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Procedural Noncompliance in Aviation Maintenance:

A Multi-Level Review of Contributing Factors and Corresponding Mitigations

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Report

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16. Abstract

Compliance with approved procedures is an essential part of ensuring safety. Despite the continued training and focus on procedure following, Failure to Follow Procedures (FFP) is one of the most pervasive human factors issues in aviation maintenance. To prevent the recurrence of FFP, this report reviews the scientific literature regarding the contributing factors to and potential mitigations for FFP in aviation maintenance. Consistent with the HFACS-ME framework, the report describes human error as a multi-level issue consisting of an interaction between the organizational context (culture, resources), supervisory conditions, working environment, and maintainer conditions (mental and physical state; crew coordination). Expanding upon the HFACS-ME framework, the current report proposes evidence-based recommendations and potential mitigations for the contributing factors at each level of the organization. Evidence suggests that implementation of these mitigations may reduce the FFP rate and improve safety in the aviation maintenance industry.

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List of Abbreviations

AMT	Aviation Maintenance Technician
AR	Augmented Reality
ASAP	Aviation Safety Action Program
ASRS	Aviation Safety Reporting System
ATSB	Australian Transportation Safety Bureau
CAIR	Confidential Aviation Incident Reporting
CHIRP	Confidential Human Factors Incident Reporting Program
CRM	Crew Resource Management
DDA	Documentation Design Aid
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulations
FFP	Failure to Follow Procedures
FRMS	Fatigue Risk Management System
HFACS-MA	Human Factors Analysis and Classification System - Maintenance Audit
HFACS-ME	Human Factors Analysis and Classification System - Maintenance Extension
HRO	High-Reliability Organization
KSAs	Knowledge, Skills, and Abilities
LOSA	Line Operations Safety Assessment
M-LOSA	Maintenance Line Operations Safety Assessment
MEDA	Maintenance Error Decision Aid
MEL	Minimum Equipment List
MEQ	Maintenance Environment Questionnaire
MRM	Maintenance Resource Management

AMT	Aviation Maintenance Technician
NASA	National Aeronautics and Space Administration
NTSB	National Transportation Safety Board
OJT	On the Job Training
PPE	Personal Protective Equipment
R-LOSA	Ramp Line Operations Safety Assessment
REPCON	Aviation Confidential Reporting Scheme
SERA	Systematic Error and Risk Analysis
SHEL	Software, Hardware, Environment, Liveware
SMBWA	Safety Management by Walking Around
SMS	Safety Management System
TiME	Time Management Scale
TEM	Threat and Error Management
TRM	Team Resource Management
VR	Virtual Reality

Abstract

Compliance with approved procedures is an essential part of ensuring safety. Despite the continued training and focus on procedure following, Failure to Follow Procedures (FFP) is one of the most pervasive human factors issues in aviation maintenance. To prevent the recurrence of FFP, this report reviews the scientific literature regarding the contributing factors to and potential mitigations for FFP in aviation maintenance. Consistent with the HFACS-ME framework, the report describes human error as a multi-level issue consisting of an interaction between the organizational context (culture, resources), supervisory conditions, working environment, and maintainer conditions (mental and physical state; crew coordination). Expanding upon the HFACS-ME framework, the current report proposes evidence-based recommendations and potential mitigations for the contributing factors at each level of the organization. Evidence suggests that implementation of these mitigations may reduce the FFP rate and improve safety in the aviation maintenance industry.

Keywords: failure to follow procedures (FFP), compliance, aviation maintenance, human factors

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Introduction

Safety behavior is critical in aviation maintenance, where errors and non-compliance with approved procedures can lead to negative safety events like incidents and accidents.[1] Many maintenance-related safety events are the result of employees not following prescribed procedures for completing a task – known as Failure to Follow Procedures (FFP; Mason, 1997). FFP refers to situations in which someone, whether intentionally or not, failed to follow a written procedure or policy (i.e., published technical data or local instructions, Reason and Hobbs, 2003). Maintenance performers should follow the written instructions exactly as written, as required by Federal Aviation Regulations (FAR) Part 43.13, "Performance rules (general)":

> "*(a) Each person performing maintenance, alteration, or preventive maintenance on an aircraft, engine, propeller, or appliance shall use the methods, techniques, and practices prescribed in the current manufacturer's maintenance manual or Instructions for Continued Airworthiness prepared by its manufacturer, or other methods, techniques, and practices acceptable to the Administrator…"*

The requirement is straightforward, but complying with it is not – there are many human factors issues that may complicate compliance with written procedures. Investigations estimate that FFP is one of the most pervasive human factors issues in aviation maintenance, contributing to between 40.5% and 87% of all maintenance-related events.[2] This rate has remained steady across the last two decades, and FFP is still cited as a top human factors challenge in aviation maintenance today (Drury et al., 2017; Johnson and Hackworth, 2008; see also Siebenmark, 2019). These events can have substantial human (e.g., injuries and loss of life)[3] and financial costs,[4] necessitating intervention.

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[1] An aircraft accident is defined as an event associated with aircraft operations that result in death or serious injury to any person or significant damage to the aircraft while an incident is an accident that has the potential to affect safety operations (National Transportation Safety Board [NTSB], 2013).

[2] Allen and Rankin (1996), Boyd and Stolzer (2015), Civil Aviation Authority (2013), Goldman et al. (2002), Langer and Braithwaite (2016), Marais and Robichaud (2012), Nord and Kanki (1999), Patankar et al. (2003), Rankin (2013), Schmidt et al. (1999, 2000, 2003), Veinott et al. (1995). Note: the FFP rate varies depending on factors such as the database, aircraft type, years of study, etc.

[3] The aviation industry also has more lost workdays due to injury compared to the industry average (Hudson, 2003); each fatal occupational injury costs around $1,000,000 (National Institute of Occupational Safety and Health, 2017).

[4] Rankin (2007) reported that 20-30% of in-flight engine shutdowns are maintenance-related and cost $500,000 each. Maintenance errors due to engine problems are responsible for 50% of flight delays and

Consider this example. A Eurocopter AS350-B2 helicopter, N37SH, crashed near Las Vegas, Nevada, in 2011 and killed five individuals (including the pilot). According to the National Transportation Safety Board (NTSB; 2013), the crash was caused by maintenance-related failures: not following self-locking nut reuse guidance/procedures, improper or lack of installation of a split (safety) pin, and inadequate post-maintenance inspection. Because the FFP was committed by a maintenance technician, the event was logged as a "maintenance failure" in the NTSB database, despite other personnel also not detecting the error. Ultimately, the NTSB report (2013) cited fitness for duty issues (i.e., fatigue), organizational work scheduling practices, and a lack of sufficient detail in the technical documentation as contributing factors to the event. Importantly, this example illustrates that FFP events can occur for many reasons within *and* beyond the control of the front-line employees, showing why it is necessary to intervene at multiple levels within the organization[5] and across the industry.

Unfortunately, events such as the Eurocopter crash are not rare. Until systemic mitigations are implemented across the aviation maintenance industry, FFP is likely to remain a high-prevalence challenge with significant human and financial costs. Therefore, the purpose of this technical report is to review the literature, with the intent of discovering the most prominent contributing factors from a multi-level perspective, and corresponding evidence-based recommendations for reducing FFP.

Review Methodology

FFPs are not unique to the maintenance environment; they are present in everyday life and, to some degree, in all work environments where standard operating procedures are in place. Because FFPs occur across safety-critical fields, there is a rich body of research literature from which to derive the contributing factors and evidence-based mitigations.

Thus, the review identified 380 peer-reviewed sources (i.e., journal articles, book chapters, conference proceedings, technical reports, and thesis/dissertations) retrieved from a Google Scholar search using keywords such as noncompliance, failure to follow, deviation, practical drift, safety performance, aviation, and maintenance safety. The literature came from many safety-critical fields including: aviation, construction, chemical processing, health care, manufacturing, nuclear industry, and transportation. A subject matter expert in human factors assessed the sources and selected over 200 for the

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cancellations, at a cost of $9,000 per hour and $66,000 per cancellation. Hobbs (2008) estimated the cost of a cancellation of a Boeing 747-400 flight at $140,000 and a delay cost of $17,000 per hour.

[5] For related arguments, see Johnson (2018a, 2018b).

current review. These articles were chosen because they investigated why FFPs occur and/or how to mitigate such events.

For ease of the reader, this report focuses on the contributing factors and potential mitigations for FFP. In the interest of transparency, we also provide a review of the methods for identifying FFP (Appendix A) and discussion on the historical response to FFP (Appendix B).

Utilizing a Multi-Level Approach to FFP Mitigation

The literature is clear: adequate solutions to FFP cannot be found using a person-centered approach that focuses on characteristics of the person performing the work (i.e., fitness for duty, training/knowledge, and attitude).[6] Instead, FFPs are an amalgamation of influences from multiple levels of the organization (see Beus et al., 2016, for a review). The numerous factors associated with FFP underscores the importance of considering the full operational context when investigating and mitigating FFP. That operational context not only contains the individuals performing the work, but also factors related to the environmental and working conditions, crew coordination (colleagues and supervision), and the organizational context (culture, resource management). When considering these broader contextual factors, a much more complex and dynamic view of FFP emerges – lending to more robust mitigation strategies.

A multi-level taxonomic framework can provide a structure for understanding the common contributing factors to FFP, how they are interrelated, and how they can inform targeted mitigation strategies. Perhaps the most widely used taxonomy is the Maintenance Error Decision Aid (MEDA), used in approximately 80% of maintenance investigations.[7,8] Developed by The Boeing Company (latest version published in 2016),[9] MEDA primarily documents what events have occurred (e.g., errors and FFPs), and the event consequences (e.g., flight cancellation, delay). There is considerably less focus on

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[6] Dekker (2001a, 2001c, 2011), FAA (2009), Holden (2009), Leveson (2004), Reason (1990); Reason & Hobbs (2003)

[7] Other taxonomies for use in aviation maintenance are an adaptation of the Software, Hardware, Environment, Liveware (SHEL) Model (developed by Edwards, 1988; adapted by Chang and Wang, 2010; Said and Mokhtar, 2014); and the HFACS-maintenance audit (HFACS-MA; Hsiao et al., 2013). There are also various taxonomies in the aviation literature that are not maintenance-specific, see: Systematic error and risk analysis (SERA; Hendy, 2003); "Wheel of Misfortune" (O'Hare, 2000); and "Swiss Cheese" model (Reason, 1990).

[8] Similarly, simulation approaches can be used to computationally represent a model of errors and performance shaping factors, though no advanced simulation models exist for aviation maintenance (Latorella and Prabhu, 2000).

[9] Allen and Rankin (1996), Rankin (2000, 2013), Rankin et al. (2000).

