AIRCRAFT MAINTENANCE AND INSPECTION

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Introduction

Without the intervention of maintenance personnel, equipment used in complex technological systems such as aviation, rail transport, and medicine would inevitably deteriorate to a point where safety and profitability would be threatened. After fuel, maintenance is the largest cost facing airlines (GRA Inc, 2007).

Despite advances such as Built-in Test Equipment (BITE), on-board sensors, and flight data monitoring, maintenance is still a largely human activity. Maintenance technicians work in an environment that is more hazardous than nearly all other jobs in the labor force. The work requires physical strength, dexterity, and balance, but also calls for clerical skills and attention to detail. The work may be carried out at heights, in confined spaces, in numbing cold or sweltering heat (Fig. 1). Communication can be difficult due to noise levels and the use of hearing protection. Although maintenance makes an essential contribution to system reliability, improper maintenance can be a major cause of system failure.

Figure 1. A maintenance technician at work. Source: Image courtesy of American Airlines

Maintenance activities can be divided into the two broad categories of preventative and corrective as shown in Fig. 2. Preventative maintenance includes lubrication, inspections, and other tasks that can be scheduled in advance. Many preventative tasks are performed regularly at airlines, sometimes daily or as part of a block of tasks such as an "A" check performed after hundreds of hours of flight. Other forms of preventative maintenance occur at greater intervals, sometimes bundled into “C” checks that may be scheduled yearly or less frequently, or heavy maintenance “D” checks. The airline industry currently outsources more than half of its preventative maintenance tasks to specialized Maintenance Repair and Overhaul (MRO) organizations.

In the early years of the airline industry, each airline developed its own preventative maintenance program that called for intensive maintenance at predetermined intervals. These programs sometimes required the complete overhaul of systems, regardless of whether the maintenance was necessary or effective. In the 1970s, there was an increasing realization that scheduled maintenance programs needed to be tailored to the needs of each component or system, based on the failure patterns of each component, and the consequences should a failure occur. Today, regulators, manufactures, and airlines work together to develop maintenance programs for aircraft fleets based on Reliability Centered Maintenance principles (Moubray, 2001) as outlined in a document known as MSG-3 (Maintenance Steering Group). This approach ensures that systems are maintained at an appropriate level, while avoiding over-maintenance and the increased potential for error that this introduces.

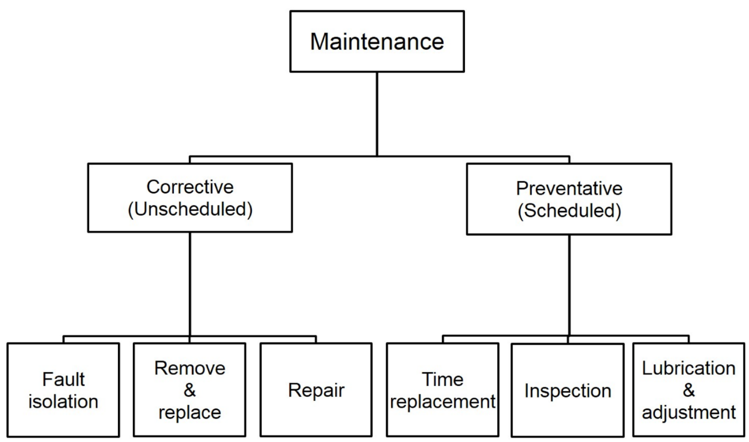

Figure 2. Major categories of maintenance. Source: US DoD (1997)

Corrective maintenance, also known as unscheduled maintenance, is performed in response to unplanned operational events such as aircraft damage, component failure, or defects discovered during a scheduled check. Corrective maintenance includes fault isolation, repair, and replacement of faulty components. Although some corrective tasks are minor, others require extensive system knowledge, problem solving, and specialized skills. Some nonscheduled inspections are initiated in response to events such as a bird strikes, lightning strikes, and heavy landings. These inspections are sometimes referred to as “Chapter 5” inspections as they are found in this chapter of maintenance manuals following the industry-standard ATA numbering system. Major nonscheduled maintenance can be particularly disruptive and expensive for airlines. An “Aircraft on Ground” (AOG) requires an immediate response that may include flying maintenance personnel to the stranded aircraft, rapidly locating spare parts, and coordinating with the original equipment manufacturer.

