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An Inductive Approach to Identify Aviation Maintenance Human Errors and Risk Controls

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Human errors can be present in any maintenance task and cause latent but dangerous situations to commercial aviation. By looking into past accidents and incidents caused by aviation maintenance errors, the importance of safety measures would be highlighted - including continuous education on maintenance human factors. Currently, the FAA Part 147 airframe and powerplant (A&P) training curriculum includes general, airframe, and powerplant modules. However, the curriculum does not mandate human factors education or aviation safety pedagogical content. The objectives of this study are to: 1. Find and analyze emerging themes of aviation maintenance-related accidents from existing documentation; 2. Apply risk assessment tools to conduct a risk assessment and identify causal and latent variables; 3. Use detailed qualitative case analysis on major accidents to identify contributing variables of human factors; and 4. Provide recommendations to advocate the importance of human factors education. This study uses a qualitative approach, employing meta-narrative analysis and the VOSviewer visualization tool to demonstrate inter-connected themes related to aviation maintenance problems. Detailed Fishbone (Ishikawa) diagrams showcasing the effectiveness of the selected tools for pedagogical purposes are followed by several case studies, together shedding light on the criticality of continuous education of maintenance human factors. The recommendations based on research findings are beneficial to maintenance training institutions for them to be more aware of potential shortcomings.

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Introduction

Aircraft maintenance is a critical success factor in the aviation sector, and incorrect maintenance actions themselves can be the cause of accidents (Illankoon & Tretten, 2019). Additionally, maintenance errors are a major cause of flight delays and cancellations, leading to financial penalties for airlines (O'Brien, 2012). In the United States, maintenance errors have contributed to 42% of fatal airline accidents from 1994 to 2004, excluding the terrorist attacks on September 11, 2001. In addition, the 2003 International Air Transport Association (IATA) Safety Report found that in 24 of 93 accidents (26%), a maintenance-caused event started the accident chain (Rankin, 2007). In 2005, Lu, Przetak, and Wetmore discovered non-flight errors and suggested emphasizing maintenance safety (Lu, Przetak & Wetmore, 2005). In 2011, Bowen, Sabin, and Patankar also discovered that emerging maintenance human factors had yielded a need for training (Bowen, Sabin & Patankar, 2011). The term "human factors" has grown increasingly important as the commercial aviation industry realizes that human error, rather than mechanical failure, underlies most aviation accidents and incidents (Federal Aviation Administration, 2018). Despite the United States' aviation industry's excellent safety record in the past few decades due to the advanced technologies installed in modern aircraft, aircraft maintenance tasks are ultimately completed by human beings. As a result, maintenance errors still pose a formidable threat to every commercial flight in the United States. While identifying potential human errors affecting maintenance safety is imperative on a daily basis, this paper embraces risk assessment methods to identify and manage human errors. Additionally, this paper discusses and recommends educational themes helping to shape safety attitude and culture.

Literature Reviews

A Quick Review of Human Factors

The Federal Aviation Administration (FAA) defines human factors as the "multidisciplinary field that generates and compiles information about human capabilities and limitations, and applies it to design, development, and evaluation of equipment, systems, facilities, procedures, jobs, environments, staffing, organizations, and personnel management for safe, efficient, and effective human performance" (FAA, 2017, p.2). Understanding the influence of human factors on aviation safety is essential because human factors contribute to human errors and result in aircraft accidents or incidents (FAA, 2018; Kharoufah et al., 2018).

The knowledge of human factors has grown increasingly popular as the commercial aviation industry has realized that human error, rather than mechanical failure, underlies most aviation accidents and incidents since the 1960s (Federal Aviation Administration, 2018). Although human factors are typically associated with flight crew, human errors in aviation maintenance have become a major concern as well. The mistakes of an aviation maintenance technician (AMT) are oftentimes present but not visible and have the potential to remain latent, insidiously affecting the safe operation of aircraft for longer periods of time (Federal Aviation Administration, 2018).

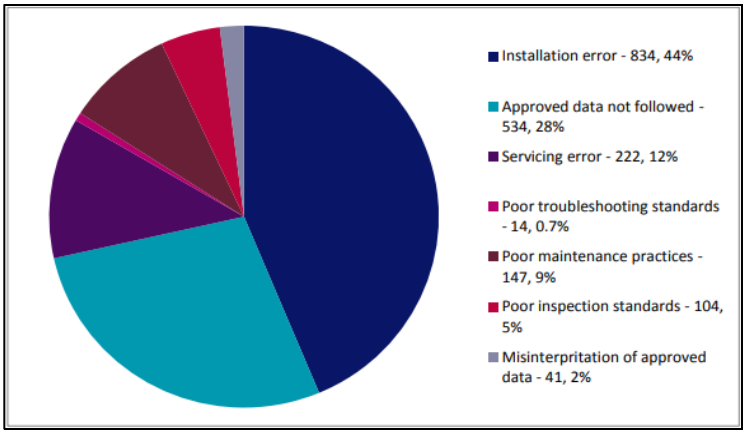
Regardless of the cognitive science, ergonomic/human-machine interface design, and psychological and behavioral variables, there is an extensive list of human factors that can affect AMTs and engineers, including boring and repetitive jobs, personal life problems, poorly designed testing for skill and knowledge, poor instructions, poor training, inadequate work conditions, incomplete or incorrect documentation, substance abuse, fatigue, poor communication, unrealistic deadlines, and lack of tools, equipment & parts. Some of these factors are more serious than others, but in most cases, when three or four of the factors are combined, they can create a problem that contributes to an accident or incident (Federal Aviation Administration, 2018). In the early 1990s, Transport Canada identified twelve human factors that degrade people's ability to perform effectively and safely, which could lead to maintenance errors (Federal Aviation Administration, 2018). These twelve human factors are known as the "dirty dozen", and include lack of communication, complacency, lack of knowledge, distraction, lack of teamwork, fatigue, lack of resources, pressure, lack of assertiveness, stress, lack of awareness, and norms. Maintenance errors, like other causal factors, are likely to be a combination of the above factors leading to an undesired event (Dupont, 2014). It is crucial for AMTs to be aware of the "dirty dozen" and its symptoms, but most importantly, AMTs must be able to understand, identify, and avoid human errors related to the "dirty dozen" (Federal Aviation Administration, 2018) in all stages of aircraft maintenance – from preventative inspections to heavy D checks.

Aircraft Maintenance Incident Analysis (United Kingdom's Civil Aviation Authority)

There have been significant improvements in aircraft system design and component reliability in recent years due to advanced aircraft design techniques, the use of new materials, and knowledge acquired from past incidents and accidents. However, despite these improvements, the maintenance schedule for a modern aircraft still demands the repeated disassembly, inspection, and replacement of millions of removable parts over the long working life of the system (Reason, 1997a). While human operators are error-prone, the process of performing maintenance tasks is involved with vulnerability (Civil Aviation Authority [CAA], 2015; Reason, 1997a). Following a number of high-profile maintenance error events in the early 1990s, considerable work was done looking at the issue of human factors and human performance within aircraft maintenance. It appeared that the growth of aircraft technologies, the prevalence of carrying out maintenance during the night, and the impact of increased pressure on the commercial needs of the operation all had the potential to create an environment where the potential for error could exist (Civil Aviation Authority, 2015).

Of the 2,733 maintenance occurrence reports from the United Kingdom's Civil Aviation Authority (CAA) Mandatory Occurrence Reporting (MOR) dataset between January 2005 to December 2011, 2,399 reports were related to maintenance human factors. According to the U.K. CAA Civil Aviation Publication (CAP) 1367 report, "installation error" was the greatest threat at 44% (see Figure 1). For example, door slides being incorrectly installed resulting from incorrect operating procedures had led to the failure of an emergency evacuation (Civil Aviation Authority, 2015).

Figure 1
MOR Maintenance Error Types from 2005-2011



Source: U.K. Civil Aviation Authority (2015).

AMTs must be fully aware of their responsibilities in the four following areas (Civil Aviation Authority, 2015):

1. Correctly recording and signing off work,
2. Identifying and carrying out safety-critical tasks or independent/duplicate inspections,
3. The importance of following procedures, maintenance instructions, reporting and investigating errors, and
4. Improving tool and debris control.

It is worthwhile to mention that the U.K. CAA has mandated aviation maintenance human factors training per Chapter 11 - *Human Factors Training for Personnel involved in Maintenance* (2009), whereas in the U.S., there are "no FAA regulations that mandate specific content requirement" for maintenance human factors (MxHF) (FAA, 2017, p.4).