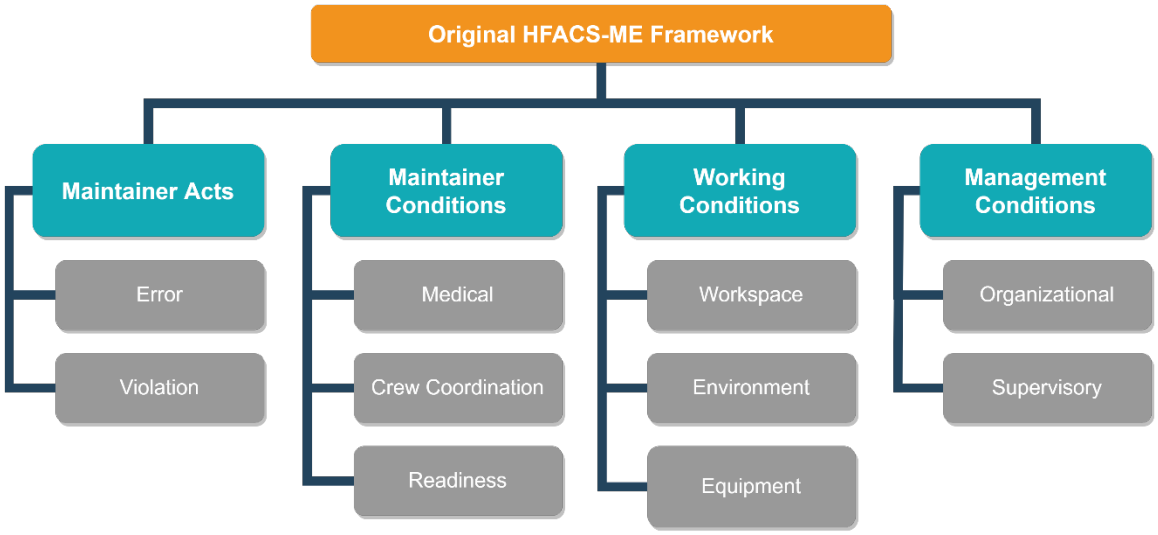
identifying contributing factors,[10] which is critical to informing targeted mitigations. Thus, MEDA can be supplemented by a framework for identifying contributing factors to the event.

The Human Factors Analysis and Classification System - Maintenance Extension (HFACS-ME) framework excels at classifying the contributing factors - *why* the event occurred,[11] examined from a multi-level approach. Based on the "Swiss Cheese" (Reason, 1990) and the "Domino Theory" (Heinrich et al., 1980) models of latent conditions contributing to human error, HFACS-ME contains four categories: **Management Conditions, Working Conditions, Maintainer Conditions, and Maintainer Acts.** The latent conditions are Management, Working, and Maintainer Conditions, which can lead to active failures in Maintainer Acts. HFACS-ME has been successfully applied to Naval aviation mishaps (Schmidt et al., 1998), commercial aviation accidents (Schmidt et al., 2003), and helicopter incidents (Rashid et al., 2014). This validation evidence, paired with the theoretical backing (i.e., Reason's model), makes HFACS-ME an ideal framework for structuring our discussion on FFP.

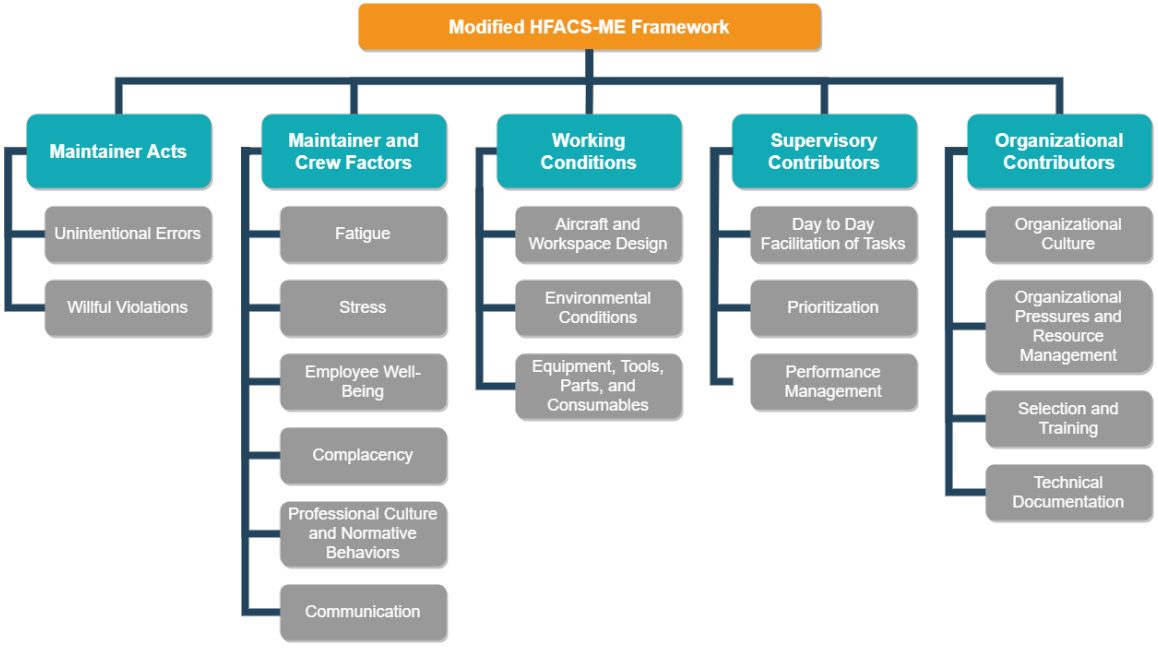
The remainder of this report reviews the most common contributing factors for FFP, as identified in the scientific literature. The discussion is structured around the HFACS-ME framework because it lends a multi-level perspective. It has been reconstituted into a modified HFACS-ME model that more accurately describes the influence of various contributing factors to FFP and more clearly delineates where the change requirement originates. Ultimately, it is our hope that this Modified HFACS-ME Framework will support the shift from the traditional "blame and train" approach to support the utilization of more effective mitigations targeted at addressing the root causes underlying the event. See Figure 1 for a comparison between the Original HFACS-ME Framework and the Modified HFACS-ME Framework utilized in this report.

[10] MEDA currently contains 9 dimensions of contributing factors, each of which involve 5-17 elements.
[11] Krulak (2004), Schmidt et al., (1998, 1999, 2000, 2003), Rashid et al. (2014).

Figure 1.
A Comparison Between (a) Original HFACS-ME Framework and (b) the Modified HFACS-ME Framework Utilized in this Report



(a)



(b)

Note: Panel (a) is derived from HFACS-ME Handbook (Naval Safety Center, n.d.). Panel (b) depicts the Modified HFACS-ME Framework utilized here.

Notable differences between the Original HFACS-ME Framework and the Modified HFACS-ME Framework utilized here include:

(1) Selection and Training are at the organizational level because the organization is responsible for providing necessary training, particularly when there are changes in technology, processes/procedures, or aircraft design.

(2) Aircraft and Workspace Design are at the working conditions level because the design affects the person interaction with the environment.

(3) Organizational and Supervisory levels are separated because different parties are responsible for these two categories. This decision was made to delineate clearly the factors that are within (e.g., day to day tasks) versus beyond (e.g., organizational culture) the purview of the supervisors (see Rashid et al., 2014). In accordance with FAR Part 5 and with Safety Management System (SMS) Voluntary Program standards and guidance, there must be an accountable executive who is ultimately responsible for providing adequate resources to the organization. On the other hand, supervisors are primarily responsible for resource allocation and day-to-day facilitation of work tasks.

(4) The Original HFACS-ME Framework addresses contributing factors from the top down – from managerial conditions down to unsafe acts, representing the latent factors that can lead to an active failure/error. In the Modified HFACS-ME Framework, the discussion of contributing factors is presented from the bottom up, in order of how the contributing factors would be uncovered in the course of an event investigation. We begin by describing the types of FFP, then their contributing factors from a multi-level approach.

To reiterate, the intent of these modifications is to more accurately describe the influence of various contributing factors to FFP, corresponding to where the change requirement originates. We further extend HFACS-ME by including a discussion on evidence-based recommendations for mitigating FFP.

It should be noted that the issues contained in this report are not a comprehensive list of reasons procedures are not followed, but rather an indication that there are numerous

intertwined contributing factors to FFPs[12] that can originate from different sources within and beyond the individuals performing the work. These contributing factors to FFP are described serially in this report; however, note that, as the Eurocopter example illustrated, these factors rarely occur in isolation and there may be interactive effects. The complexity involved in FFP events underscores the importance of having a multi-level approach to investigation and mitigation.

Maintainer Acts

FFP can be classified into two major categories: *unintentional errors* and *willful violations*. This distinction is important because research has shown these different types of FFP have different contributing factors (Hobbs and Williamson, 2003) and may produce different outcomes (Reason and Hobbs, 2003).

Unintentional Errors

The most common type of FFP is unintentional errors, which contribute to between 40.5-87% of accidents/incidents in aviation maintenance.[13] In a more recent analysis, Bao and Ding (2014) classified 3,783 maintenance reports in the Aviation Safety Reporting System (ASRS) database and found that 91% of maintenance events involved human errors; the highest percentage of which involved inspection (33%) and installation (32%).

Unintentional errors can be further classified into different types, each having their own contributing factors, frequency of occurrence, and outcomes. We organize them in accordance with HFACS-ME but with additional information from Hobbs and colleagues,[14] who have conducted extensive work to classify the different error types:

- *Attention/Memory and Perceptual Errors* involve recognition failure (e.g., failure to detect a defect), memory lapses (e.g., forgetting a step), action slips (i.e., performing a task automatically without attention), and/or distractions/interruptions. These errors are most associated with time pressure, fatigue, and the environment.[15] They can cause confusion or disorientation, tasks to be overlooked, critical steps to be skipped, and workplace injuries.

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[12] The MEDA contributing factors list has 9 dimensions and 103 factors; Rashid et al. (2014) included a list of 197 specific failures in their analysis.
[13] Nord and Kanki (1999), Patankar et al. (2003), Schmidt et al. (1999, 2000, 2003), Veinott et al. (1995).
[14] Hobbs (2001), Hobbs and Williamson (2002a, 2002b), Reason and Hobbs (2003).
[15] Memory lapses are the most common form of error (Hobbs, 2001; Hobbs and Williamson, 2000) and can be associated with distractions, interruptions, multitasking, and retrieval failures (more common with older age). See also Dismukes (2012) for recommendations how to improve memory performance: avoid

- *Skill/Technique-Based Errors* may involve the application of a bad rule or misapplication of a good rule, poor/inappropriate technique, inadequate skills, or improper cross-check (Rashid et al., 2010; Suzuki et al., 2008b). They are often referred to as unsafe behavior, and are commonly associated with worker injuries (Hobbs and Williamson, 2002a).
- *Knowledge/Rule-Based Errors*, which are typically unintentional violations of unspoken norms, are closely associated with inadequate knowledge (training deficiencies) about the task, process, or aircraft. They may also arise from procedural problems, coordination difficulties, time pressure, equipment deficiencies, and previously committed errors (Hobbs and Kanki, 2008; Hobbs and Williamson, 2003).
- *Judgment/Decision-Making Errors* arise in circumstances where the individual is faced with a new problem or situation that can be misjudged, be misperceived, be misdiagnosed, or exceed the worker's ability. These errors are commonly associated with training (Reason and Hobbs, 2003; Suzuki et al., 2008b).

Willful Violations

Violations can be defined as "deliberate departures from rules that describe the safe or approved method of performing a particular task or job" (Lawton, 1998; p. 78). Researchers estimate that 16-34% of FFPs are willful violations,[16] which contribute to between 15.5-47% of accidents/incidents.[17] Violations can be further classified as routine, infraction/situational, and exceptional/flagrant (Reason and Hobbs, 2003; Wiegmann and Shappell, 2003).

- *Routine Violations* are normative behaviors, committed because there is a faster/easier way (Civil Aviation Authority, 2003), to demonstrate skill, or because of group norms (Reason and Hobbs, 2003). Hobbs and Williamson (2002a) found that routine violations were more commonly associated with quality incidents that impact the safety of the aircraft.
- *Infraction/Situational Violations* are isolated incidents such as inappropriate use of tools/equipment and procedural deviations. This violation type is most commonly associated with quality of the technical documentation (Reason and

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deferring crucial tasks; utilize reminder cues; avoid multitasking; use external memory aids, checklists, and cross-checking.