Maintenance Steering Group-3 defines three levels of inspections: general visual, detailed, and special detailed. General visual inspections are carried out within touching distance of the area being examined, to detect obvious damage such as clearly visible cracks, corrosion or dents. These inspections do not require special equipment, although ladders or workstands may be used, and there may be a need to open access panels. Detailed inspections involve intense visual and/or tactile examination for less obvious defects, sometimes with the use of lenses or mirrors. There may also be a need for extensive disassembly to gain access to the area to be inspected. Lastly, special detailed inspections are examinations of an area involving the use of non-destructive inspection (NDI) techniques. These include ultrasound, thermography, X-ray, and dye penetrant techniques. The effectiveness of inspections relies on the ability of the inspector to detect the sensory signs that could indicate a defect, and then decide whether a detect is actually present. Factors such as lighting, time of day, monotony, vigilance, and the adequacy of rest breaks can all impact inspector performance (Drury and Watson, 2002).

Maintenance Personnel

In many countries, including those covered by the rules of the European Aviation Safety Agency (EASA), aircraft maintenance licenses are divided into two basic categories. The first category enables the technician to certify work on structures, engines, mechanical, and electrical systems. The second category applies to avionics (the electronic systems used on aircraft). Some personnel possess both licenses or additional qualifications providing further signature authority. In most cases a licensed technician with the appropriate type rating has the authority to certify that their own work or that of a colleague was performed correctly.

In the United States, qualified maintenance mechanics are referred to as Aviation Maintenance Technicians (AMTs) or Airframe and Powerplant technicians (A&Ps). Unlike other regulatory authorities, the US Federal Aviation Administration (FAA) does not require technicians to possess a specialized qualification to work on avionics systems. The FAA system also relies on independent inspectors as part of the quality control process. In addition to performing general and specialized inspections of structures and components, quality control inspectors certify that critical tasks have been performed correctly by AMTs.

Quality Lapses in Maintenance

According to the International Air Transport Association, improper maintenance was a factor in 17% of airline accidents in the period 2014–18 (IATA, 2019). Maintenance errors not only pose a threat to flight safety, but can also impose significant financial costs through delays, cancellations, diversions, and schedule disruptions. For example, in the case of a large wide-body airliner, a flight cancellation can cost the airline around USD $200,000, while delays at the gate can cost over USD $20,000 per hour. Therefore, even a small reduction in minor maintenance problems can result in major savings for the airline.

Throughout the 1980s and 1990s, a series of landmark accidents drew attention to the fact that aircraft inspection and maintenance relies on human performance. Improvements in the quality and efficiency of maintenance requires an understanding of the capabilities and limitations of maintenance personnel.

Improper maintenance was a primary factor in the world's worst single-aircraft accident, an event that claimed 520 lives. The 747- 100 was on a short domestic flight in Japan when it experienced a sudden decompression due to the failure of the aft pressure bulkhead. The escaping air caused most of the vertical stabilizer and rudder to separate, and a loss of hydraulics pressure from all four systems. The pilots attempted to maneuver the aircraft using engine power, however they were unable to maintain control and after about 30 min the aircraft crashed into a mountain northwest of Tokyo.

The investigators found that the aft pressure bulkhead had failed in flight due to a fatigue fracture in an area where a repair had been made seven years previously. The repair had involved replacing the lower half of the bulkhead. The new lower half should have been spliced to the upper half using a doubler plate that would have extended under three lines of rivets. However, part of the splice was made using two plates instead of a single plate as intended (Fig. 3). As a result, the join relied on only a single row of rivets. After the repair, the aircraft flew over 12,000 flights and underwent six C checks before the accident occurred (Japan Ministry of Transport, 1987).

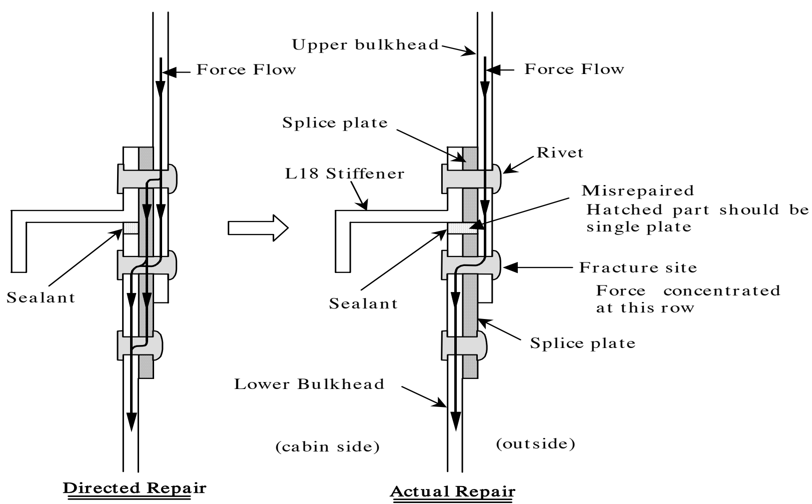

Figure 3. The repair to the aft pressure bulkhead as specified in the repair instructions (at left), and repair as actually carried out (on right). Note gap of doubler plate between top two rivets. Source: Terada and Kobayashi (2006).