Mitigating Human Factors in Aviation Maintenance

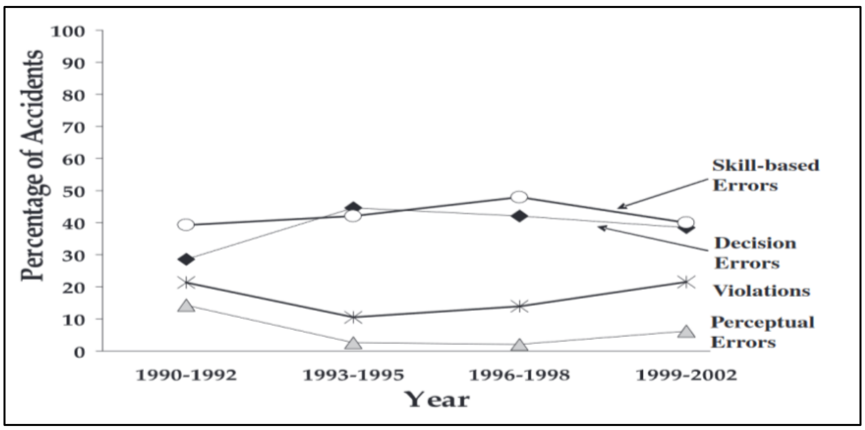
The mitigation of human factors in maintenance is important because the consequences of maintenance-related accidents are often serious. When it comes to aviation fatalities, approximately 15% are caused by maintenance errors (Lu, Bos & Caldwell, 2005; Masson & Koning, 2001). The nature of aviation maintenance typically refers to the jobs done by either the aircraft inspector or other maintenance personnel (Latorella & Prabhu, 2000). In 1995, the FAA published an aviation safety plan providing protocols and advanced maintenance concepts of human factors (Federal Aviation Administration [FAA], 1995) due to the increasing complexity of modern aircraft besides technologically advanced systems (Latorella & Prabhu, 2000). While modern aircraft must go through routine inspections and airworthiness reviews mostly per every 100-hour operation, the specified tasks could open up more opportunities for human error to occur such as the lack of training and qualification, corner-cutting, just to name a few (FAA, 2004).

Human Factor Management Program

When it comes to human factors, the aviation industry has come up with many different programs which could be enforced with the intent of decreasing the number of accidents caused by human error. In Figure 2, there is a decrease in the percentage of accidents caused by skill-based errors and decision errors (Reason, 1997b) from 1996-1998 and 1999-2002 (Shappell & Wiegmann, 2009). However, an increase is seen in perceptual and violation errors. This shows that the accidents were caused due to the lack of proper procedure, which correlates to what was found in many NTSB reports of accidents caused by maintenance. In the wake of the urgent need to improve maintenance safety, the FAA promulgated safety programs to help reduce problematic areas or maintenance human factors (Wiegmann, 2001).

Figure 2

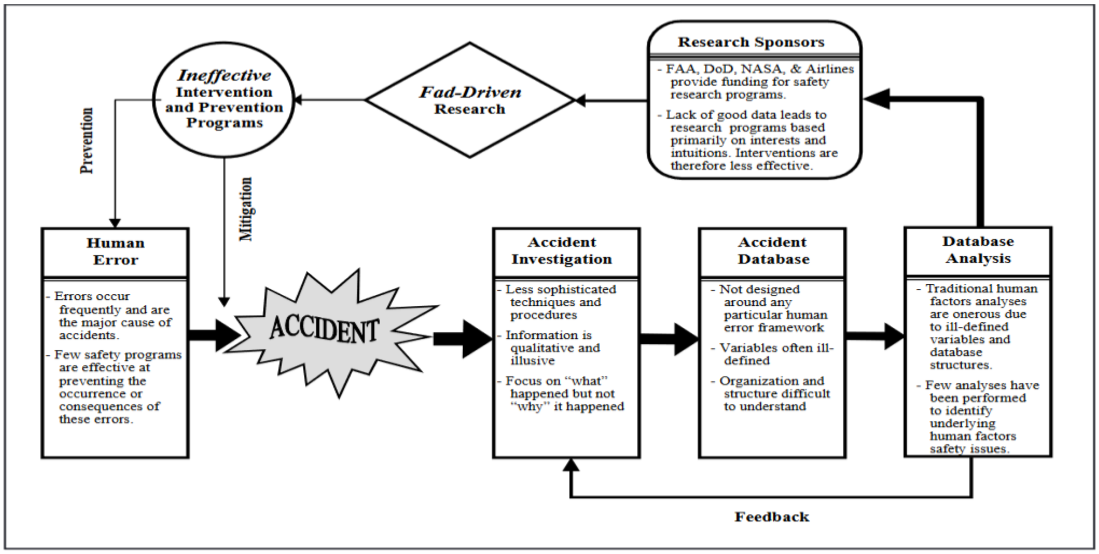
Percentage of Accidents Associated with Unsafe Acts



Source: Shappell, S. & Wiegmann, D. (2009, p. 254).

Figure 3 shows the FAA's systemic process to identify, analyze, and control human factors after an accident had occurred. However, there are many different sets of data that go into creating a program, including past intervention programs, which were proven to be ineffective for various reasons. An accident is one of the starting places that trigger the initiative to impulsively create a safety program. If an accident is due to human errors, the FAA forms a cohort task force to create a solution to preventing a similar accident from happening. This typically results in a drive to look for ineffective safety programs or desires to create or revise a safety program. The process is reactive in nature, and fad/intuition-driven research is normally ineffective or not inexpensive (Reason, 1997b).

Figure 3
FAA's Process for Human Factors Identification and Control



Source: Wiegmann, D. (2001, p. 3)

Research Questions

Any latent variables could lead to an undesired event if they are not properly controlled. Safety researchers and educators shall proactively identify and control possible contributing variables using lessons learned or existing cases. While the pedagogical content of human factors is not required by the FAA airframe & powerplant (A&P) curriculum, many researchers and safety practitioners have discovered the causality from human factors to operational errors and to aviation accidents. It is beneficial to retrospect those important research concerns and topics that had been covered to reflect on the merit of human factors. By doing so, not only can a holistic picture of the completed projects be realized, but it also presents readers with themes or areas for maintenance safety education. Furthermore, as most accidents are due to multiple variables, what are those salient ones that could affect aviation maintenance safety?

The research questions of this study are:

1. What are the emerging research themes of maintenance errors affecting the aviation industry?
2. What are the common contributing variables leading to aviation maintenance related accidents?

Research Methodology

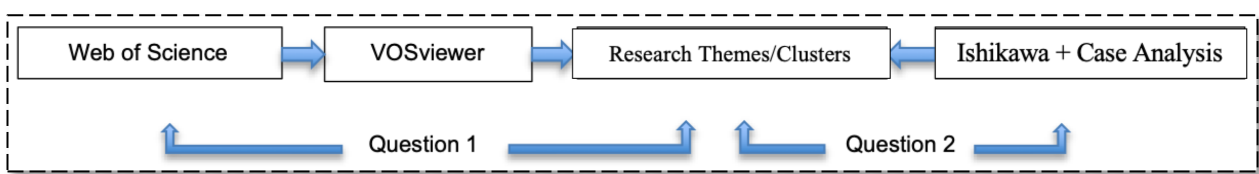
This study uses a series of research approaches to answer the proposed questions. Methods and tools include qualitative meta-narrative analysis, VOSviewer qualitative visualization tool, and detailed case study.

VOSviewer uses a smart, locally moving algorithm that efficiently identifies nodes and edges. This smart, locally moving algorithm constructs networks at different levels to break down the complexity and continually processes the sub-network. This algorithm reiterates itself until a maximum level of optimization has been achieved when processing a large number of iterations on larger-sized networks. The qualitative meta-materials use specific keywords to search the *Web of Science* for related downloadable documents (Waltman & van Eck, 2013; Waltman, van Eck, & Noyons, 2010; van Eck & Waltman, 2010). In this study, the authors use eight (8) keywords to retrieve articles. These combined keywords for article reviews are "aviation maintenance safety", "aircraft maintenance safety", "aviation maintenance error", "aircraft maintenance error", "aviation maintenance safety human factors", "aircraft maintenance safety human factors", "aviation maintenance error human factors", and "aircraft maintenance error human factors."

After all related articles are downloaded, all eight "txt" datasets are uploaded to VOSviewer for visualization and mapping. The purpose of theme mapping is to triangulate findings and generate important themes for selected research studies. The themes are then compared with the results of the Fishbone (Ishikawa) Analysis and Case Studies on selected aviation accidents to reflect on existing theories, such as the FAA's maintenance human errors, Transport Canada's "dirty dozen", James Reason's Swiss Cheese Model, and SHELL Model. The authors formed research reliability and validity using inter-rater reliability and construct validity (Salkind, 2012). The inter-rater reliability was coined by mapping all individual reports and thus yielded a collective agreement on findings.

Figure 4 below demonstrates the research approach of this study.