[16] McDonald et al. (2000b), Reason and Hobbs (2003), Hobbs and Williamson (2000).

[17] Boquet et al. (2004), Schmidt et al. (1999, 2000, 2003), Suzuki et al. (2008b).

Hobbs, 2003), but may also result from time pressure, workload, staffing levels (Bates and Holroyd, 2012).

- *Exceptional/Flagrant Violations* are least common and vary in severity. Examples are falsifying qualifications, not using required equipment, and signing off without inspection. These violations may occur from malice, thrill seeking, or other dispositional attributes related to the individual (Reason and Hobbs, 2003).

To summarize, there are multiple types of FFP, each one associated with different contributing factors. The following sections provide a multi-level consideration of why these errors and violations may occur, along with corresponding mitigations.

Maintainer and Crew Factors

Maintainers, working individually and in crews, are the first line of defense for safety in the organization. They ensure safety in almost 100% of normal operations (Dekker, 2001c; Hollnagel et al., 2006), and are most aware of the hazards, making their reports a valuable source of information for effective safety management (Dekker, 2011). On the other hand, maintainers occasionally make mistakes and historically they have been blamed for events, with failures being attributed to their capabilities, motivation, or risk-taking behavior (Holden, 2009). The decision to describe these individual contributing factors is driven by the abundance of literature, rather than our own assertions about the appropriate attributions and mitigations for FFP. Mitigations for these contributing factors can be mitigated at the individual level but there are times that organizational factors limit or constrain the effectiveness of individual mitigations and necessitate organizational changes. Often, the organization should share responsibility for mitigating FFPs due to their role in generating some of the psychosocial risks that impact aspects of the maintainer and crew factors. For example, individuals can implement effective fatigue countermeasures in their personal lives, but individual actions are limited by organizational constraints/requirements (e.g., if the organization is understaffed and requires personnel to work back-to-back shifts). Conversely, an organization can have the best scheduling practices to maintain optimum alertness, but individuals could still have a fatigue-induced event at work if they do not take personal responsibility for their fitness for duty outside of the workplace.

This category refers to factors relating to readiness for the job (i.e., *Fatigue; Stress; Employee Well-Being;* and *Complacency*) and relating to crew coordination (i.e., *Professional Culture and Normative Behaviors;* and *Communication*).

Fatigue

Fatigue/alertness has been a concern and a focus of research across all aviation-related environments (Avers and Johnson, 2011), and the maintenance environment has all criteria for increased fatigue risk, with long shifts, overtime, and "back of the clock" night operations (Hobbs and Williamson, 2000; Johnson et al., 2001). Studies have shown that 96% of Aviation Maintenance Technicians (AMTs) surveyed indicated they (or someone they know) had made fatigue related errors (Santos and Melicio, 2019) and that one in seven shifts is operating at elevated fatigue risk levels, increasing the rate of incidents by 83% (Avers and Mollicone, 2019).

Employees and the organization share a responsibility for mitigating fatigue. Recommendations for employees focus on the integration of the work schedule with family life, gaining adequate nutrition and sleep, taking rest breaks, and the possible use of breaks for naps. Research has shown the benefits of strategic napping, with ideal durations short enough (<45 min.) or long enough (110-120 min.) to avoid waking from deep sleep, which would result in greater sleep inertia.[18]

Recommendations for an organization geared towards reducing fatigue risk include: shift scheduling practices to allow more time for rest and recovery between shifts, use scheduling tools to optimize shift schedules, ensure frequent rest periods, fatigue education,[19] improve shift turnover procedures, and implement a Fatigue Risk Management System (FRMS).[20]

These recommendations are important considerations given previous research showing that tasks requiring greater cognitive effort – those that may be more complex and safety-critical – are at greatest risk for fatigue-related errors (Rhodes et al., 2003).

Stress

Studies have shown the negative impact of mental and other stressors on performance (Fogarty, 2004, 2005; Wang et al., 2016). Although much of the research focuses on individuals' sources of stress (e.g., personal lives), research points to a number of work-related stressors as well, such as the balance between job resources and demands, time pressure, workload, circadian rhythm, lighting, noise and microclimate, distraction/interruption, job role, relationships with others at work, career prospects and

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[18] Caldwell et al. (2019), Milner and Cote (2009), Purnell et al. (2002).
[19] Resources to promote fatigue awareness are available at Skybrary (n.d. –a) and at Federal Aviation Administration (n.d.).
[20] Hobbs et al. (2011), Rhodes et al. (2003), Santos and Melicio (2019), Wong et al. (2019).

progression, and organizational structure and climate.[21, 22] As discussed in the following sections, there is also a large managerial role in reducing time pressure, workload, and other work-related stressors.

Employee Well-Being

Traditionally, employee wellness has been viewed independently of workplace safety, but more recent research has illustrated that the two are intertwined. Specifically, research has linked employee well-being (e.g., health, stress) to organizational safety outcomes (Fogarty et al., 2018; Loeppke et al., 2015). Given this, managerial and supervisor support for well-being concerns is needed. Organizations should consider implementing wellness programs, psychosocial climate assessment tools (see Hall et al., 2010; Owen and Dollard, 2018), career development guidance, and other such interventions to improve employee well-being, as these efforts may ultimately translate to improved productivity and safety performance.[23] Guidelines for those efforts are provided by WHO's Healthy Workplaces, NIOSH's Total Worker Health Program, and the EU Agency for Safety and Health's Managing Stress (Cox et al., 2000).

Complacency

Hazardous attitudes like complacency and lack of assertiveness can also contribute to FFP.[24] Complacency was cited as one of the top three human error challenges for maintenance in an industry survey (Johnson and Hackworth, 2008), and workers may be more prone to complacency in accident-free or ultra-safe[25] environments like aviation (Mason, 1997). Recommendations for reducing complacency involve supervisory and employee behaviors such as consistently using safety checklists, understanding procedures, stopping when attention is low, stepping away to reassess the situation, and verifying completed work (see Barth et al., 2020).[26]

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[21] Francioisi et al. (2019), O'Driscoll and Brough (2010); see also International Labor Organization (2016).
[22] Employees should utilize stress management techniques; see Skybrary (n.d. –b; n.d. –c).
[23] c.f. Hesketh et al. (2020) for a discussion on mental health and wellbeing interventions in the workplace.
[24] MEDA mentions other hazardous attitudes and personality factors such as overconfidence, arrogance, invulnerability, risk seeking, and others. However, reviews of the literature across safety critical domains (Alper and Karsh, 2009; Christian et al., 2009; Holden, 2009) and empirical studies (Fugas et al., 2012) have found that individual personality and attitudes have a weaker relationship with FFP than organizational and environmental variables (i.e., safety climate, competing demands, group norms; see also Beus et al., 2015; Mason, 1997).
[25] See also Amalberti (2001, 2013) for discussion surrounding ultra-safe environments such as aviation.
[26] NASA SkyLab (Barth et al., 2020); see also FAA Safety Team (n.d.).

Professional Culture and Normative Behaviors

Work norms are much like social norms – they are both sets of unspoken and understood rules of behavior. The work norm of interest regarding FFPs is the development of alternative, non-approved methods for task completion.[27] In the literature, these are often referred to as *practical drift* or *normalization of deviance.* Normative deviation from approved procedures was among the top three human error challenges (Johnson and Hackworth, 2008).

Non-approved methods of task completion can develop for many reasons, such as search for efficiency (Leveson, 2004), time pressure,[28] complacency (Baron, 2009), inaccurate or poorly written procedures,[29] ambiguous situations (Cheng, 2018), and cultural norms (i.e., "because it has always been done that way"). These violations can be perpetuated and normalized by team members or supervisors (Reason and Hobbs, 2003). Such pressure can be real or perceived pressure, such as from the boss to cut corners, or peer pressure (Mason, 1997), which can cause an unwillingness to use manuals because it is seen as a lack of skill or confidence (Santiago, 2007).

Within aviation maintenance, there is a strong professional culture of AMTs committed to safety who must do their best to negotiate competing demands (i.e., productivity and safety; McDonald et al., 2002) in an error-prone environment.[30] Although they are strongly committed to and responsible for safety, they believe in their professional judgement, experience and skill. They often view the procedures as guidance, instead developing unauthorized "black books" that allow workarounds or "more efficient" routes to getting the job done (McDonald, 2001; see also Leveson, 2004).

Conversely, management expects the technicians to fully follow the procedures, though it is well understood that this would cause delays and decrease in productivity[31]. As a result, technicians perform the task differently than expected. McDonald et al. (2000a) wrote,[32]

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[27] i.e., where there are no written procedures documenting or prohibiting the alternative method of completing the task.
[28] See Baron (2009), Holden (2009), McDonald (2001), McDonald et al. (2000a, 2000b, 2002).
[29] McDonald (2001), McDonald et al. (2000a, 2000b), McKenna (2002), van Avermaete and Hakkeling-Mesland (2001).
[30] Aase et al. (2009), Alper and Karsh (2009), Reason and Hobbs (2003).
[31] See also Leveson (2004), who noted that workers sometimes 'work to rule' by strictly following procedures to put pressure on management as an alternative to going on strike.
[32] The difference between "official" and "actual" way of doing things has also been described as "work as imagined" versus "work as done" in the safety management literature (Hollnagel, 2017).

> *"Arguably, this professional sub-culture provides the flexibility to deal with situations which are not fully anticipated or planned and to make the judgment to do what it takes to get the job done. On the other hand, when this divergence between the management system and sub-culture becomes routine and institutionalized, then the difference between the 'official' way of doing things and the 'actual' way of doing things becomes impervious to scrutiny" (p. 174).*

However, work norms do not necessarily come from deliberate disregard of safety. Instead, most violations are social, adaptive responses to circumstances (Holden, 2009; Leveson, 2004). In this sense, technicians are doing their best to resolve competing demands[33] – as they are incentivized for doing – by shortcutting what they view as "unimportant steps" (McDonald et al., 2002).[34] Thus, these shortcuts and alternative methods of performing work tasks are often acceptable in organizations and may even help operations to run more efficiently.[35] Management often overlooks deviance or use of non-approved procedures if operations are running smoothly and no incidents occur; however, this reinforces the normalization of deviance, which could lead to accidents/incidents in the long run.

Management should be aware of the practical drift phenomenon, should implement methods to detect and mitigate practical drift, and should set clear criteria for acceptable behavior (Hudson, 2003); this provides the ability to proactively manage safety boundaries and prevent failure (Stolte et al., 2010). It is important for management to understand that practical drift occurs gradually over time and is, to some extent, part of an organization's evolution; thus, consistent attention to this issue is critical to continually ensure compliance. Management and employees should collaborate in discussions about organization policies and procedures, so both can provide insight into the most effective means of ensuring safety, compliance, and productivity.

To mitigate the use of unauthorized procedures, we recommend that management review procedures to ensure usability and accuracy (Chaparro and Groff, 2002b; see also *Technical Documentation*) and correct deviations from procedures, even if operations are running smoothly (Stolte et al., 2010).

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[33] See Aase et al. (2009), Alper and Karsh (2009), Baron (2009), Battmann and Klumb (1993).
[34] Including those that are only viewed as a mechanism for signing off for completing of a task, rather than a required way of completing said task.
[35] These may be captured by the procedure writing process described above. See Dekker (2001a, 2001b, 2001c, 2003), Leveson (2004), McDonald (2001).