In April 1988, an Aloha Airlines Boeing 737-200 en-route to Honolulu experienced an explosive decompression in which approximately 18 ft of cabin skin and structure separated from the aircraft. The pilots were able to make an emergency landing, however the accident resulted in one death and eight serious injuries. The NTSB determined that the accident was caused by the failure of the airline to detect the presence of significant disbonding and fatigue damage that ultimately led to the failure (National Transportation Safety Board, 1989). As a result of the accident, the human factors of inspection became a major issue of concern, particularly in the United States, where the FAA sponsored an extensive research program on the topic. Details of the FAA work can be found in the recommended reading.

Little more than a year after the Aloha accident, inspection was once more the focus of attention when a United Airlines DC-10 suffered a catastrophic engine failure that damaged the aircraft's hydraulic system, resulting in a loss of flight controls. In a remarkable feat of airmanship, the crew was able to partially control the aircraft for a crash landing using engine thrust alone. 111 passengers died, however 175 passengers and 10 crewmembers survived. The engine failure occurred when the stage 1 fan rotor disk separated from the center engine as a result of an undetected fatigue crack. Fifteen months prior to the accident, the component had been inspected using a dye penetrant technique. A fluorescent fluid was applied to the component, which was then inspected under ultraviolet light to reveal the presence of cracks or discontinuities, however the inspection failed to find a 0.5 inch long fatigue crack. The National Transportation Safety Board (1990) concluded that the root cause of the accident was inadequate consideration of human factors limitations in the inspection and quality control procedures.

Human Factors in Maintenance

The accidents described above, and others like them, led to a major worldwide effort to understand the human factors of airline maintenance. Research sponsored by the FAA, Transport Canada, and other agencies has brought to light the unique human factors of maintenance and inspection. The lessons are now being applied by operators and regulatory authorities worldwide. Some of the most commonly observed lapses in maintenance are:

- Equipment or part not installed (typically small parts such as O-rings or washers)
- Failure to detect damage during inspection
- Incomplete installation—often a nut or fastener left “finger tight” and not torqued
- Cross connections—electrical wiring or control cables
- Wrong parts fitted
- Parts fitted in the wrong location or orientation
- Loose objects or tools left in aircraft
- Panels, caps, or cowlings not secured.

Some maintenance quality lapses may remain undetected for months or years before discovery, or until an operational consequence occurs. Without doubt, some maintenance irregularities are never detected, and continue to fly with the aircraft until the end of its service life. Quality lapses in maintenance usually involve one or more human errors, however the culture of maintenance has tended to discourage the open reporting of minor maintenance errors. In recent years, confidential incident reporting systems and the application of “just culture” concepts have enabled the industry to gain a better understanding of the nature of maintenance error.

Human Error in Maintenance

Maintenance personnel make an invaluable and essential contribution to continuing airworthiness. As with all complex human/ machine systems, however, some level of human error is inevitable, and the use of the term “error” should not automatically imply blame or fault. While individual human errors cannot be predicted, estimates of error rates are used widely in risk assessments. Table 1 shows estimated error probabilities for maintenance tasks, based on military data. The reader should note that these numbers, although useful, should be seen as “best guesses,” to be treated with an appropriate level of skepticism. Error rates will vary according to the nature of the task, the environment, training, and other factors. Nevertheless, rates such as these can provide a general awareness of the level of risk introduced by human error. Although the probability of error for each instance of a task may be relatively low, if the task is performed numerous times, the overall chance of an error can become high.

Table 1. Estimated probabilities of maintenance errors

Task	Estimated chance of error during task
Install nuts and bolts	0.2%
Connect electrical cable	0.3%
Install O ring	0.3%
Tighten nuts and bolts	0.4%
Read pressure gauge	1.1%
Install lock wire	3.2%
Check for error in another person's work	10.0%

Source: Gertman and Blackman (1993).