Figure 4
Research Approach of the Study



Findings & Discussion

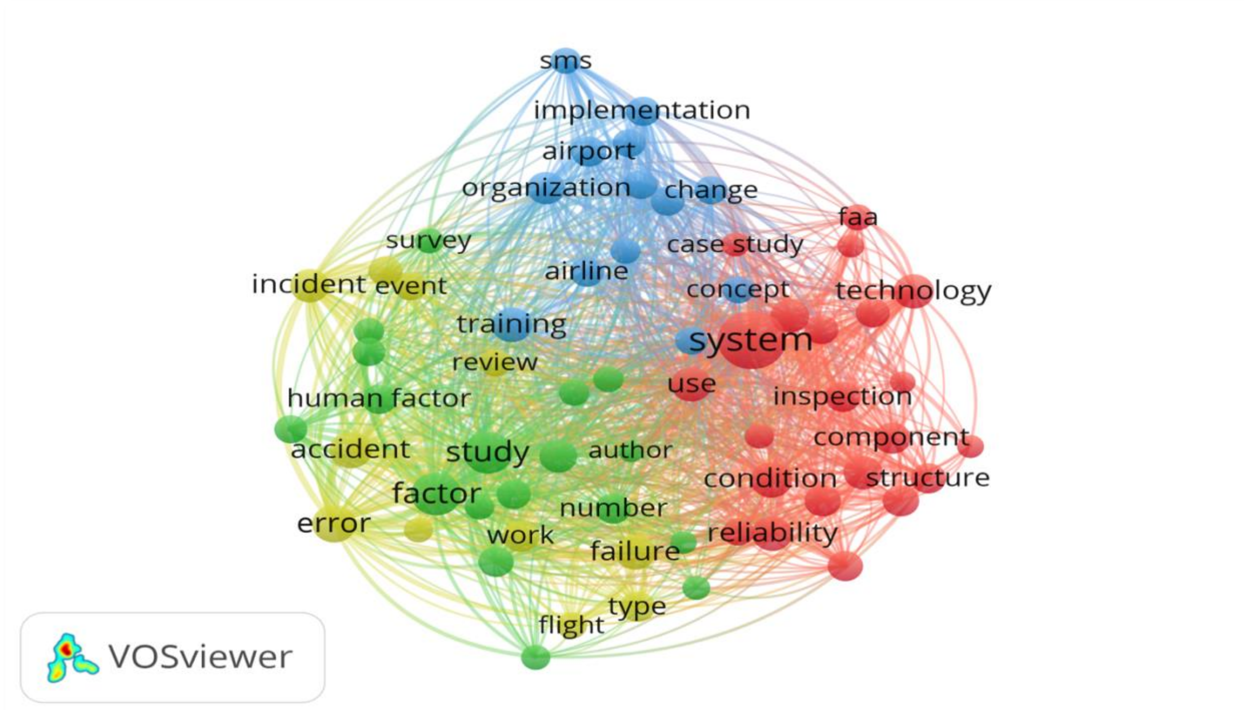
What Are the Emerging Themes of Maintenance Errors Affecting the Aviation Industry?

As described in the Methodology section, the authors used eight (8) keywords and VOSviewer to generate the following charts.

Based on 30 occurrences within 60 papers, Figure 5 below shows three major color-coded clusters under "aviation maintenance safety" including the study of human factors, safety systems, and organizational safety management. This chart indicates that existing research projects focused on aircraft system technology improvement, organizational management & safety program implementation, and human factors training to improve maintenance safety.

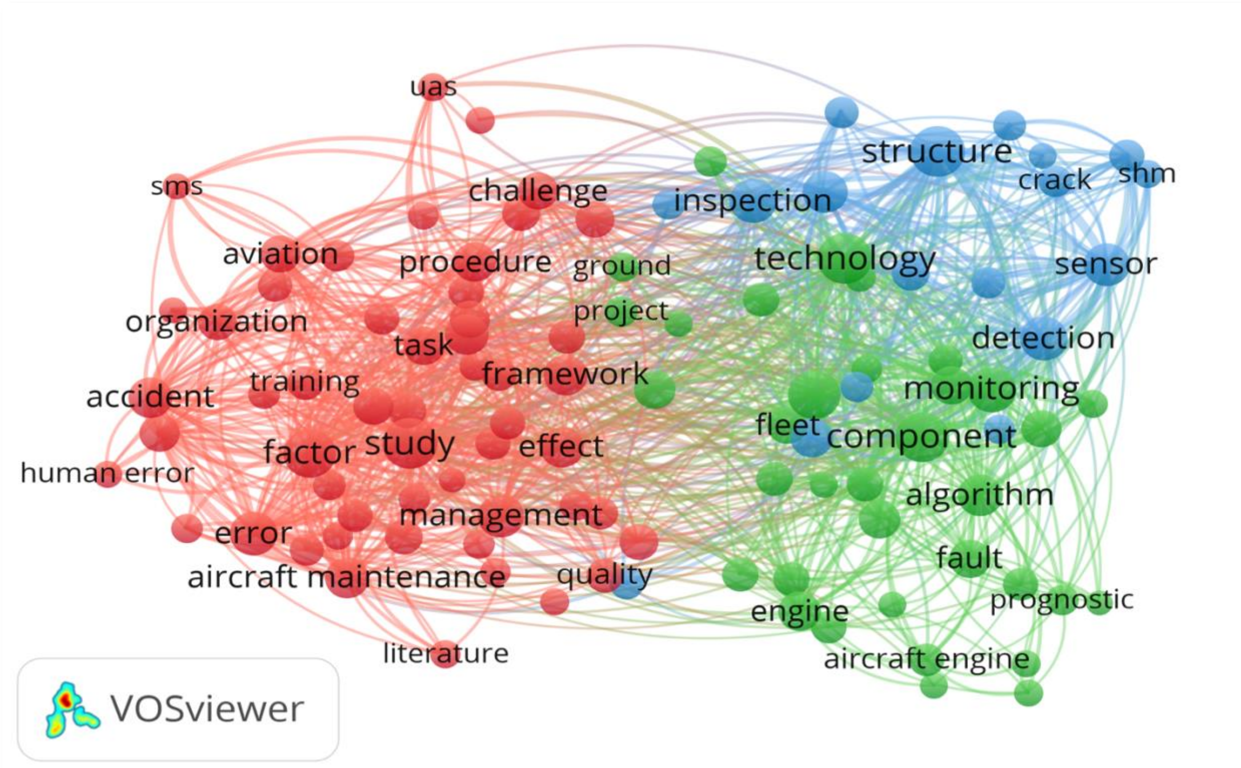
Using the keyword of "aircraft maintenance safety", the following three color-coded clusters were created. Figure 6 indicates that management cluster, inspection skills, and monitoring process are three (3) major color-coded clusters of the maintenance safety study using 30 occurrences as the benchmark within 1,077 research papers and projects.

Figure 5
Aviation Maintenance Safety



Source: VOSviewer software.

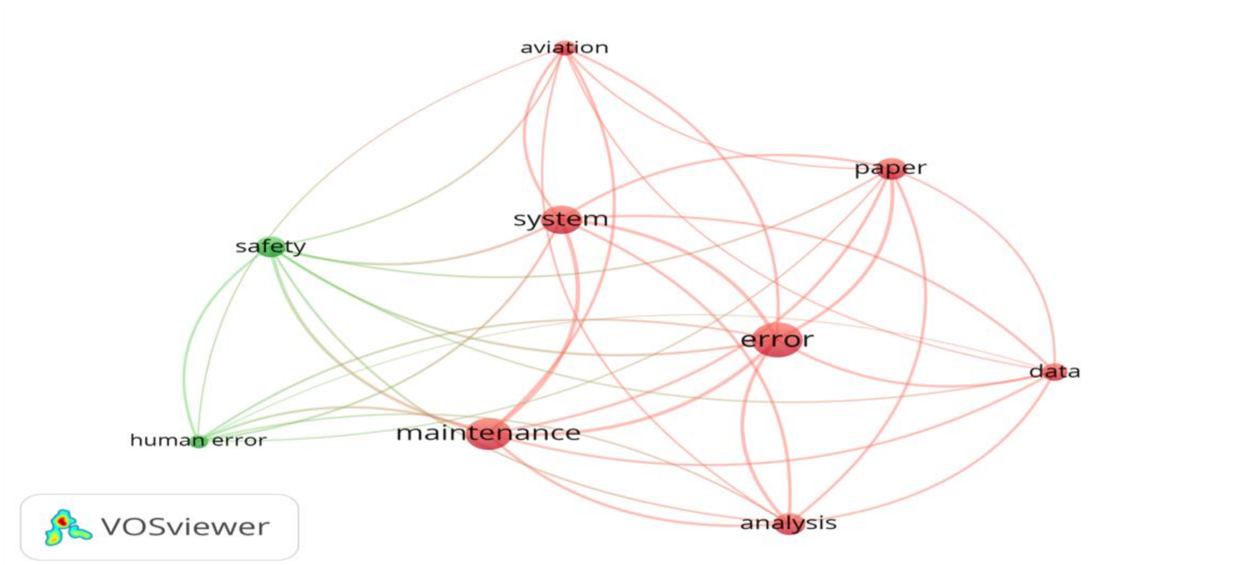
Figure 6
Aircraft Maintenance Safety



Source: VOSviewer software.