Communication

The final maintainer and crew condition is coordination and communication. Verbal and written communication for information sharing can support situational awareness of what each crew member is doing and how they can best work together to complete the tasks (Endsley and Robertson, 2000; Latorella and Prabhu, 2000). Unfortunately, miscommunications are often a contributor to incidents/accidents and injuries in the workplace (see Chatzi et al., 2019).[36]

Poor coordination was involved in 17% of ASRS maintenance database events (Suzuki et al., 2008a). Of those, 79% occurred within maintenance departments, with frequent errors involving not delivering information, sending wrong information, and lack of responsibility (Suzuki et al., 2008a), and lack of situational awareness (Endsley and Robertson, 2000). Another study found one particular coordination task, shift turnover, was involved in 51% of all maintenance communication errors (Parke and Kanki, 2008).

To mitigate FFP specifically related to shift turnover, communication should not only include a description of completed tasks, but also include the identification of potential problems and concerns (Campos et al., 2012), and optimally, involve the use of a checklist (see Parke and Kanki, 2008, for an example). Further, research shows that a combination of face-to-face communication and paper documentation is preferred, as it is the easiest way to transfer information and results in fewer errors.[37]

Not only do AMTs need to communicate within the maintenance department, but also with other departments such as flight crews. Approximately 15% of communication errors in Suzuki et al.'s (2008a) study were inter-departmental, with more than half (59%) involving conflicts regarding the airworthiness of the aircraft.[38] Studies show that mechanics hold lower views than pilots on the overall helpfulness and level of information provided in logbook entries needed to complete maintenance tasks (Munro et al., 2004). Such coordination challenges may be compounded when the maintenance and other departments are not co-located, reducing information exchange and limiting safe work practices (Aase et al., 2009). These studies point to the need for improved

[36] See also Bates and Holroyd (2012), Bos and Roessingh (2003), DeJoy et al. (2004), Ek and Akselsson (2007), Endsley and Robertson (2000), Evans et al. (2007), Fogarty and Buikstra (2010), Hahn and Murphy (2008), Hobbs (2008), O'Connor et al. (2011), Taylor and Thomas (2003), Tretten and Nosmark (2015), Vieira et al. (2014), Vincent et al. (1998), Zohar (1980).
[37] Campos et al. (2012), Parke et al. (2010), Warren (2011).
[38] i.e., discrepancies in judgment regarding the Minimum Equipment List (MEL; i.e., the list of equipment that must be operable for the aircraft to be deemed airworthy).

information exchange. Adequate and complete information from pilots allows maintenance personnel to diagnose and resolve the issues faster; in turn, pilots feel more comfortable regarding airworthiness when the maintenance reports are complete.

Mitigations for improving situational awareness within and across departments include sharing information and mental models across teams, verbalizing decisions, improving shift meetings and teamwork, improving feedback, and providing situational awareness training (Endsley and Robertson, 2000). Another potential mitigation designed to promote effective communications is training on interpersonal communication and coordination, task allocation, conflict resolution, and decision making (i.e., CRM, MRM, or TRM[39]); however, additional research is warranted regarding the effectiveness of that training in the operational maintenance environment (Chatzi et al., 2019).

Summary

At the maintainer and crew level, contributors to FFP pertain to readiness for the job (e.g., fatigue, stress, well-being, complacency) and crew coordination factors (e.g., professional culture, normative behavior, and communication). Although front-line employees have partial responsibility to manage these contributors, there are also changes within the organization that can reduce or mitigate the overall impact of various psychosocial stressors.

Table 1.
Maintainer and Crew Factors - Contributing Factors and Recommendations

Contributing Factor	Recommendation	Reference
Fatigue	Employ strategic napping (ideal duration <45 min or 110-120 min).	Caldwell et al. (2019); Milner and Cote (2009); Purnell et al., (2002).
	Employees should consider the integration of the work schedule with family life, gaining adequate nutrition and sleep, taking rest breaks, and the possible use of breaks for naps.	Rhodes et al. (2003).

[39] Crew Resource Management, Maintenance Resource Management, and Team Resource Management, respectively.

Contributing Factor	Recommendation	Reference
	Organizations should consider: shift scheduling practices to allow more time for rest and recovery between shifts, use scheduling tools to optimize shift schedules, ensure frequent rest periods, fatigue education, improve shift turnover procedures, and implementation of a FRMS.	Rhodes et al. (2003); Santos and Melicio (2019); Wong et al. (2019).
	Exert control over distractions.	Hobbs and Kanki (2008); Hobbs and Williamson (2003); Suzuki et al. (2008b).
Stress	Employees should utilize stress management techniques.	Skybrary (n.d. -c).
Employee Well-Being	Organizations should consider implementing wellness programs, psychosocial climate assessment tools, career development guidance, and other such interventions to improve employee well-being.	Hall et al. (2010); Owen and Dollard (2018); EU Agency for Safety and Health's Managing Stress, NIOSH's Total Worker Health Program, and WHO's Healthy Workplaces.
Complacency	Consistent use of safety checklists, understanding procedures, when attention is lowering stop, step away and reassess the situation, and verify work.	Barth et al. (2020).
Professional Culture and Normative Behavior	Management should implement methods to detect and mitigate practical drift, and should set clear criteria for acceptable versus unacceptable behavior.	Hudson (2003); Stolte et al. (2010).
	Management should review procedures to ensure usability and accuracy and correct deviations from procedures, even if operations are running smoothly.	Chaparro and Groff (2002b); Stolte et al. (2010).
Communication	Communication should include a description of completed tasks as well as the identification of potential problems and concerns, and optimally, involve the use of a checklist.	Campos et al. (2012); see Parke and Kanki (2008) for an example checklist.

Contributing Factor	Recommendation	Reference
	A combination of face-to-face communication and paper documentation is preferred.	Campos et al. (2012); Parke et al. (2010); Warren (2011).
	Mitigations for improving situational awareness within and across departments include sharing information and mental models across teams, verbalization of decisions, improved shift meetings and teamwork, improved feedback, and situational awareness training.	Endsley and Robertson (2000).
	A potential mitigation designed to promote effective communications is aviation training (CRM, MRM, or TRM); however, additional research is warranted.	Chatzi et al. (2019).

Working Conditions

The design of the aircraft, environment/workspace, and equipment/tools are commonly associated with accidents and injuries,[40] contributing in up to 67% of all maintenance mishaps in the NTSB database (Schmidt et al., 2003).

This category refers to factors relating to the environment (i.e., *Aircraft and Workspace Design; Environmental Conditions;* and *Equipment, Tools, Parts, and Consumables*).

Aircraft and Workspace Design

Some maintenance events are attributable to design of the workspace and/or aircraft. For instance, the aircraft and surrounding working conditions can be confining, obstructed from view, or inaccessible (Hobbs, 2008). Specific issues include hard-to-reach areas, obstructions to vision, rows of identical looking controls, and gauges that provide misleading information (Hobbs, 2008). An intervention improving the ergonomic design of the workplace environment was successful, leading to improved aircraft availability, delivery times, employee morale and customer satisfaction (Ward and Gaynor, 2009).

A related issue involves the implications of more advanced automation and the need for a greater emphasis on design-for-maintainability. While considerable attention has been

[40] Dhillon (2009), Ghobbar et al. (2009); see also Hobbs (2001).

focused on cockpit design during the last few decades, this is less true regarding the design of the aircraft for maintainability. Pettersen and Aase (2008) noted that trial-and-error efforts are often needed to resolve conditions where the fault appears to be hidden in the complexity of the aircraft's technology. As aircraft design becomes increasingly complex, the addition of alerts, sensors, etc. may also complicate troubleshooting and diagnosing issues requiring maintenance. The introduction of new diagnostic tools and technologies, such as nondestructive inspection and built-in sensors to assess an aircraft's structural condition,[41] will require new policies, procedures, and training. Careful attention will be required to ensure that employees understand and follow the new methods of troubleshooting and performing maintenance on increasingly complex systems. Further research is warranted regarding the testing of effective diagnostic tools, maintenance training and procedural needs, and other impacts of system complexity on design-for-maintainability.

Environmental Conditions

Working in environmental conditions that are inadequate or unsafe can contribute to FFPs.[42] Such conditions can be those outside the human comfort zone, such as poor lighting, extreme temperatures and exposure to weather, and uncomfortable noise levels (Bosley et al., 1999; Johnson et al., 2001). Insufficient housekeeping/cleanliness and exposure to hazardous/toxic substances are also environmental factors of note. Several researchers have shown that environmental factors contribute to skill-based errors due to impaired cognitive function[43] and increase risk of error on highly cognitive tasks (Rhodes et al., 2003). Also, as research has shown, high complexity tasks are more error prone. The complexity of tasks increases with the number of moving parts, support equipment, and/or coordination required (Bos and Hoekstra, n.d.; Bos and Roessingh, 2013).

Although some of the environment and facility attributes are inherent in aviation maintenance, we recommend that organizations try to minimize the impact of environmental conditions whenever possible to prevent FFPs due to impaired cognition and fatigue.

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[41] see Sandia National Laboratories (2014).
[42] Allen and Rankin (1996), Johnson et al. (2001), Krulak (2004), Virovac et al. (2017).
[43] Dreisbach (2012), Hobbs and Kanki (2008), Hobbs and Williamson (2003), Jansen et al. (2013), Suzuki et al. (2008b).

Equipment, Tools, Parts, and Consumables

The adequacy of materials such as equipment, tools, parts, and consumables are frequently identified in research as contributing to between 11.8 and 27% of all maintenance events.[44] Specific concerns include the use of materials that are damaged/faulty, unavailable or inappropriate for the task, uncertified or mis-calibrated. Others concern the availability and condition of personal protective equipment (PPE) to guard against hazardous materials, weather, electrical shock, burns, noise levels, and other hazards. Demonstrations by management regarding concern for employees' health and safety can provide a positive framework for the workplace. It is incumbent on the organization to ensure the provision of adequate materials. Supervisors need to ensure that materials are readily available, reinforce their use, and ensure that following their use, materials are returned to their proper locations (Hobbs and Williamson, 2003). Ideally, this would involve a system that prevents work without the tools being taken from a controlled environment (e.g., tools storage) and systemic training for every new tool and equipment added to the system (see Virovac et al., 2017).

Summary

Working conditions that are beyond employee levels of comfort (e.g., noise, lighting), or are in poorly designed work places (e.g., confined space, inaccessible) are oft-cited contributors to FFP. Other relevant working condition factors pertain to the availability, accessibility, and adequacy of equipment, tools, parts, and consumables. A final consideration is designing for maintainability as system complexity increases with the introduction of advanced technologies.

Table 2.
Working Conditions - Contributing Factors and Recommendations

Contributing Factor	Recommendation	Reference
Aircraft and Workspace Design	Improve the ergonomic design of the workplace environment.	Ward and Gaynor (2009).
Environmental Conditions	Organizations should try to minimize the impact of environmental conditions whenever possible to prevent FFPs due to impaired cognition and fatigue.	Rhodes et al. (2003).

[44] Allen and Rankin (1996), Hobbs and Williamson (2003), Virovac et al. (2017).

Contributing Factor	Recommendation	Reference
Equipment, Tools, Parts, and Consumables	Supervisors need to ensure the materials are readily available, reinforce their use, and that following their use, and they are returned to their proper locations.	Hobbs and Williamson (2003); Virovac et al. (2017).

Supervisory Contributors

Supervisors can be a major source of support for maintenance employees. They serve as intermediaries in communicating safety policies/procedures and are a key influence on safety outcomes,[45] predicting compliance behavior (Neitzel et al., 2008), and promoting organizational resilience (Akselsson et al., 2009). Yet, supervisors' actions can also contribute to FFP. Studies consistently find that supervisory conditions were involved in ~60% of all maintenance-related events.[46]

This category refers to factors relating to the supervisor (i.e., *Day to Day Facilitation of Tasks; Prioritization;* and *Performance Management*).