In some cases, particularly if a maintenance error has been discovered or reported in a timely manner, it will be possible to examine not only the observable outcome of the error (such as failing to tighten a nut), but also the thinking processes that led the technician to make the error. Human factors analysis not only gives us a powerful insight into the origins of the error, but also helps us develop ways to prevent or capture future errors. Applying human error models to maintenance discrepancies reveals that underlying these events are a limited range of cognitive error forms. More than 50% of the maintenance errors in the aviation industry can be placed in one of four categories: memory failures, procedural noncompliance, assumption errors, and Knowle-based errors (Hobbs and Williamson, 2003).

Memory Failures

One of the most common errors in maintenance incidents is memory failure. Rather than forgetting something about the past, the technician typically forgets to perform an action that they had intended to perform at some time in the future. Psychologists refer to memory for intentions as prospective memory. Two common examples are forgetting to reconnect a disconnected system at the end of a task and leaving an oil cap unsecured. Failures of prospective memory are particularly likely when a maintenance task has been interrupted and must be picked up again later.

Procedural Noncompliance

The maintenance hangar is a highly-regulated workplace. Technicians are expected to carry out their duties while observing legal requirements, manufacturer's maintenance manuals, company procedures, and unwritten norms of safe behavior.

When asked about their most recent task, 34% of aircraft maintenance technicians in Europe acknowledged that they had not strictly complied with the formal procedures (McDonald et al., 2000). Examples are, signing off a task before it was completed, and performing a task without the correct tools or equipment. In most of these cases, the maintainer could probably have justified their actions, nevertheless the ubiquity of procedural noncompliance indicates a common divergence between formal procedures and actual task performance.

Assumption Errors
An assumption error occurs when a person misidentifies a situation or fails to check that their understanding of a situation is correct. False assumptions usually occur in familiar situations where the person has the expertise to deal with the task. In maintenance, this commonly takes the form of a misunderstanding between colleagues, such as incorrectly assuming that another person has performed a task step. Careful communication is essential for effective shift handovers, when work-in-progress is continued from one shift to another.

Knowledge-Based Errors
The term "knowledge-based error" refers to mistakes arising from either failed problem-solving or a lack of system knowledge. Most maintenance technicians enjoy variety in their work, but to achieve this, they must be assigned unfamiliar tasks from time to time. Many maintenance technicians report that they experience some level of uncertainty when performing such tasks. Ambiguities encountered during the preparation stage, such as unclear procedures, may set the scene for errors that will emerge later in the task. Supervisors must ensure that technicians are able to draw on the support of experienced personnel whenever they are assigned nonroutine or challenging tasks.

Performance-Shaping Factors in Maintenance

Although some workplace errors or deviations from procedures reflect random variability in human performance, most are related to performance-shaping factors in the workplace. Some of the most common factors in maintenance incidents are time pressure, interruptions, fatigue, and documented procedures that are inadequate for the task. Memory lapses are often associated with interruptions and fatigue; procedural noncompliance is known to occur in response to both time pressure and inadequate procedures. Assumption errors are more likely when there is inadequate communication and coordination between technicians.

A widely-recognized description of error-producing conditions in maintenance is the "Dirty Dozen" developed by Gordon Dupont at Transport Canada. The following list of 12 factors is commonly used in human factors training for maintenance technicians.

1. Lack of communication
2. Complacency
3. Lack of knowledge
4. Distraction
5. Lack of teamwork
6. Fatigue
7. Lack of resources (including documentation, parts, staffing)
8. Pressure (externally and self-imposed)
9. Lack of assertiveness
10. Stress
11. Lack of awareness
12. Norms

Interventions to Improve the Quality of Maintenance and Inspection

The remainder of this section describes several interventions that can lead to improved human performance in maintenance. These interventions are; nontechnical skills training, improved documentation and procedures, design for maintainability, fatigue management, and learning from incidents.

Nontechnical Skills Training

The International Civil Aviation Organization (ICAO), the European Aviation Safety Agency (EASA), Transport Canada, the Australian Civil Aviation Safety Authority, and many other regulatory agencies require maintenance staff to have an understanding of human factors principles. While stopping short of requiring such training, the FAA has released extensive educational material on maintenance human factors.

EASA (Part 66) requires that human factors knowledge is included among the basic initial knowledge requirements for certifying maintenance staff on commercial air transport aircraft. EASA (Part 145) requires that maintenance organizations provide regular human factors training to staff. The training is required not only for certifying staff, engineers, and technicians, but also for managers, supervisors, store personnel, and others. Human factors continuation training must occur every two years. Over 60 human factors topics are listed in the guidance material associated with the EASA regulation, including violations, peer pressure, memory limitations, workload management, teamwork, assertiveness, and disciplinary policies. The EASA human factors requirements are becoming a de-facto standard, even in regions of the world not regulated by EASA.