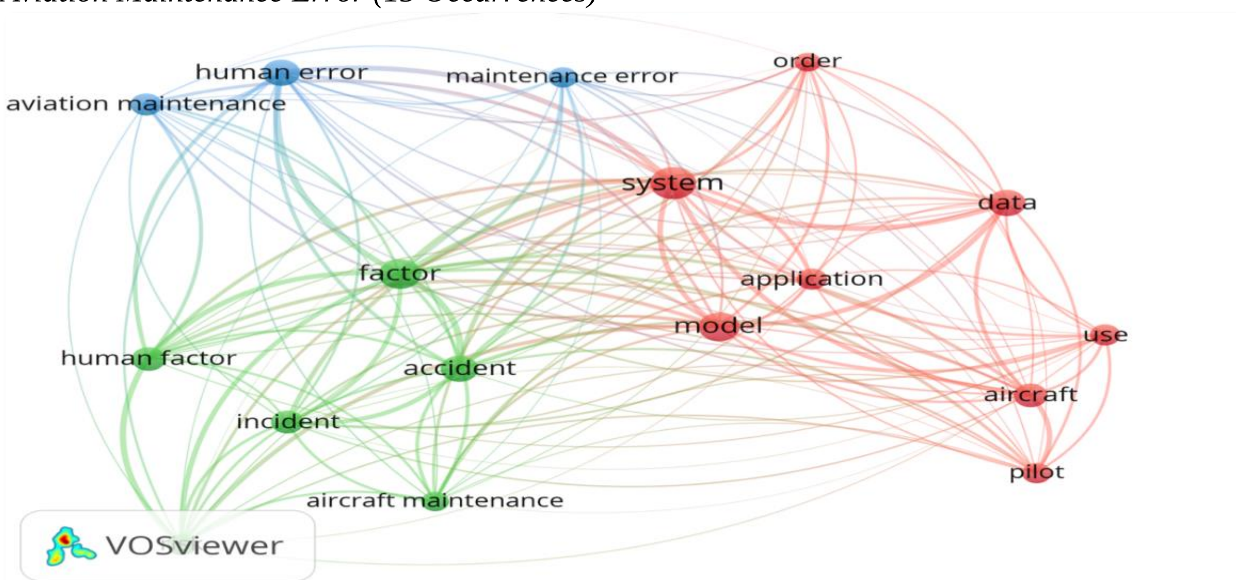
Using 30 occurrences as the benchmark within 212 papers, Figure 7 below shows two simple research clusters. To further identify research similarities and differences, the authors reduced the occurrence benchmark from 30 to 15 (Figure 8). When 15 occurrences are used as the benchmark (Figure 8), the chart indicates three meaningful clusters. The additional cluster is human error and error management.

Figure 7
Aviation Maintenance Error (30 Occurrences)



Source: VOSviewer software.

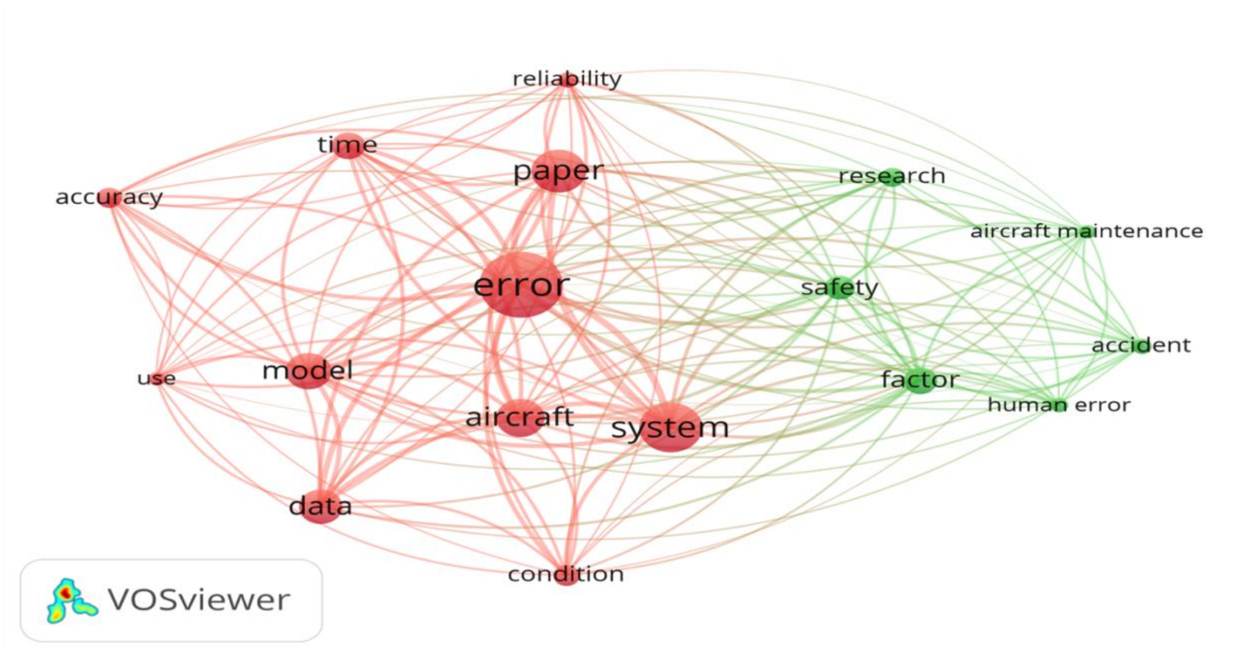
Figure 8
Aviation Maintenance Error (15 Occurrences)



Source: VOSviewer software.

Figure 9 shows two clusters – aircraft design reliability & maintenance human factors. The specific theme "human factors" surfaced when using "aircraft maintenance error" as the quired keyword, providing an informative finding. This analysis used 30 occurrences as the benchmark within 326 papers.

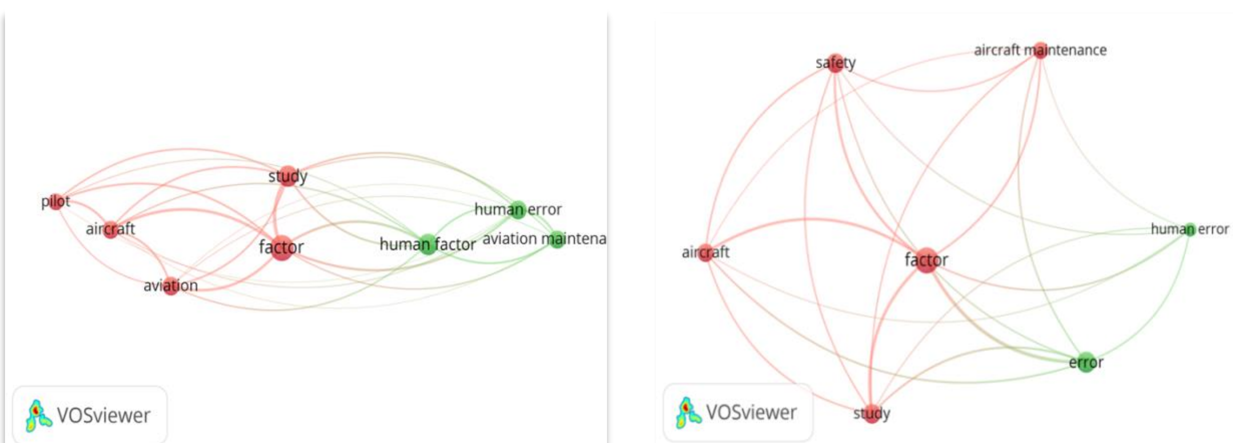
Figure 9
Aircraft Maintenance Error



Source: VOSviewer software.

In Figure 10, the author used 15 occurrences as the benchmark due to the number of downloadable papers. The keyword of human factors is inter-connected to human error and safety study. It also echoes that "aircraft" human factors are more related to pilot operation and engineering design, whereas "aviation" human factors are operator errors, safety study/non-engineering research, or the like.

Figure 10
Aviation Maintenance Safety Human Factors (122 Papers) & Aircraft Maintenance Safety Human Factors (104 Papers)

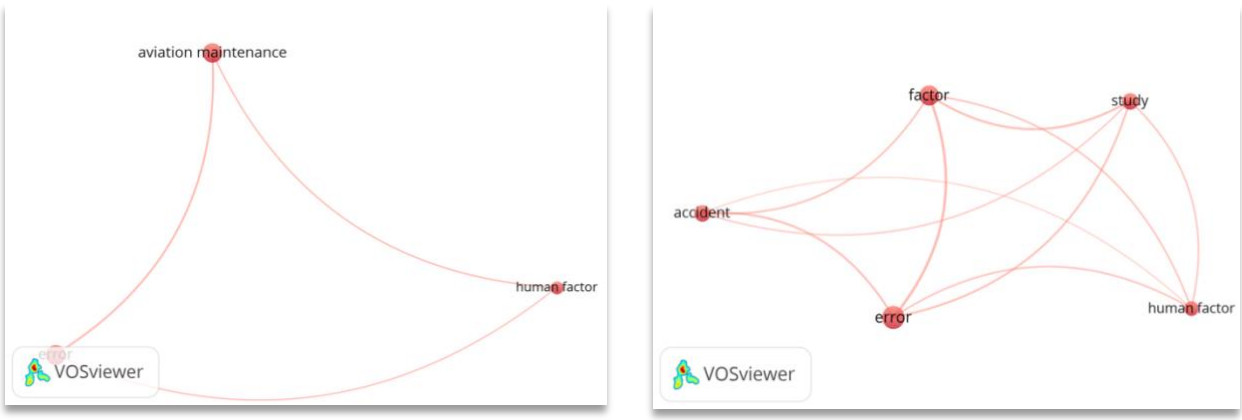


Source: VOSviewer software.