Day to Day Facilitation of Tasks

Among a supervisor's responsibilities are planning and organizing resources, such as finances, personnel, and physical resources (e.g., equipment and tools, documentation). Inadequate management and supervisory attitude both contribute to FFP (Mason, 1997). The provision of adequate resources is a critical driver of both safety culture and safety performance (Fogarty et al., 2018); thus, careful attention should be paid to resource allocation.

When supervisors fail to plan work tasks appropriately, resulting in unachievable workloads for maintenance personnel, performance is undermined and following procedures is challenged. Workload has been associated with FFP in other industries[47] and in aviation. In a survey by Ek and Akselsson (2007), respondents reported that workload was third most likely to have a negative influence on compliance with safety rules (41%), just after time pressure (74%) and staff size (70%). Surveys of maintenance

[45] Flin et al. (2000), Hofmann et al. (2017), Hofmann and Morgeson (2004), Zohar (2000).
[46] Krulak (2004), Schmidt et al. (1998, 1999, 2000, 2003).
[47] For example, the railroad industry (Lawton, 1998), nurses' medication administration practices (McKeon et al., 2006), and in clinical medicine (Vincent et al., 1998).

personnel found 75-80% believed they could not complete the job in time if they followed all the procedures (Mason, 1997; van Avermaete and Hakkeling-Mesland, 2001). Additionally, strenuous employee work schedule was one of the top job stressors reported by maintenance workers (52%; Wang et al., 2016).

Supervisors should organize personnel resources and delegate tasks carefully to prevent unachievable workload. Part of this is ensuring that tasks are assigned to personnel who are qualified to perform them and that there is an equitable distribution of work across personnel. However, we acknowledge depending on the nature of the tasks and the personnel available, that there are limits within which the supervisor can reduce FFP associated with workload.

Supervisors should schedule with task complexity and fatigue in mind, as research has shown that task complexity and fatigue lead to impaired cognition, in turn increasing the likelihood for error (Bos and Roessingh, 2013; Rhodes et al., 2003). One specific scheduling-related mitigation is to assign multiple personnel to complete tasks that are prone to cognitive-related errors. Providing a "second set of eyes" is a recommended mitigation for FFP (Barnes and Drury, 2019; The Boeing Company, 2016).

A final comment about supervisors' facilitation of daily tasks is that they should also be cognizant of involving their employees in decision-making and acknowledging the importance of employee morale.[48] There is an established relationship between job satisfaction/morale and safety-related outcomes such as incidents, violations, and errors (Fogarty et al., 2018).

Prioritization

One of the most commonly cited contributors for FFP is competing demands (e.g., productivity and safety), and organizational emphasis on the bottom line. Often, shortcutting is overlooked by management if no incidents have occurred. Thus, one of the main roles of the supervisor is to explicitly communicate the importance of safety over production. Research provides evidence that supervisors can limit the use of non-approved procedures by overtly communicating the importance of safety over competing operational demands like time pressure.[49]

One of the earliest investigations was conducted by Zohar (2002), who designed an intervention aimed at increasing the supervisor's safety- and productivity-related

[48] Cooper and Phillips (2004), Cox and Flin (1998), Fogarty (2004).
[49] Neitzel et al. (2008), Santiago (2007), Zohar and Luria (2005).

communications. The result was increased supervisory safety practices, increased use of PPE, increased safety culture ratings, and decreased minor-injury rates. Similarly, Kines et al. (2010) used a pre-test post-test design to determine the effects of coaching supervisors on their verbal safety communication. In one intervention group, safety was discussed in only 6% of baseline supervisory-employee exchanges. After training, the supervisors used more safety communications (~60%), with corresponding increases in both safety performance and safety climate compared to the control group. This kind of safety communication intervention strategy has also been successful in various fields outside aviation,[50] demonstrating the important role of supervisors' communications in ensuring that employees follow procedures and that safety behaviors are reinforced in the workplace.

There are factors to consider when considering the application of these results to the aviation maintenance environment. First, these studies were conducted in safety-critical fields outside aviation. Research is needed to determine the benefits of supervisory communications in aviation maintenance. Second, research has demonstrated that supervisors are more committed and engaged when employees are more visible in the workplace (Luria et al., 2008). Employee visibility reinforces more frequent exchanges between supervisors and employees, which in turn reinforces improved safety behavior. This presents a possible challenge in the maintenance environment where confined and enclosed spaces may reduce employee visibility.

Performance Management

Supervisors are also responsible for setting and enforcing performance expectations. Failure on the part of supervisors to meet their responsibilities (e.g., poor accountability, ineffective disciplinary procedures, and inadequate positive rewards) can lead to FFP (Mason, 1997).

Supervisors should directly engage with employees about their job performance and have informal conversations about safe behaviors.[51] Supervisors should also publicly recognize employees for safe behavior (Beus et al., 2016) and provide corrective feedback when errors are made (Schmidt et al., 1998).

The ability to provide feedback depends on supervisors interacting with employees and being present in the work area. A large-sample study, conducted over a three year-period,

[50] E.g., dairy production plants (Eklöf et al., 2017), firefighter crews (Allen et al., 2010), and manufacturing (Cooper and Phillips, 2004).
[51] Komaki and Apter-Desseles (1998), McSween (2003), Waterman and Peters (1982).

found that a supervisory technique promoting visibility called "safety management by walking around" (SMBWA; Luria and Morag, 2012) was successful in reducing FFP. In this program, managers, supervisors, and peers walked around observing technicians' behaviors and providing feedback: positively reinforced safe behavior, questioned inappropriate behavior, and provided job training on proper task completion. This program reduced non-compliances, increased identification of hazards, and increased safety communications (Luria and Morag, 2012). Other research using similar intervention strategies have found significant improvements in safety climate, safety behavior, subjective workload, teamwork, and safety audit scores for experimental groups, compared to a control group with no intervention (Zohar and Polachek, 2014).[52]

Summary

Supervisors serve as important intermediaries in communicating safety policies/procedures, and are a key influence on safety outcomes (contributing to about 60% of all FFPs). Supervisors need to carefully allocate resources and tasks, and remain cognizant of workload, qualifications of personnel, task complexity, and fatigue, as these conditions are more prone to error. Additionally, supervisors are responsible for clearly communicating priorities (emphasizing the importance of safety over competing demands) and for setting and maintaining performance expectations.

Table 3.
Supervisor Factors - Contributing Factors and Recommendations

Contributing Factor	Recommendation	Reference
Day-to-Day Facilitation of Tasks	Supervisors should organize personnel resources and delegate tasks carefully to prevent unachievable workload; including assigning tasks to personnel who are qualified and ensuring an equitable distribution of work across personnel.	Ek and Akselsson (2007), Wang et al. (2016).
	Supervisors should schedule with task complexity and fatigue in mind.	Bos and Roessingh (2013); Rhodes (2003).

[52] A notable exception is that safety behavior increased in the control group as well as the experimental group, suggesting that the change in safety behavior may have been due to being measured in the study, rather than an actual change in safety behavior due to intervention (i.e., the Hawthorne effect; Landsberger, 1958).

Contributing Factor	Recommendation	Reference
	Assign multiple personnel or a "second set of eyes" to complete tasks that are prone to cognitive-related errors.	Barnes and Drury (2019); The Boeing Company (2016).
Prioritization	Supervisors can limit the use of non-approved procedures by overtly communicating the importance of safety over competing operational demands like time pressure.	Neitzel et al. (2008), Santiago (2007), Zohar and Luria (2005).
Performance Management	Supervisors should directly engage with employees about their job performance and have informal conversations about safe behaviors.	Komaki and Apter-Desseles (1998); McSween (2003); Waterman and Peters (1982).
	Supervisors should publicly recognize employees for safe behavior and provide corrective feedback to their employees when errors are made.	Beus et al. (2016); Schmidt et al. (1998).
	Consider employing the practice of SMBWA.	Luria and Morag (2012).

Organizational Contributors

To detect and mitigate FFPs, one must consider the broader organizational context within which they occur. Previous analyses of event reporting databases found organizational problems were a contributing factor in 13.7-26.7% of maintenance-related incidents (Schmidt et al., 2000; Suzuki et al., 2008b). Rashid et al. (2010) found that together, supervisory and organizational conditions contribute to 44% of all events. Organizational level contributors to FFP are culture, pressure and resource management, selection and training, and the quality of technical documentation.

This category refers to factors relating to the organization (i.e., *Organizational Culture; Organizational Pressures and Resource Management; Selection and Training;* and *Technical Documentation*).

Organizational Culture

Organizational culture is the shared beliefs about work practices, values, and expectations within an organization. In the case of aviation maintenance, we advise adopting

principles of High-Reliability Organizations (HROs).[53] HROs are characterized as having informed, reporting, just, learning, and safety cultures. This type of organization has fewer adverse events because they recognize humans are fallible and that things can go wrong (Committee Summary Report, 2004). Features of HROs include (Reason, 2000):

- Recognizing the multifaceted nature of causal factors
- Implementing safety management practices as a means of prevention
- Considering safety in terms of making the system robust to human and operational hazards
- Anticipating potential risks by equipping themselves to mitigate errors at all levels of the organization

Recommendations for improving organizational culture are to reduce barriers to reporting (fear of blame), encourage honest reporting, assure management commitment, and stress the importance of the collection, analysis, and sharing of risk-related information within and across organizations/industries (Committee Summary Report, 2004).

One primary way to promote a positive organizational culture is to support a voluntary program for reporting hazards, errors, and other mishaps. Companies need to educate their employees how to file reports, and what types of hazards and events should be reported (Dekker, 2011). The program should be accessible, protected (confidential), and non-punitive.[54] Companies should have clear criteria for what kinds of reports will be accepted. As part of this, managers and supervisors need to operationally define different types of willful violations, communicate them to employees, and consistently employ appropriate corrective actions.[55] The boundaries between acceptable and unacceptable behavior and the consequences for willful violations need to be clearly communicated with employees to maximize compliance and to support a just and safety culture (Hudson, 2003).

It is essential that employees know that any reported incidents and FFPs will be handled justly[56] and that the organization is committed to learning from mistakes rather than simply punishing the individuals who make them (Reason and Hobbs, 2003). To that end,

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[53] HROs are those operating in hazardous conditions, such as nuclear aircraft carriers, air traffic control systems, and nuclear power plants. The five HRO principles are preoccupation with failure, reluctance to simplify, sensitivity to operations, commitment to resilience, and deference to expertise (Rochlin, 1999; Weick and Sutcliffe, 2015).
[54] Barach and Small (2000), Dekker (2011), Ioannou et al. (2017).
[55] The corrective action likely will depend on the severity of the violation and the consequences of it.
[56] E.g., punish when boundaries have been clearly/deliberately crossed; do not punish otherwise.

management should respond by analyzing reports to identify areas in need of improvement, and by providing feedback on corrective actions taken. By demonstrating that reporting efforts are not punitive and that outcomes are used to improve the operational environment, the overall culture and SMS will improve.[57]

Organizational Pressures and Resource Management

The current aviation market is competitive, with advances in technology, increased complexity, globalization,[58] rising fuel costs, and so on (Gallaway, 2009; Suzuki et al., 2008b). Financial strategy and company policy represent the most significant risk factors for organizations (Said and Mokhtar, 2014). Although the term "Safety first" is oft repeated, the ultimate goal of many organizations is something other than safety (e.g., mission and/or finances; Gallaway, 2009). This imposes competing demands on the workforce, which include time pressure, work pressure, workload, perceived risk, conflicting priorities, and other factors (Alper and Karsh, 2009).

