technicians. On the other hand, elements under the *Resources* and *Environment* categories identified under the PEAR framework in this study, are frequently intrinsically tied to managerial and organizational elements of maintenance organizations. Consequently, to continuously increase the safety of aviation, when designing and implementing maintenance instructions, elements that contribute to the actual understanding and implementation of said instructions – i.e. considering the "working environment" thereof – are critical and need to be considered.

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