Using longer keywords in the search yields a smaller number of results. Figure 11 shows the interconnection among “maintenance”, “error”, “human factors”, and “accident”. Obviously, human factors could lead to human errors and thus accidents. In Figure 12, the combined inter-connection analysis shows the overlapping themes between aircraft maintenance and aviation maintenance – “analysis”, “error”, and “human factors”. “Error” was the major theme for a “paired” analysis based on the density visualization.

Figure 11

Aviation Maintenance Error Human Factors & Aircraft Maintenance Error Human Factors



Source: VOSviewer software.
https://www.vosviewer.com/

Figure 12

Combined Interconnection Analysis – Aviation/Aircraft Maintenance Error Human Factors

Source: VOSviewer software. https://www.vosviewer.com/

What are the Common Contributing Variables Leading to Aviation Maintenance Related Accidents?

Research question 2 is answered by case analysis using Fishbone (Ishikawa) Diagrams along with an in-depth qualitative narrative analysis of selected accident cases. The qualitative narrative analysis is obtained by thoroughly reviewing the original accident reports and conducting a comprehensive analysis using existing safety-related theories to find upper-level contributing variables that are beyond the original probable cause. Along with the identification and analysis of contributing variables, a synopsis of the accident is provided and includes the main points and highlights. Furthermore, the analysis includes the authors' findings on what led to the accident/incident chain.

1. Atlantic Southeast Airlines, Flight 529, Embraer EMB-120 Brasilia, N256AS

Synopsis. On August 21, 1995, Atlantic Southeast Airlines Flight 528 suffered from propeller separation that resulted in significant damage to the engine mounting frame and inadequate levels of lift from the left wing. The aircraft then crashed after a barely controllable descent into terrain (NTSB, 1996).

Causal Factors. *T*he major factor leading to the crash has been identified as the inflight fatigue fracture of one of the blades on the left-hand engine (NTSB, 1996).

Researchers' Additional Findings. Additional findings are based on Swiss Cheese and Fishbone Ishikawa analyses and are provided as follows:

Swiss Cheese Model – Latent Conditions. According to the well-known Swiss Cheese model for accident hazard identification, each accident sequence consists of both active failures and latent conditions, where latent conditions are mostly involved organizational risks (Reason, 1997b). These failures and conditions create "holes" in the layers of defense that a system has in order to prevent a hazard from leading to an accident. An active failure is an unsafe act that is likely to immediately impact the safety of the system at the moment. Latent conditions are decisions made within a system that go beyond the operator committing an unsafe act. Following James Reason's Swiss Cheese analysis, the authors list the following latent factors:

1. It was found that the decision by Hamilton Standard to stop the procedure of "shot peening" the internal area of the propeller made the blades more susceptible to early fatigue cracks than if the shot peening procedure had been continued (Armendariz et al., 2014).
2. Hamilton Standard and the FAA agreed on the usage of a chlorine-soaked cork inside the propeller, causing a situation where the inside of the blade could be corroded over time by the chlorine and creating an environment for fatigue cracks to form.
3. The accident blade had been ultrasonically scanned by Atlantic Southeast Airlines (ASA) maintenance personnel for imperfections following two incidents with propeller failures.
4. The technician that inspected the blade using a borescope was unable to detect any cracking inside the propeller due to unsatisfactory tools and the aircraft was returned for services.
5. The technician conducted a procedure in which he blended and resealed the interior of the blade to eliminate what he believed to be erroneous manufacturing imperfections. The technician ended up covering up the existing evidence of cracking that his borescope procedure had failed to detect.
6. Two fatigue cracks that had been missed by the inadequate inspection techniques eventually joined together to form one large crack.

7. The failure of Atlanta Center to expeditiously notify emergency services after the crash. Had the Carroll County Fire Department been notified when requested, they would have been able to respond to the crash site much quicker (NTSB, 1996).

Fishbone (Ishikawa) Analysis. The Fishbone (Ishikawa) Analysis is an effective tool for identifying and categorizing the various contributing factors that combined to result in the accident (Liang et al., 2019). This is referred to as a root cause analysis, which is a structured process for identifying the various underlying causes or factors that result in an accident. Figure 13 below is a Fishbone Ishikawa diagram incorporating the SHELL model.

Proposed Controls. Following Swiss Cheese and Fishbone Ishikawa analyses, safety controls for improvement include shaping a reporting culture, implementing SMS and

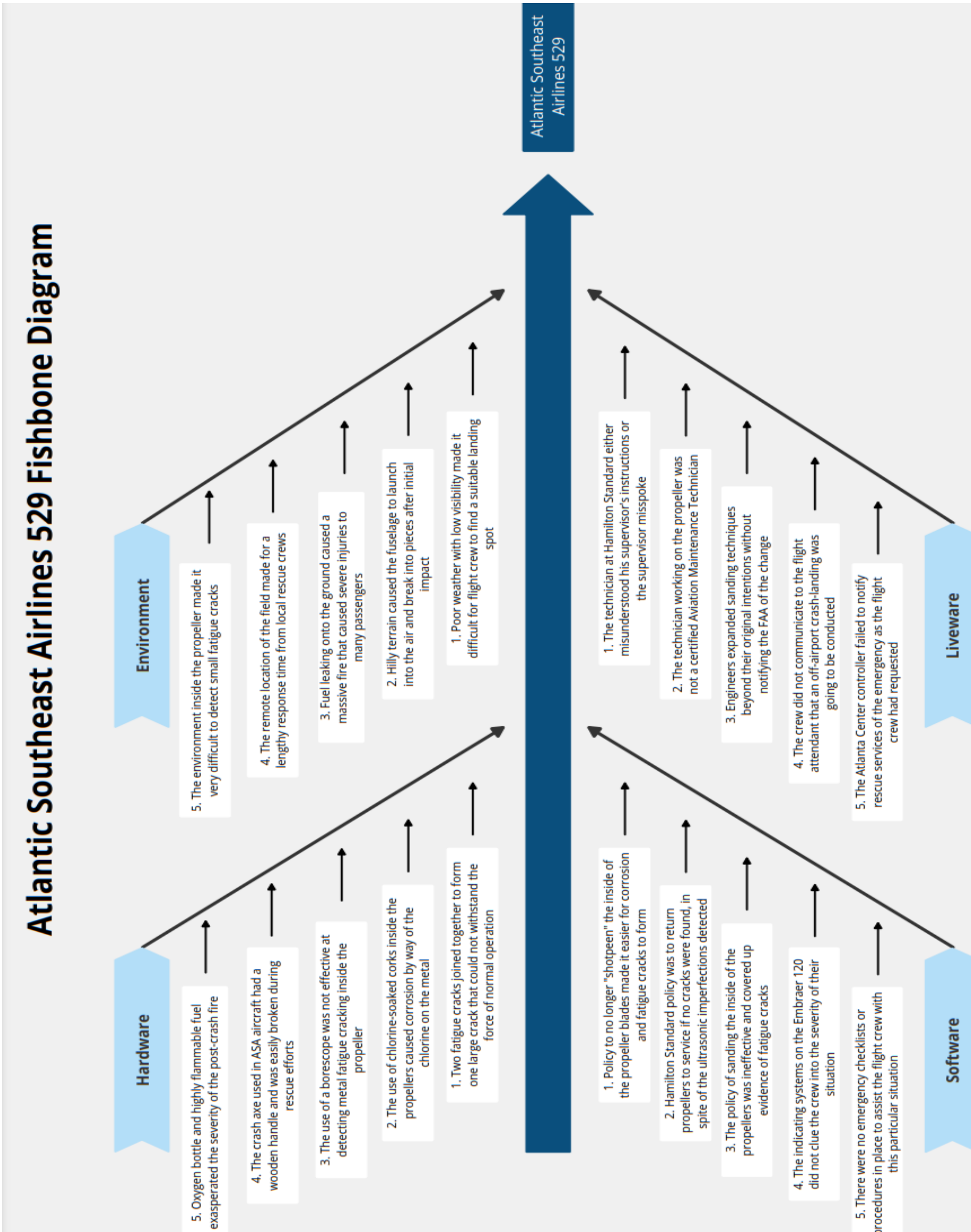
Reporting Culture. A tangible control is a change in culture regarding how potential human errors are identified and mitigated. To truly be successful in achieving safe design, manufacturers and maintenance organizations need to be proactive rather than reactive (Ballesteros, 2007). For the Atlantic Southeast Flight 529 accident, there had been previous accidents related to propeller design issues. In a reactive manner, the propeller manufacturer Hamilton Standard made some changes to increase inspections and change repair techniques. However, these measures had only put a bandage on the wound rather than preventing wounds from occurring in the first place. A high emphasis on identifying the latent factors of human errors could significantly reduce the risk of recurrent accidents.

Assertiveness. Some of the confusion on the part of the technician related to this accident had to do with miscommunication of policy, the uncertainty of correct usage of tools, and unclear work instructions. A quality documentation hierarchy places emphasis on clear policy, procedures, work instructions, and quality records (Stolzer & Goglia, 2015). The process of manufacturing and maintaining aircraft parts does not allow for ambiguity or confusion. Clear and concise documentation and procedures by the company would be beneficial for Hamilton Standard in reducing the chances of these types of errors from occurring.