Efforts to improve financial viability in commercial aviation has focused on reducing turnaround time. This, in turn, has led to increased time pressure on maintenance personnel. Time pressure is cited as one of the most critical factors contributing to FFPs in industrial and organizational settings (Lawton, 1998); and has repeatedly been deemed to be one of the more prevalent contributors to all maintenance errors.[59] Research across several domains has demonstrated that increased time pressure generally results in lowered performance and an increase in errors, especially in complex work environments[60] and for decision-making.[61]

Although pressure is an inherent part of the aviation maintenance environment, organizations can make impactful improvements that reduce pressure among front-line employees. As one mitigation, Burt et al. (2010) developed a time management scale (TiME), for which lower scores (indicating a worse time management environment) were associated with higher job stress and intentions to quit on average. Additional research is

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[57] See Darvau and Hannon (2017); Dekker (2011); Douglas et al., (2014); Ioannou et al. (2017) for further description of effective reporting systems.
[58] In an effort to reduce cost, airlines are moving to outsourced maintenance. Recent investigations found that 61% of heavy maintenance is outsourced (Government Accountability Office, 2016), and spending on outsourced maintenance had increased from $1.5 billion to $4.2 billion by 2011 (Office of Inspector General, 2013). This is problematic, as research shows these outsourced facilities may be riskier and subject to less regulatory oversight (Gregson et al., 2015; Quinlan et al., 2013, 2014).
[59] 22% according to Geibel et al. (2008); 23.5% according to Australian Transportation Safety Bureau (2001). See also Hobbs (2004), Hobbs and Benier (2006).
[60] Aase et al. (2009), Hobbs and Williamson (2000), Hodges and Gardner (2014), Suzuki et al. (2008b).
[61] Suzuki et al. (2008b); see also Alexandre and Gael (2003), Atak and Kingma (2011).

required for understanding how improved time management processes can improve AMT job performance.

Another source of organization pressure is allocation of scarce human resources. The aviation maintenance industry is facing a global shortage of personnel in the next decade (Aviation Technician Education Council, 2020). There is an aging workforce close to retirement, pay is not competitive with other industries (resulting in poor employee retention), and lack of interest among younger generations in entering the aviation workforce. This shortage has resulted in fewer front-line employees each handling an increased workload (Gallaway, 2009). As previously noted, supervisors should allocate personnel resources to minimize excess workload pressure. Further, as an industry, education and outreach programs are needed to help recruit the next generation of aviation personnel.

Selection and Training

A well-trained workforce will be more efficient and less likely to make errors in the use of new equipment, technology, and procedures. Organizations must have in place a process to first select and hire individuals based on the knowledge, skills, and abilities (KSAs) to perform the job, and then provide on-the-job (OJT) and recurrent training to ensure that employees can maintain and update the necessary KSAs.

Regarding selection, the workforce of the future will likely require different KSAs and other characteristics. Gallaway (2009) describes how recent and ongoing technological changes impact the required knowledge and skills of aviation maintenance personnel. There are also implications associated with the aging of the maintenance workforce and the introduction of new technologies and procedures into the work environment. Further, Gallaway (2009) noted a mismatch between the Federal Aviation Administration's (FAA's) certification requirements and the maintenance requirements associated with these new technologies (see also Shanmugam and Robert, 2015a). In light of technological change and increasing system complexity, further consideration is warranted for design-for-maintainability. Additionally, we recommend a job task analysis to identify the needed KSAs for the future, and critical training needs. We refer the reader to Hoffman et al. (2014) for a thorough discussion of training needs, and methods for the next generation of personnel who will support increasingly complex and cognitively intense work tasks.

Regarding training methodology, most of the critical skills for AMTs are acquired through OJT (~90%; Walter, 2000). However, OJT is often unstructured and inconsistent, involving shadowing the lead mechanic or trained AMT. Other issues concern the selection of qualified trainers who possess the technical knowledge and

motivational/interpersonal skills to be successful, rather than selecting based on convenience or operational constraints. Additionally, there is a need to ensure objective evaluations of trainees' performance rather than relying on subjective perceptions. Efforts should be made to improve OJT by establishing clear selection criteria for trainers, performance criteria for trainees, and objective assessments of trainees' performance (Usanmaz, 2011).

In addition to technical skills, AMTs need education about human factors that can contribute to errors and FFPs on the job. Human factors training not only makes workers aware of issues that may impact their performance, but it also offers strategies to lessen the impacts and creates a dialogue that can improve safety and performance. For guidance on developing maintenance human factors training, see FAA Advisory Circular 120-72A (FAA, 2017). A series of web-based training courses on human error and noncompliance are available on the FAA Safety team website.[62,63]

Advances in technologies such as Virtual Reality (VR) and Augmented Reality (AR) create unique opportunities for improved training. AR and VR technologies allow for hands-on practical exercises to supplement classroom training, and may be more cost-effective than traditional methods of practical exercises due to reduction in training time.[64]

Technical Documentation

One frequently cited reason for FFPs is issues with the technical documentation itself (Avers et al., 2012). Hobbs (2008) noted that maintenance personnel spend 25-45% of their time on maintenance documentation. Yet despite the amount of time and effort spent on technical documentation, there are clear signs that they are deficient. When questioned whether the maintenance manual describes the easiest way to do a procedure, only 18% agreed, and only 13% agreed that the "manual understands" how they do maintenance. Incomplete or inaccurate technical documentation, which includes missing, incorrect, conflicting, or difficult to interpret information, is a common contributor to FFPs[65] and has been a contributing factor in multiple accidents and incidents (NTSB, 2004, 2013).

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[62] https://www.faasafety.gov/gslac/ALC/course_catalog.aspx

[63] Another option is the "wobbly steps" training framework developed by Cromie et al. (2015), which demonstrates the relationship between organizational conditions and human performance. If the organizational resources are inadequate, employees develop their own "wobbly steps" (i.e., risky behaviors) to complete the assigned tasks. Efforts are underway to validate this training program.

[64] Pozzi (2016); see also Bowling et al., (2008), Keesling (2019).

[65] Alper and Karsh (2009), Australian Transportation Safety Bureau (2001), Baron (2009).

One survey found that technicians rarely referred to the procedures (33.5% occasionally referred, 39.6% not often/not very often referred) and were misled by the documentation (50.4% occasionally misled, 17% often/very often misled; Hobbs and Williamson, 2000).

Challenges with technical documentation mainly relate to how understandable and accessible the content is for AMTs. Specific concerns are: multiple printed and digital formats; easy to get lost in warnings, linked-texts and other details (Avers et al., 2011); illustrations do not appear accurately; conflicting instructions; not validated or checked against task performance; errors are not corrected and manuals not updated (Ricci, 2003; see also Alper and Karsh, 2009); and poor usability.[66] These challenges with technical documentation may arise due to constraints faced by procedure writers, such as writers not being familiar with the work environment, requirements, and users' needs. Procedure writers also face time pressure (Virtaluoto, 2013), resulting in a lack of time for proactive usability testing of the documentation, which often leads to writers receiving feedback only after the procedures are implemented into work practice.

Technical documentation should be written for AMT comprehension and usability. Best practices in technical documentation writing include:

- Utilize the Documentation Design Aid (DDA) to improve comprehension and readability of airline workcards (Drury, 2000).[67]
- Validate maintenance procedures against standard human factors techniques (Chaparro and Groff, 2002b).
- Use clear and consistent language, active tense, concrete vocabulary, clear structure, and connecting words (Virtaluoto, 2013).
- Improve integration and linkages of content across maintenance documents, usability of the format, accessibility and training of technological improvements in documentation (Drury and Johnson, 2013).
- Conduct usability beta testing (Virtaluoto, 2013).
- Make user-focused revisions to fix any errors or confusions in the documents (Drury and Johnson, 2013; Virtaluoto, 2013).

[66] Chaparro and Groff (2002a), Drury (2000), Drury and Johnson (2013).
[67] See also Patel et al. (1994a, 1994b) for information related to workcard design.

- Improve communications between technicians, technical writers, regulators and other stakeholders (Chaparro and Groff, 2002b; Drury and Johnson, 2013).
- Ensure prompt feedback of actions taken to improve procedures (Chaparro and Groff, 2002b).
- Collaborate across industry to identify maintenance procedures that should be systematically validated (Chaparro and Groff, 2002b; Drury and Johnson, 2013).
- Maintain manufacturers' databases containing user-reported errors, feedback to users, and actions taken to mitigate errors (Chaparro and Groff, 2002b).

Technological advances such portable digital aids, laptops, and wearable computers may also improve the usability of technical documentation.[68] Features of such aids may include digitizing documents, auto-fill forms, digital signatures, and ability to send photos/videos to communicate with remote personnel. These process-oriented applications ensure the information is available in a way that more directly support maintenance activities. Therefore, we recommend[69] that further efforts to reduce FFPs should be directed toward digitizing maintenance documentation that is process oriented, including interconnectivity of maintenance information systems, and incorporating portable support systems so the materials are easily accessible[70] and widely available to technicians (Buderath et al., 2008; Taylor, n.d.).

AR has been identified as a potentially feasible technology for displaying maintenance instructions because it gives users real time access to procedures, 3D visualization of airframe and components, and interconnectivity of maintenance information systems. Integration of AR technology into the working environment has been shown to reduce preparatory and repair time for certain tasks (Jo et al., 2014), improve user satisfaction (De Crescenzio et al., 2011), reduce AMT learning curve for troubleshooting an aircraft, and speed up task performance (Pozzi, 2016; see also Bowling et al., 2008). However, there are also potential usability, ergonomic/comfortability, and safety constraints to consider (see Keesling, 2019). Additionally, the AR must be developed for each task and aircraft type, and there is also a cost of the hardware (e.g., headworn devices), so total costs can add up quickly. Finally, AR may limit the cognitive reference that touching a

[68] Buderath et al. (2008), Goossen et al. (2011), Hakkeling-Mesland and van de Merwe (2008), Tretten and Normark (2015), Ward et al. (2008), Worsfold and Asseman (2008).
[69] See also Barshi et al. (2016), Feldman et al. (2017), and Mauro et al. (2012).
[70] Cone (2006) found that connectivity issues, poor network reliability, and inadequate training of digitized documentation may result in underutilization. These issues should be considered when designing and integrating digitized documentation into the workplace.

page allows a seasoned maintainer. Further work is needed to resolve potential roadblocks to the implementation of AR/VR to ensure that the applications are dedicated to tasks in a way that maximizes safety and compliance, and honors differences in work preferences and styles.

Summary

Organizational culture, inadequate resource allocation, and competing pressures are top contributors to FFP, exacerbated by constraints like financial viability and an industry shortage of maintenance personnel. Additional organizational-level factors include recruitment, selection and training to ensure employees have the necessary KSAs to perform the work, and ensuring the technical documentation is accurate and usable; else it is unlikely to be followed.

Table 4.
Organization Factors - Contributing Factors and Recommendations

Contributing Factor	Recommendation	Reference
(High-Reliability) Organizational Culture	Adopt principles of HROs.	Committee Summary Report (2004); Reason (2000); Rochlin (1999); Weick and Sutcliffe (2015).
	Recommendations for improving organizational culture are: reduce barriers to reporting (fear of blame); encourage honest reporting, assure management commitment; stress the importance of the collection, analysis, and sharing risk-related information within and across organizations/industries	Committee Summary Report (2004).
	Support a voluntary program for reporting hazards, errors, and other mishaps. Companies need to educate their employees how to file reports, and what types of hazards and events should be reported. The program should be accessible, protected (confidential), and non-punitive.	Barach and Small (2000); Dekker (2001, 2011); Ioannou et al. (2017).
	Managers and supervisors need to operationally define different types of willful violations, communicate them to employees,	Hudson (2003).