Safety Awareness and Informed Culture. The technician that worked on the accident aircraft's propeller was not a certified aviation maintenance technician, nor was he required to be by law. It would be a plausible idea for them to place an increased emphasis on aviation safety education and training, such as maintenance resource management (MRM) and human factors (HFs). A strong educational and training program that goes above and beyond to teach employees how to conduct their duties in a safe and regimented manner creates an environment where employees are more likely to recognize potentials for hazards and ask questions if things don't make sense (Wood, 2003). These employees are more empowered and take ownership of the safety system within their organization. Furthermore, this would help enhance the organization's safety culture through the implementation of a better "informed culture". Informed culture requires that working personnel understand hazards and risks, ask questions, as well as have the relevant knowledge and skills pertaining to their job (CANSO, 2008). Better hazard identification kills and job knowledge through safety education and training allows technicians to be more informed and aware of potential hazards.

Figure 13

Fishbone (Ishikawa) Analysis – Atlantic Southeast Airlines Flight 529



2. Air Midwest, Flight 5481, Beechcraft 1900D, N233YV

Synopsis. On January 8, 2003, Air Midwest Flight 5481 suffered from a stall shortly after takeoff and crashed into a hangar after reaching 54 degrees of pitch. The NTSB concluded that the probable cause was the incorrect rigging of the elevator control system, which caused the pilots to have insufficient pitch control (NTSB, 2004).

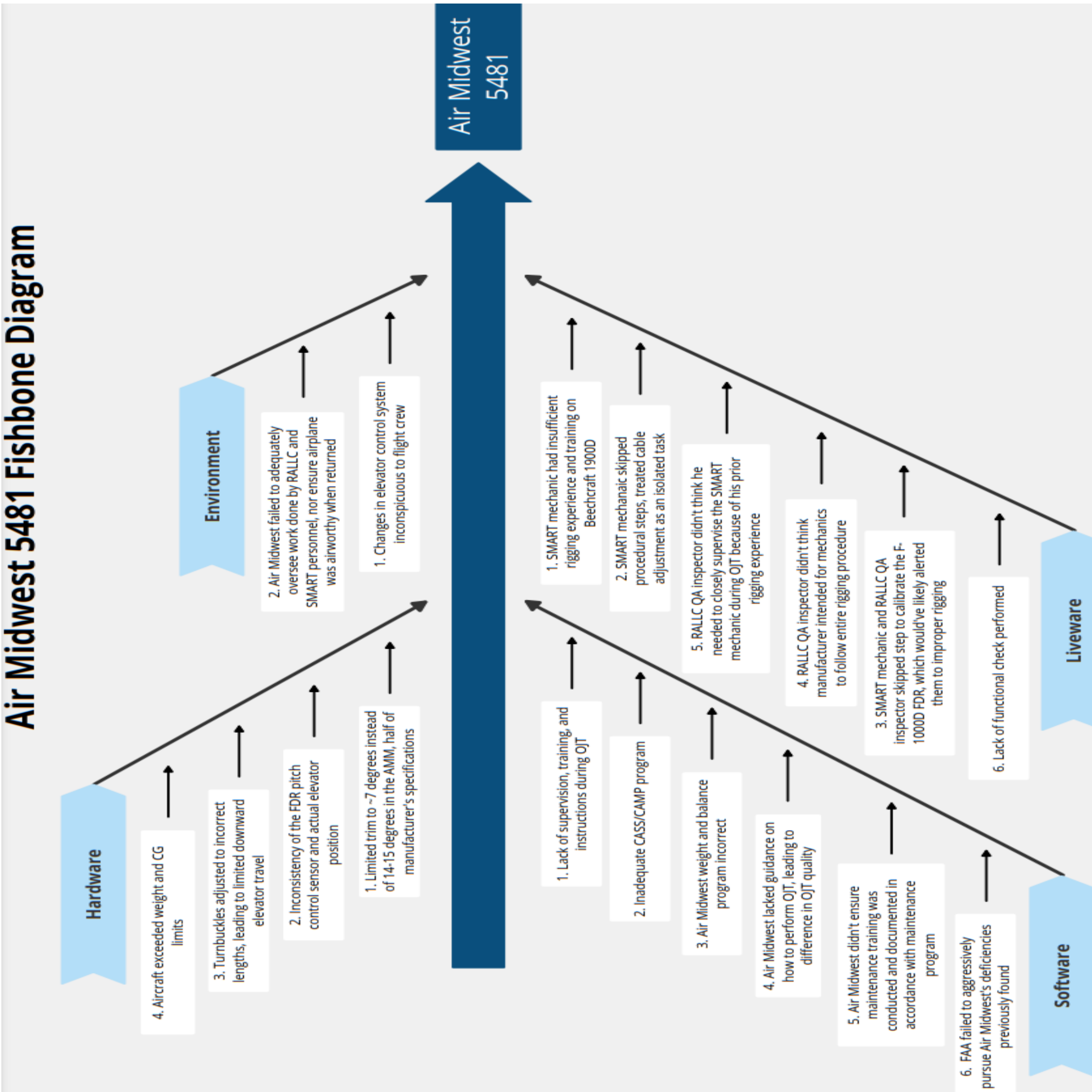
Causal Factors. The incorrect rigging restricted the elevator travel to about one-half of the downward travel specified by the manufacturer. This was caused by deficiencies in the rigging process, oversight, and training. Firstly, nine steps were skipped during the rigging procedure (NTSB, 2004). The mechanic violated the procedure and treated the cable adjustment as an isolated task. One of the skipped steps would've signaled the improper rigging, but this step was ignored. Skipping steps was in violation of 14 CFR 121.367 (U.S. Government Printing Office, 2011), the airline's procedures, and the manufacturer's manual.

Researchers' Additional Findings. Additional findings are extracted from another approach using the combined application of Fishbone Ishikawa Analysis and the SHELL model. Figure 14 below is a Fishbone (Ishikawa) diagram incorporating the SHELL model.

Based on the Fishbone (Ishikawa) analysis (Figure 14), the following are up-stream contributing factors:

- Software: 1. Lack of supervision, training, and instructions during OJT; 2. Inadequate Continuing Analysis and Surveillance System (CASS)/ Continuous Airworthiness Maintenance Program (CAMP); 3. Air Midwest weight and balance program incorrect; 4. Air Midwest lacked guidance on OJT procedures, leading to a difference in OJT quality; 5. Air Midwest failing to ensure maintenance training and proper documentation; and 6. FAA failing to aggressively pursue Air Midwest's deficiencies previously found.
- Hardware: 1. Limited trim to ~7 degrees instead of the 14-15 degrees specified in the AMM and manufacturer's specifications; 2. Inconsistency between the FDR pitch control sensor and actual elevator position; 3. Turnbuckles adjusted to incorrect lengths, limiting downward elevator travel; and 4. Aircraft exceeding weight and CG limits.
- Environment: 1. Changes in elevator control system inconspicuous to flight crew; and 2. Air Midwest failing to oversee work done by RALLC and SMART personnel, nor ensuring the aircraft was airworthy when returned.
- Liveware: 1. Mechanic having insufficient rigging experience and training on Beechcraft 1900D; 2. Mechanic skipping procedural steps, treating cable adjustment as an isolated task; 3. QA inspector failing to closely supervise mechanic during OJT because of his prior rigging experience; 4. QA inspector not thinking that manufacturers intended mechanics to follow entire rigging procedure; 5. Mechanic and QA inspector skipping the step to calibrate the F-1000D FDR, which would've likely alerted them to improper rigging; and 6. Lack of functional check performed.

Figure 14
Fishbone (Ishikawa) Analysis – Air Midwest Flight 5481



3. Alaska Airlines, Flight 261, McDonnell Douglas MD-83, N963AS

Synopsis. On January 31, 2000, Alaska Airlines Flight 261 crashed into the Pacific Ocean about 2.7 miles north of Anacapa Island, California. The NTSB determined that the probable cause of the accident was a loss of airplane pitch control resulting from the in-flight failure of the horizontal stabilizer trim system jackscrew assembly's acme nut threads. The thread failure was caused by excessive wear resulting from Alaska Airlines' insufficient lubrication of the jackscrew assembly. Furthermore, while not specifically mentioned in the

NTSB findings, the acme nut grease fitting passenger - which allows the grease to reach the jackscrew and acme nut threads, was found plugged with dry residue (Federal Aviation Administration, n.d.).

Causal Factors. The NTSB determined that the primary causal factors were the lack of emphasis on maintenance and safety. Numerous management positions, such as the Director of Maintenance, Director of Operations, and Director of Safety were vacant. Furthermore, the authority and responsibility of the roles were poorly defined (NTSB, 2002).

Researchers' Additional Findings. Safety culture was lacking at Alaska Airlines before and at the time of the accident. John Liotine, a mechanic working at Alaska prior to the accident, reported supervisors approving records of maintenance without authorization or when work was incomplete. Furthermore, he said that a supervisor had overruled his recommendation to replace the jackscrew and gimbal nut of the accident aircraft. The causal factors and the incident described here, along with the poor leadership propagated the lack of a safety culture, or if at best, a poor one throughout the airline from top to bottom. Another contributing factor was inadequate maintenance training. The general maintenance manual (GMM) didn't specify training curriculum or on-the-job (OJT) procedures and objectives (Software). The program was also informal and administered at discretion (Software). Alaska's lubrication practices were deficient, as the extension of service intervals decreased the chances of detecting inadequate/missed lubrication (Software). The mechanic performing the lubrication also lacked knowledge of the lubrication process, omitting the step to check for grease as specified in the procedures (Liveware), and did not use enough time to complete the procedure (Liveware). Finally, the FAA's oversight of Alaska's maintenance operations was deficient (Software).

4. Tuninter Airlines, Flight 1153, ATR 72-200, TS-LBB

Synopsis. On August 6, 2005, Tuninter Flight 1153 ditched into the Mediterranean Sea following the failure of both engines due to fuel exhaustion (Agenzia Nazionale per la Sicurezza del Volo, n.d.). On impact with the surface of the sea, the aircraft broke into three pieces. The Agenzia Nazionale per la Sicurezza del Volo (ANSV), an Italian government agency for aircraft accident investigation analyzed the accident using James Reason's Swiss Cheese model since the final ditching was caused by a series of interconnected events.

Causal Factors. The ANSV determined that the primary contributing factor was the incorrect replacement of the fuel quantity indicator (FQI) by Tuninter maintenance personnel (ANSV, n.d.).

Researchers' Additional Findings. Other contributing factors relating to human error in maintenance include errors made by ground mechanics when searching for and correctly identifying the fuel indicator (Liveware), such as not using the IPC as required to check parts compatibility, as well as unsatisfactory maintenance and organizational standards (Software). Furthermore, maintenance personnel lacked adequate training for the aircraft management and spares information system (AMASIS) being used (Software). Complicating the problem was that there was no responsible person appointed for managing the system itself (Software). Hardware similarities for the fuel quantity indicator on the ATR 42 and ATR 72 made it possible to install an ATR 42 type indicator in an ATR 72, and vice versa (Hardware). Finally, the fuel indicator replacement procedures lacked a step that called for a manual check using the dripsticks (Software) (ANSV, n.d.). Using James Reason's Swiss Cheese model, the accident barriers included established systems like the IPC and AMASIS. However, their effects are nullified by active and latent failures, like the omission of IPC usage and lacking a responsible person for managing AMASIS, respectively. Additional latent failures include unsatisfactory maintenance and organizational standards and lacking adequate training for the AMASIS system.

5. Colgan Airways, Flight 9446, Beechcraft 1900D, N240CJ

Synopsis. On August 26th, 2003, Colgan Airways Flight 9446 was destroyed after impacting water near Yarmouth, Massachusetts in a nose-dive. The NTSB concluded that the accident was due to the aircraft losing pitch control because of improper replacement of the forward elevator trim cable.

Causal Factors. Three days before the accident, the aircraft underwent a Detail Six phase check, which included checking the elevator trim actuators. The actuators failed the test and subsequent complications required the elevator trim tab cables to be replaced. However, the technicians skipped a step and did not follow the AMM to use a lead wire as instructed, instead of marking the top pulley with a "T" (NTSB, 2004). Subsequent investigations suggested that the cables would have to be crossed to reverse the system. However, because the technicians skipped the step to use a lead wire, they were likely not alerted. Furthermore, AMM depictions of the trim drum were backward. Despite being incorrect, the AMM instructions were ignored. This resulted in the discrepancy of the elevator trim system. These causal factors show that there were deficiencies both in the maintenance manual and training of technicians.

Researchers' Additional Findings. A series of upstream, latent and active procedural human errors constituted this accident. Aside from the maintenance technicians being ignorant of the procedures or having slips (latent), the captain of the flight crew had made active cockpit procedural errors. Prior to the flight, the captain did not address the cable change noted on the maintenance release, nor perform the preflight checklist that included the elevator trim check (NTSB, 2004). These steps would've likely alerted the captain to the error with the trim system. Skipping procedural steps is a major issue resulting in this accident, prevalent in both the technicians and flight crew. Furthermore, this suggests additional awareness is needed in encouraging personnel to follow all procedural steps and requirements.

6. China Airlines, Flight 611, Boeing 747-200, B-18255

Synopsis. On May 25th, 2002, China Airlines Flight 611 crashed into the Taiwan Strait after suffering from an inflight breakup. Authorities believe that this in-flight break-up was caused by structural failure of the aft lower lobe section of the fuselage due to an improperly repaired tailstrike 22 years prior (Aviation Safety Council, 2004).

Causal Factors. A major contributing factor to the accident was the 29 missed inspections and safety defects that the aircraft had been operating with, starting approximately 4.5 years prior in 1997. These missed inspections were in violation of Boeing's B747 Aging

Airplane Corrosion & Control Program Document and CAL's AMP. China Airlines had changed inspection intervals from letter checks to calendar-year requirements, and this caused some aircraft with a low flight time to be overdue (Aviation Safety Council, 2004). Miscommunication between CAL's Maintenance Operations Center and Maintenance Planning Sections was mainly to blame. Inefficient communication creates barriers towards the accomplishment of organizational goals (Schmidt et al., 2000). However, there is also a problem with the poor-quality assurance procedures, and lack of management oversight and coordination, perhaps even hinting to poor leadership.

Researchers' Additional Findings. The accident chain started with incorrectly accomplished repairs that remained latent for 22 years. In May 1980, a tailstrike was repaired using inappropriate methods in violation of the Boeing SRM. A doubler was installed over the scratched skin and failed to cover the entire damaged area (Aviation Safety Council, 2004). This repair method led to the accumulation of undetected fatigue cracks, weakening that area every time the aircraft was pressurized. CAA's report mentioned that eddy current and visual inspection non-destructive testing (NDT) methods couldn't be used to detect the hidden cracks. However, why did the technicians not use other methods for the inspection? If a method doesn't work in accomplishing a task, that doesn't mean the task does not need to be completed; another method should be used instead (ultrasonic testing, dye penetrant, etc). This, combined with the lack of coordination and leadership mentioned above points to a problem with negligence and safety culture at CAL. Maintenance personnel should care that a task is done fully and correctly, even if there are obstacles. Management, on the other hand, has the duty of ensuring that an order is clearly understood by all parties and provides oversight and direction. Furthermore, management should also provide resources to overcome difficulties maintenance personnel face, as well as ensure the correct accomplishment of a task. Finally, this accident also reveals a serious flaw in the training of maintenance personnel. The tailstrike was classified as a minor repair instead of a major repair, thus omitting the need to document the fix (Aviation Safety Council, 2004). This suggests that technicians have not been well trained in the difference between the types of repairs, as well as flaws in the documentation procedures. CAL's procedure is deficient in that it may make it hard for root cause analysis of future accidents, especially when analyzing variables that remain latent or seem insignificant at first.

7. British Airways, Flight 5390, BAC 1-11, G-BJRT

Synopsis. On June 10, 1990, British Airways Flight 5390 experienced an explosive decompression on the windscreen, partially sucking out the captain. The United Kingdom Civil Aviation Authority (CAA) concluded that incorrect diameter bolts were used when replacing the windshield (Deniz, 2000), as well as "a series of poor work practices, poor judgments, and perceptual errors…" (Department of Transport, 1992).

Causal Factors. This incident was largely due to the result of an accident chain started by the shift maintenance manager's complacency. His work lacked sufficient care and he used poor trade practices and ignored established procedures. These acts included - not using the IPC to identify required bolts' part numbers; not using the stores TIME system to identify the stock level and location of quired bolts; using physical matching of old and new bolts by touch and eye over comparing part numbers, leading to a mismatch; and over-torquing bolts which differed from the Maintenance Manual (Department of Transport, 1992). Furthermore, his complacency led him to ignore numerous cues, such as not questioning the choice to use A211-7D and A211-8C bolts one night and using the correct A211-8D bolts the next night for the same task. Furthermore, he did not use his glasses while performing the windscreen replacement despite requiring mild corrective lenses when reading small print.

Researchers' Other Findings. Complacency is one of the twelve common causes of human factors errors (FAA, n.d.). The causal factors listed above are representative that complacency is an underlying problem that has happened previously, as people become complacent after many repetitions of the same task (FAA, n.d.). The fact that similar errors were likely made in the past without being detected points to the fact that British Airways lacked quality controls. First, the product samples and quality audits department did not directly monitor working practices (Department of Transportation, 1992). Second, the shift maintenance manager's work being the only individual whose work wasn't subject to review created a single point of failure. Combined, these factors led to the detection failure of the inadequate standards used. Aside from complacency and the quality department, management is also a latent variable. Management allowed the maintenance manager's work to become a single point of failure and the complacency to continually repeat itself without being detected by the quality department. This raises an important question about the management's attitude – does management care if an error occurs but nothing happens? If the answer is no, this reveals a deeper flaw in the airline's safety and organizational culture. Using James Reason's Swiss Cheese Model to analyze the accident, the single point of failure combined with the latent variables (management, complacency, & quality department) allowed the hazard of using the incorrect bolts to pass through the barriers to failure (monitoring work practices & the quality department). If the work of the shift maintenance manager was monitored and management's attitude was to aggressively pursue all errors, his working practices would've been corrected, and the hazard would not result in the undesired incident. Further awareness in educating maintenance personnel about human factors susceptibility and complacency is needed.