Contributing Factor	Recommendation	Reference
	and consistently employ appropriate corrective actions.	
	Management should respond by analyzing reports to identify areas in need of improvement, and by providing feedback on corrective actions taken.	Reason and Hobbs (2003).
Organizational Pressures and Resource Management	Supervisors should allocate personnel resources to minimize excess workload pressure.	Ek and Akselsson (2007), Wang et al. (2016).
	As an industry, education and outreach programs are needed to help recruit the next generation of aviation personnel.	Aviation Technician Education Council (2020); Gallaway (2009)
Selection and Training	Perform a job task analysis to identify the needed KSAs of the future, and critical training needs.	Hoffman et al. (2014).
	Efforts should be made to improve OJT by establishing clear selection criteria for trainers, performance criteria for trainees, and objective assessments of trainees' performance.	FAA Advisory Circular 120-72A; Usanmaz (2011).
	AMTs need education about human factors that can contribute to errors and FFPs on the job. A series of web-based training courses on human error and noncompliance are available on the FAA Safety team website.	FAA (2017).
	Technical documentation should be written for AMT comprehension and usability. Best practices in technical documentation writing include: ● Utilize the DDA to improve comprehension and readability of airline workcards. ● Validate maintenance procedures against standard human factors techniques. ● Use clear and consistent language, active tense, concrete vocabulary, clear structure, and connecting words. ● Improve integration and linkages of content across maintenance documents, usability of the format, accessibility and training of	Chaparro and Groff (2002b); Drury, (2000); Drury and Johnson (2013); Virtaluoto (2013).

Contributing Factor	Recommendation	Reference
	technological improvements in documentation. ● Conduct usability beta testing. ● Make user-focused revisions to fix any errors or confusions in the documents. ● Improve communications between technicians, technical writers, regulators and other stakeholders. ● Ensure prompt feedback of actions taken to improve procedures. ● Collaborate across industry to identify maintenance procedures that should be systematically validated. ● Maintain manufacturers' databases containing user-reported errors, feedback to users, and actions taken to mitigate errors.	
Technical Documentation	Further efforts should be directed towards digitizing maintenance documentation that is process oriented, including interconnectivity of maintenance information systems, and incorporating portable support systems so the materials are easily accessible and widely available. Consider also the integration of AR/VR technology.	Bowling et al. (2008); De Crescenzio et al. (2011); Jo et al. (2014); Keesling (2019); Pozzi (2016).

Discussion

FFP contributes upwards of 87% of all maintenance-related safety events (Schmidt et al., 1999, 2000, 2003), which have significant costs.[71] The frequency of FFP appearing as a top contributor in psychological and human factors research indicates that much work in mitigating them still needs to be done. The historic approach of managing FFP events was a person-centered approach of "blaming and training", attributing the events to workers' lack of skill or fitness for duty/knowledge. Although blaming-and-training can be faster and easier in the short term, the scientific literature has found that such person-centered mitigations do not effectively reduce FFP. Instead, a systematic approach is needed, where contributors at all levels of the organization are considered and mitigated. FFP is a complex phenomenon involving multiple contributing human factors at various

[71] Hudson (2003), National Institute of Occupational Safety and Health (2017), Rankin (2007).

levels of the organization.[72] Therefore, a multi-level approach to FFP mitigation is needed, where the broader operational context is considered. While there is general agreement among researchers that mitigating FFPs requires a multi-factor (within a level) and multi-level (across levels) approach, the research also indicates that this viewpoint has not yet been implemented in the industry. This is self-evident, as FFP persists as a top human factor issue in many organizations year after year and individual training is the most common mitigation.[73] This is not a systemic approach, it seems to be a quick fix but is not showing a reduction in FFP events.

This review of the literature on FFP within and beyond aviation, identified the most common contributing factors and evidence-based recommendations to mitigate FFP in the aviation maintenance field. These recommendations are based on current knowledge and practices regarding how to deal with the complexity of human factors involved in FFPs.[74] Effective management and prevention of FFPs in the workplace must take into account the contributing factors of individuals, crew coordination/communication (colleagues and supervision), the working conditions, and the organizational context.

Limitations and Future Directions

Before turning to the broader implications and conclusions of this effort, several limitations merit consideration. First, our review provides a reasonably complete, but not exhaustive, discussion of FFP contributing factors and mitigations. An exhaustive discussion would overwhelm the reader with unnecessary detail and limit the practical import of the paper. Thus, we selected the most important (or well discussed) contributing factors from the literature, leaving others for future research. For example, personality/attitude and physical characteristics (e.g., body size/strength, sensory impairment, health) are commonly touted as contributors to FFP. However, the available research suggests their contributions are minimal,[75] and there is little research on the practicality and benefits of potential mitigations (e.g., change the person). Therefore, we excluded them from our report, but they may warrant further investigation, especially regarding actionable mitigations.

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[72] Hollnagel et al. (2006), Leveson (2011a, 2011b), Woods (1988), Woods et al. (1994).
[73] This disconnect could stem from lack of awareness on the industry side; poor communication of findings/interventions on the research side; expense of multi-level mitigations; or other factors. Additional research is needed to determine why this disconnect exists and how to bridge the gap.
[74] The reader is referred to Dekker (2014), Dhillon (2009), and Reason and Hobbs (2003) for additional discussion on recommended mitigations for FFP.
[75] Beus et al. (2015), Chiu and Hsieh (2016), Suzuki et al. (2008b).

Second, although HFACS-ME is the chosen framework for the report, it is not without limitations. As argued by Beaubien and Baker (2002), the limitations of the HFACS coding system are that latent threats are difficult to identify, particularly within short narratives provided in reporting systems; the taxonomy does not identify the chain of events, so it is difficult to separate causes from effects; and it may be too coarse to identify specific problems and corresponding interventions. On the other hand, inclusion of too many contributing factors can make the taxonomy overly cumbersome and reduce inter-rater reliability (see O'Connor, 2008). The *more specific* a taxonomy is, in terms of narrowing down the root cause of a given adverse event, the more actionable it is but the *less reliable* it is in terms of inter-rater reliability. On the flip side, the more general a taxonomy is, the less actionable mitigations can be generated. Ultimately, this limits the practical application of the taxonomy for industry use. Additional research is warranted to strike a healthy balance between generality (enough to be reliable and easy to use) and specificity (enough to generate actionable mitigation) of taxonomies for use within aviation maintenance investigations. On the other hand, in presenting a 'new view' of human error, Dekker (2014) argues a shift from efforts to count and categorize errors to gaining a more complete understanding of the gap between 'work-as-imagined' and 'work-as-done'. Why does the gap exist, what keeps it in place, and how does it relate to possible conflicts in organizational goals? Additional effort is warranted to operationalize such an approach in aviation maintenance.

A related limitation is that our multi-level discussion was organized heuristically, and factors were discussed at the level where they have been most prominently investigated in the literature. However, some factors bear influence on multiple levels of the organization, and there may be interactions or correlation among factors (e.g., KSAs are inextricably linked with training). In the FFP literature, there is a paucity of investigations regarding these potential interrelations between factors. For example, poor practices at the organizational level may manifest in stress/fatigue. Additionally, the impact of individual-level factors such as practical drift may emerge at higher group or organizational levels (e.g., culture) as well. Therefore, caution is warranted when inferring interrelations among the factors presented in this report. Further research is needed to examine the system complexity and the inextricable connections between factors at multiple levels of the organization.[76]

[76] See also Dekker (2001c) for a related argument. Also note, the ability to perform such an analysis depends on the level of detail provided in the databases (e.g., event reports, accident reports).

Practical Implications

Despite these limitations, we believe there is value for both researchers and industry**.** This review and compilation of over 200 scientific reports provides researchers with a better understanding of the current landscape of FFP identification and mitigation. Further, the contributing factors for FFP were organized in a structure that can serve as a foundation for further development and utilization of classification schemes/taxonomies for investigation of human error. Finally, this review identified areas where future research is needed to support the integration of advances in technology, tools, etc. into the aviation maintenance environment.

For industry, we provided updated statistics regarding the prevalence of FFP in the aviation maintenance industry and demonstrated why a person-centered mitigation strategy is ineffective for reducing the FFP rate. Then, we provided a comprehensive discussion of the multi-faceted contributing factors for FFP and corresponding actionable mitigation strategies targeted to the specific contributing factors. Implementation of these mitigations is expected to ultimately reduce the FFP rate in the aviation maintenance industry. While the discussed mitigations may each seem self-evident, our contribution is a compilation of countermeasures that can be used to build a systematic response to FFP where contributors at all levels of the organization are considered and mitigated.

At the maintainer and crew level, contributors to FFP pertain to readiness for the job (e.g., fatigue, stress, well-being, loss of attention, complacency) and crew coordination factors like teamwork and communication. Although front-line employees have partial responsibility to manage contributors like these, such as by getting enough rest/breaks and utilizing stress management techniques, there are also changes within the organization that can reduce or mitigate the overall impact of various psychosocial stressors. Organizations can implement fatigue risk management systems (FRMS), reduce the workload and time pressure that places undue stress on employees, and foster employee well-being programs, as research has shown these programs are an important means of reducing psychosocial stressors (Hesketh et al., 2020; Owen and Dollard, 2018). Other factors at this level include complacency, professional culture and normative behaviors (i.e., shortcutting). These factors require vigilance on the part of employees but may also be combatted at the organizational level by reviewing processes to correct deficiencies and employing 2-step task verification to ensure tasks were completed correctly. Finally, situational awareness and good communication within and across departments can reduce FFP. Tactics to improve situational awareness and communication are sharing information and mental models across teams, verbalizing decisions, improving shift meetings and teamwork, improving feedback, and providing situational awareness training (Endsley and Robertson, 2000).

Working conditions that are beyond employee levels of comfort (e.g., noise, lighting), or poorly designed work places (e.g., confined space, inaccessible) are oft-cited contributors to FFP. Improving the ergonomic design of the workplace and aircraft has been shown to improve overall performance (Ward and Gaynor, 2009). Other relevant working condition factors pertain to the availability, accessibility, and adequacy of equipment, tools, parts, consumables, and technical documentation. The organization is ultimately responsible with providing adequate resources needed to perform the job. Additionally, as system complexity increases, additional consideration is warranted regarding design-for-maintainability and how best to support technicians with maintaining increasingly complex aircraft (e.g. through improved diagnostic tools, training, and procedural needs).

Supervisors serve as important intermediaries in communicating safety policies/procedures, and are a key influence on safety outcomes (contributing to about 60% of all FFPs). Careful attention should be paid to resource allocation, as this is considered a critical driver of both safety culture and safety performance (Fogarty et al., 2018). When assigning tasks, supervisors should be cognizant of workload, qualifications of personnel, task complexity, and fatigue; as these conditions are more prone to error. Additionally, supervisors must clearly communicate priorities and emphasize the importance of safety over competing demands (e.g., productivity); resolving this conflict will improve performance. Finally, research shows many benefits from setting and enforcing performance expectations by providing timely feedback (both positive and corrective).

To mitigate contributors to FFP at the organizational level, a potential solution could be the adoption of principles of HROs, since the emphasis on learning from negative events makes the system robust to human operational hazards. Recommendations for improving organizational culture in the literature are: reduce barriers to reporting (fear of blame), encourage honest reporting, assure management commitment, ensure employee involvement throughout the process, and stress the importance of the collection, analysis, and sharing of risk-related information within and across organizations/industries.

Organizations should also strive to reduce pressure (e.g., time, workload) and carefully manage resources, in light of constraints like financial viability and an industry shortage of maintenance personnel. Organizations need a robust process for recruitment, selection, and training to ensure that employees can maintain and update the necessary KSAs to perform the work. Finally, organizations must ensure the technical documentation is accurate, complete, and usable; else it is unlikely to be followed.