Maintenance Related Accidents

For ease of review, tables below have been included that simplify the authors' findings into major contributing variables of maintenance related accidents, relevant cases, supporting details, and brief explanations. Contributing variables generally fall into four categories: 1. Poor training of maintenance personnel; 2. Deficient maintenance procedures, manuals, & tools; 3. Ignoring established procedures; and 4. Poor safety/organizational culture. Tables 1 to 4 below provide the inductive summary of each contributing variable.

Table 1
Poor Training of Maintenance Personnel

Poor Training of Maintenance Personnel	***Excerpt from Qualitative Narrative Analysis***
Atlantic Southeast Airlines 529	Technicians unintentionally covered up existing evidence of cracking on the blade after mistaking it for manufacturing imperfections.
Air Midwest 5481	Mechanic had insufficient rigging experience and training on Beechcraft 1900D; QA inspector not thinking that the entire rigging procedure was to be completed; lack of post-repair functional check.
Alaska Airlines 261	The mechanic performing the lubrication lacked knowledge of the lubrication procedure and relevant steps to check for grease.
Tuninter Airlines 1153	Maintenance personnel lacked adequate training for the AMASIS system.
China Airlines 611	Technicians incorrectly repaired tailstrike using inappropriate methods; tailstrike was incorrectly classified as a minor repair rather than a major repair.

Table 2
Deficient Maintenance Procedures, Manuals, & Tools

Deficient Maintenance Procedures/Manuals/Tools	Excerpt from Qualitative Narrative Analysis
Atlantic Southeast Airlines 529	The technician conducting borescope inspection on the blade was not able to detect cracking inside the propeller due to unsatisfactory tools; Hamilton Standard's decision to stop "shot peening" the internal area of the propeller made caused the blades to be more susceptible to early fatigue cracks; Hamilton Standard's usage of a chlorine-soaked cork inside the propeller allowed the blade to be corroded over time and fatigue cracks to form.
Alaska Airlines 261	Alaska's extension of service intervals decreased the chances of detecting inadequate or missed lubrication.
Tuninter Airlines 1153	Fuel indicator replacement procedures lacked a step that called for a manual check using the dripsticks.
Colgan Air 9446	The AMM depictions were incorrect, depicting the trim drum backward.

Deficient maintenance procedures, manuals, and tools pertaining to human factors education such that it may serve as a marker of reporting culture issues. It is presumed that it is not the first implementation of such and that prudent maintenance personnel would question the use of such tools or procedures. So, why did nobody raise a question or concern until it was too late? Could it be an effect of a lack of safety mentality among the technicians or perhaps that they didn't care to report because they didn't think it would be taken seriously? This may be a sign that more human factors education is needed to teach technicians to improve safety mentality and awareness.

Table 3
Ignoring Established Procedures

Ignoring Established Procedures	**Excerpt from Qualitative Narrative Analysis**
Air Midwest 5481	Mechanics skipped procedural steps, treating cable adjustment as an isolated task; mechanic and QA inspector skipping the step to calibrate the F-1000D FDR.
Tuninter Airlines 1153	Mechanics did not use the IPC as required to check parts compatibility.
Colgan Air 9446	Technicians did not follow the AMM and skipped a step to use a lead wire as instructed, instead marking the top pulley with a "T".
British Airways 5390	Shift maintenance manager engaged in a series of poor trade practices, including not using the IPC to identify required bolts' part numbers; not using the stores TIME system to identify the stock level and location of quired bolts; using physical matching of old and new bolts by touch and eye over comparing part numbers, leading to a mismatch; and over-torquing bolts which differed from the Maintenance Manual.

Table 4
Poor Safety & Organizational Culture

Poor Safety/Organizational Culture	***Excerpt from Qualitative Narrative Analysis***
Air Midwest 5481	Poor oversight and training from Air Midwest's responsibility to monitor RALLC and SMART personnel, as well as deficient OJT procedures point to management problems and poor safety culture. Furthermore, the airline lacked an adequate CASS/CAMP program and a proper weight and balance program. Management issues are seen on all levels and divisions within the company*.
Alaska Airlines 261	Management issues: Numerous management problems contributed to organizational accidents, such as the vacancy of the Director of Maintenance, Director of Operations, and Director of Safety positions; Leadership issues: Supervisors approving records of maintenance without authorization or when work was incomplete; Reporting culture issues: Supervisor overruled John Liotine's recommendation to replace jackscrew and gimbal nut and chose to ignore a safety concern**. A combination of these problems points to poor organizational culture on multiple levels of command and throughout the company.

Tuninter Airlines 1153	The vacancy of a responsible person for the AMASIS system and the unsatisfactory maintenance and organizational standards points to poor organizational culture***.
Colgan Air 9446	The technicians ignoring the procedures and more importantly, the captain not addressing the maintenance release or performing the preflight checklist possibly reveals poor safety and organizational culture. This type of attitude is persistent in more than one division, hinting to organizational and leadership issues.
China Airlines 611	Poor quality assurance procedures, lack of oversight and coordination, perhaps even poor leadership contributed to a problem of negligence and poor safety culture. Management failed to provide oversight and direction, as can be seen by the poor communication between maintenance divisions and the lack of sufficient instructions for NDT. In this case, management also does not care that the task is done fully and correctly, in turn contributing to poor safety and organizational culture.
British Airways 5390	Management allowed the shift maintenance manager's work to become a single point of failure and the complacency to continually repeat itself without being detected by the quality department. If management does not care if an error occurs but nothing happens, this reveals a deeper flaw about the airline's safety and organizational culture****.

Notes

*It can also be inferenced that Air Midwest suffered underlying organizational accidents and poor organizational culture.

**Safety culture is comprised of just culture, learning culture, reporting culture, and flexible culture. Reporting culture emphasizes that safety concerns will be taken seriously and acted upon.

***Organizational culture is formed by top level management, who in turn sets the standards for the company.

****Furthermore, either: 1. a leadership issue exists; or 2. a management issue exists, possibly resulting from deeper organizational accidents.

Discussion

Many of the maintenance-related accidents were caused by deficiencies in a combination of various human errors stemming from human factors. In a few of the cases investigated, the airlines had implemented quality control programs, such as CASS and CAMP. However, these programs could fail because they did not directly monitor onsite working practices, ensure compliance with established procedures, supervise maintenance personnel, and lacked knowledge and resources. Finally, the FAA, as a regulatory organization, sometimes failed to find and pursue deficiencies in airlines' maintenance and quality control programs. These factors lead to and exacerbated the negative effects of human errors, ultimately leading to catastrophes. This observation yields an opportunity to reconcile various opinions when considering the required education of maintenance human factors, despite of the potential cost that training institutes would incur.

Conclusion

Despite the United States' airline industry's excellent safety record in the past decade, maintenance errors still pose a formidable threat to the nearly 30,000 daily commercial flights in the country. Today, almost 80% of accidents are caused by human error from pilots, air traffic controllers, and mechanics. Human errors, especially among mechanics, can cause latent and dangerous situations to aviation. Therefore, it has become exponentially important to mitigate or prevent them as much as possible.

To achieve the research objectives (emerging themes of maintenance related accidents, risk analysis discovering latent variables, detailed accident analysis identifying human factors, and advocating the importance of human factors for aircraft maintenance training), this study used VOSviewer to discover themes and clusters reflecting on the focus of maintenance human errors. This study also revealed upstream contributing factors leading to accidents. Based on the case studies, incorrect procedures and inadequate training are major factors in aviation accidents caused by human errors. In addition, the authors found that other root causes and contributing factors include poor supervision, lack of knowledge, inspection, and quality control, negligence, and failure to follow protocol. Poor safety and organizational culture also generated human factors because the former can allow for the latter to be present, remain latent, and serve as a contributing variable to accidents. Human errors can be prevented through education and raising awareness on all levels of the company. If maintenance technicians and engineers were educated early in their career paths, they could be more knowledgeable on human errors and prevent unwanted events. When management understands the essentiality of maintenance human factors, they will be more willing to invest in maintenance safety. Hence, "training the trainers" is imperative.

In summary, aviation is the safest form of transportation (International Air Transport Association, 2018) simply because many measures are in place to make sure catastrophes don't occur. These measures range from personnel education, with the implementation of safety attitude and knowledge, to procedures and documentation, to airlines' safety culture, and includes the FAA and government regulations. Per James Reason's Swiss Cheese model, a catastrophe would occur if all defenses failed. These defenses include human operators' qualifications, skills, and knowledge. It is therefore important for all stakeholders, including aircraft maintenance professionals to be constantly vigilant.

Future Study

In this study, the authors focused on airline maintenance related problems between 1994 and 2004 due to the consequence of the accidents. While technologies have been developed and installed to help flight operations in the cockpit, they have simultaneously helped aircraft maintenance personnel avoid errors. It is suggested to continue this study and explore technology-induced benefits in diminishing maintenance errors.

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