While these recommendations may ultimately reduce the frequency of certain FFPs, they will not prevent all instances, and there is no single *best* way to manage errors (Reason

and Hobbs, 2003). Many of the events that occur have more than a single contributor or performance shaping factor, with factors interacting across multiple levels, and include aspects of the work processes. The complex nature of FFPs, along with the advances of new technology, tools, and procedures, will require continued human factors research and oversight. Remember, the focus should be on learning from the events and further enhancing safety within the organization. Further efforts are needed to enhance the efficiency, safety, and resilience of aviation maintenance operations.

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Appendix A: Methods for Identifying FFPs

FFPs are not unique to the maintenance environment; they are present in everyday life and, to some degree, in all work environments where standard operating procedures are in place. In the biomedical field, examples of FFPs include not wearing mandatory eye protection or improper medication administration, which can result in harm to the healthcare workers and/or their patients (Bates and Holroyd, 2012).[1] In the legal system, FFPs such as improper handling of evidence can result in dismissal of a criminal case.

Within aviation, examples of FFPs include nonstandard checklist protocols, non-compliances with speed policy, unstabilized approach landing, and not completing flight check controls before takeoff.[2] Specific to aviation maintenance, FFPs are events and behaviors like incorrect installation of new or existing parts, an incorrectly documented or signed-off task, failure to sign off or inspect a task, errors in maintenance documentation, no tool inventory check, inadequate ground support equipment, or miscommunication when turning a task over to another AMT.[3]

These examples demonstrate that even highly trained professionals across many different safety-critical environments are prone to FFPs.

Most of the literature summarized in this report has primarily analyzed data from:[4] 1) event investigations (data from accident/incidents and reporting systems), 2) questionnaires, and 3) observational methods. These various methods support the identification and quantification of FFPs; however, each method has advantages and weaknesses.

Event Investigations

The conventional method to identify FFP is through investigations of accident and incidents by regulatory authorities such as the NTSB. The purpose of such investigations is to determine the nature of the event, its contributing factors, and potential corrective actions. A related method to identify FFP is through mandatory or voluntary reporting systems, used to report accident precursors - hazards/threats/incidents (i.e., near misses or close calls). Example reporting systems sponsored by regulatory authorities include the National Aeronautics and Space Administration's (NASA) ASRS, the FAA's Aviation Safety Action Program (ASAP), the U.K.'s Confidential Human Factors Incident Reporting Program (CHIRP), and Australia's Aviation Confidential Reporting Scheme (REPCON).[5] Organizations may also implement their own voluntary disclosure reporting program for internal use (in which case, the data may not be reported to the regulatory authorities).

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[1] See also McKeon et al. (2006); Pape et al. (2005); Westbrook et al. (2016).
[2] See Giles (2013); Holden (2009); Karwal et al. (2000); Klinect (2013).
[3] See Dhillon (2009), Dhillon and Liu (2006) for a review of the literature on maintenance human error.
[4] FFPs can also be identified via electronically-recorded data from the flight deck (i.e., Flight Operations Quality Assurance), but this is not specific to aviation maintenance.
[5] Previously, REPCON was referred to as the Confidential Aviation Incident Reporting (CAIR) system.

The majority of research still relies on data gained from accident/incident databases, but the overall low frequency of these events makes it difficult to develop reliable intervention strategies. Conversely, more data may be available from voluntary reporting programs, but a fundamental concern with voluntary reports is that there can be no determination of whether the data collected are truly representative of all error and FFP cases (Latorella and Prabhu, 2000). Another important limitation is that the data from these reporting program reports may be proprietary or kept confidential. Therefore, researchers typically cannot access the large volume of event data collected by industry for use in trend analysis and developing reliable intervention strategies. The development of intervention strategies is further complicated because reporting systems may lack a theoretical model of human performance/error, may not explicitly consider supervisory and organizational factors, and may not document the consequences/outcomes associated with the FFP (Beaubien and Baker, 2002). These data quality issues prevent the reporting systems from being used to their full potential.

Questionnaires

The second method is the use of questionnaires or interviews to gather information from personnel concerning the contributing factors associated with unsafe acts/events. Much of the maintenance-specific work using this method has been conducted outside the United States.[6] Hobbs and Williamson (2000) developed the Maintenance Environment Questionnaire (MEQ), which revealed seven latent factors contributing to the occurrence of FFPs.[7] Later, Fogarty et al. (2018) validated a safety climate questionnaire, incorporating questions related to the causal pathways for errors and violations. Managers can use the results from questionnaires and interviews to develop intervention strategies based on the contributing factors identified. It should be noted that questionnaires and interviews provide subjective, self-reported data that may not accurately reflect issues within the organization.

Observational Methods

The final method involves gathering observational data of the real-time operational environment. One tool used to collect aviation observational data is the Line Operations Safety Assessment[8] (LOSA) in flight operations, Ramp Line Operations Safety Assessment (R-LOSA) in ramp operations, and Maintenance Line Operations Safety Assessment (M-LOSA) in maintenance operations.[9] A similar observational method, the Maintenance Operations Safety Survey (Langer and Braithwaite, 2016), was based on LOSA to detect threats and errors in maintenance operations in the United Kingdom. These assessment methods are structured around the Threat and Error Management (TEM) model (Helmreich et al., 2001; Klinect et al., 1999; Klinect et al.,

[6] E.g., Australia. See Australian Transportation Safety Bureau (ATSB; 2001); Hobbs (2004); Hobbs and Benier (2006); Hobbs and Williamson (2000). See also Bates and Holroyd (2012); Lawton (1998).
[7] The seven latent factors revealed by the MEQ are: Defenses, Fatigue, Coordination, Equipment and Procedures, Time Pressure, Knowledge, and Supervision. See also Hobbs and Williamson (2003).
[8] Also known as the Line Operations Safety Audit.
[9] Ma et al. (2011); Ma and Rankin (2012); Ma and Zylawski (2016).

2003; Klinect, 2005; Rankin and Carlyon, 2012), which provides a framework for coding observations of normal operations. The goal is to identify active threats, develop strategies to manage threats and errors that may occur, and learn from past errors to anticipate future events.

Though LOSA is a demonstrated safety tool in flight operations (Helmreich et al., 2001; Rankin and Carlyon, 2012), proactive safety tools such as this typically enjoy relatively less utilization and success in maintenance operations, possibly owing to persistent blame culture and the latent nature of errors in maintenance compared to flight operations (Langer and Braithwaite, 2016).

Another factor to consider is that it is more difficult to remain unobtrusive in maintenance compared to operational LOSA, as the observer must follow the AMT around different areas of the work environment to obtain the required tools, parts, and documentation before returning to the aircraft. As is the case for any audit, it can be intrusive to the work environment and must be performed by experts with domain expertise[10] and human factors knowledge, usually a rare combination (Latorella and Prabhu, 2000). A final limitation of observational data is that it is a very time- and resource-intensive process, taking perhaps 125 hours for the conduct of a M-LOSA program depending on the complexity of the task observed and the training time involved (Langer and Braithwaite, 2016; Ma and Zylawski, 2016). There is a tradeoff between depth and breadth of analysis given the time available (Latorella and Prabhu, 2000).

[10] Often, organizations can use their own employees as LOSA observers. These observers intervene only if a safety issue is imminent.

Appendix B: Historical Response to FFP

To further illustrate why a multi-level approach to FFP mitigations is needed, it is necessary to consider the historic approach to aviation safety management.

What is the historic response? The historic response was a person-centered, "blame and train" response to errors or mishaps, focusing on characteristics of the person performing the work (i.e., fitness for duty, training/knowledge, and attitude).[1] (Holden, 2009). Individuals were viewed as "bad people in safe systems", rather than "well-intentioned people in imperfect systems" (Dekker, 2014, p. 3). Correspondingly, the common mitigations implemented to control human error were selection, training, writing new policies/procedures/regulations, better enforcement of compliance, and disciplinary action (up to termination).[2]

Why does this response happen? Overreliance on training, procedure writing, and other person-centered mitigations has been the prevailing safety management strategy not only in aviation, but, across healthcare, nuclear power, and other safety-critical fields.[3] This response has been described as both fundamentally human and the industry norm (Holden, 2009), and for pragmatic reasons. Person-centered mitigations are a quick, financially expedient way of gaining closure and moving forward from the event on a well-trod, but ultimately incorrect, path (Dekker, 2001a).

What are the consequences/why doesn't it work? Mitigations targeting the individual are often unsuccessful as a standalone intervention. Researchers and regulators agree that a person-centered approach is not sufficient for effective safety management,[4] for several reasons:

- Even experienced workers can make errors (Reason and Hobbs, 2003),[5] whether willfully or not (Leveson, 2004; McDonald et al., 2000a).
- Blaming and training prevents learning from the event (Dekker, 2001a; see also Latorella and Prabhu, 2000).

[1] Individual factors include competence, personal attitudes, values, beliefs, level of stress and fatigue, personality, attention to detail, and general well-being.
[2] FAA (2009), Holden (2009), Reason (1990).
[3] Dekker (2001a, 2001c, 2011), Holden (2009), Hollnagel et al. (2006), Leveson (2004, 2011a, 2011b), McDonald et al. (2000a), Reason and Hobbs (2003).
[4] Dekker (2001a, 2001c, 2011), FAA (2009), Holden (2009), Reason (1990).
[5] Though, risk perceptions differ between experts and novices, with more variability in novices' ratings of risk in different scenarios (Chionis and Karanikas, 2018).

- Blaming and training can impede SMS effectiveness – with unintended consequences of undermining just culture, reducing employees' trust and willingness to report future near-misses (i.e., precursors to incidents) and FFPs (Avers et al., 2014; Dekker, 2001a, 2011).

Research shows that errors typically occur due to the complex, multi-level interaction of several factors (e.g., between individuals and teams, workplace and tasks, and latent organizational conditions). Linear event causal chains cannot adequately capture such complexities (Leveson, 2004)[6]. Experts in safety management and resilience engineering argue that adverse events occur in a nonlinear, dynamic way instead of a single failure point (i.e., the individual performing the work).[7] That is why single-point fixes like counseling, disciplinary actions, and other person-centered mitigations are not effective. What is needed is a shift to viewing human error as a symptom of failure, rather than the cause of it (Dekker, 2001a).

Though these ideas are well-established in the scientific literature, they are slow to be adopted by the aviation industry, as evidenced by the perpetuation of FFP as a top human factors issue for decades running.

So what's the solution? To break the "blame cycle", it is important to recognize: 1) human performance is shaped by situational and environmental factors, 2) simply instructing operators to not make unintentional errors is ineffective, 3) errors often result from multiple contributing factors, both within and beyond the control of the operators, and 4) situations and environments are usually easier to alter than operators.[8] Thus, the "blame and train" response has fallen out of favor, being replaced by an approach to safety focusing on the complex, multi-level interaction between individuals, the work environment, and other factors.[9] Rather than focusing on the individual operators responsible for the specific FFP, it is essential to look at the contributors to FFP from a multi-level perspective when making safety improvements and mitigations targeting FFP (Leveson, 2004; Reason, 2000).

[6] Further, Leveson (2004) argues that attempts to find a single human-centered 'cause' reflect the investigative biases and inadequate event causation models.
[7] Hollnagel et al. (2006), Leveson (2004, 2011a, 2011b), Woods et al. (1988, 1994).
[8] Allen and Rankin (1996), Dekker (2001a, 2001c), Latorella and Prabhu (2000), Reason (1990).
[9] Hollnagel et al. (2006), Leveson (2004, 2011a), Woods et al. (1988, 1994).