Improved Documentation and Procedures

According to the FAA (2012), aviation maintenance personnel spend between 25% and 40% of their time dealing with maintenance documentation. Poor documentation is one of the leading causes of maintenance incidents, and maintainers often report that procedures do not fully meet their needs (Chaparro and Groff, 2002). Documentation can be particularly challenging at MROs where technicians must switch between the maintenance procedures of different airlines.

There are some very basic aspects of document design that can have a major impact on the usability of a document. The Simplified Technical English specification developed by the AeroSpace and Defence Industries Association of Europe (2017) can help to create succinct and unambiguous text. This is particularly crucial when the reader has a first language other than English. Simplified English is used widely in the production of aerospace manuals and is now used by both Boeing and Airbus. Simplified English limits the number of words used to describe steps, and also ensures that each word only has one meaning. For example, in everyday English the word “tap” could have several different meanings including the tap above a sink, the action of removing fluid from something, or to listen in on a telephone conversation. In simplified English, “Tap” only has the meaning of to hit something, as in “tap with a hammer.”

Improving documentation is one of the most cost-effective ways to improve quality and reduce maintenance error. Maintenance organizations generally have systems to allow personnel to report problems and make suggestions for improvements in documentation. In many cases however, mechanics express frustration at the slow pace of such systems and the lack of responses to their suggestions.

Design for Maintainability

Significant improvements in cockpit design and layout have occurred since WWII. Yet the design of equipment for ease of maintenance has received less attention. Poor design is a major factor leading to maintenance problems. Examples include:

- Plumbing or electrical connections that permit cross connection
- Components that are difficult to reach, particularly where unrelated components must be disconnected to enable access
- Obstructions to vision
- Procedures that require levels of precision or force that are difficult for the technician to deliver
- Components that can be installed in the reverse sense.

Design standards such as the US Department of Defense Handbook 470-A contain numerous guidelines for maintainability, many of which have relevance to aircraft design (Department of Defense, 1997). Illustrative examples are listed in Table 2.

Table 2. Examples of maintainability guidelines

Guidelines number	Description
EC-26	Avoid using identical electrical connectors in adjacent areas.
EC-15	The removal or replacement of electronic equipment should not require the removal of any other piece of equipment.
EC-24	Use electrical connectors that incorporate alignment keyways to reduce incidence of damage due to improper engagement.
ENG (G)-12	Provide a clear and viewable access envelope to fuel and oil filters
CONT-06	Design all cables and brackets associated with cable installations so they are accessible by a 75 percentile male hand.

Fatigue Management

Aviation maintenance personnel face a heightened risk of fatigue due to night shift work, the potential for long duty times, and the sleep disruption that can result from these working arrangements.

In recent years, comprehensive Fatigue Risk Management Systems (FRMS) have been applied to aviation maintenance (FAA, 2016). An FRMS is a data driven and scientific approach to fatigue management that utilizes a range of strategies. Some of these interventions assist the individual; examples are educational material, medical screening, and treatment of sleep disorders. Other interventions are aimed at tasks. These include avoiding the scheduling of critical tasks during times of heightened fatigue risk, and keeping the most critical tasks out of the hands of the most fatigued people (progressive restriction of responsibilities). A typical FRMS will also include a statement of policy and management commitment, a risk assessment strategy, and an incident reporting and analysis system. At the core of most FRMS are limits on the working hours of maintenance personnel.

Professor Simon Folkard has developed a set of widely-adopted working hours guidelines for airline maintenance technicians. They can be found in full on the website of the UK Civil Aviation Authority (CAA). Five key items from Folkard's guidelines are:

- There should be a 12-h limit on shift duration
- No shift should be extended beyond 13 h by overtime
- A break of at least 11 h should occur between shifts
- There should be a work break every 4 h
- A month's notice of work schedules should be provided.

Learning from Incidents

Incident reports are one of the few channels for organizations to identify organizational problems in maintenance, yet the culture of maintenance around the world has tended to discourage the open reporting of maintenance incidents. This is because the response to errors has frequently been punitive. In some companies, technicians who make errors will be punished by days without pay, or even instant dismissal. It is hardly surprising that many minor maintenance incidents are never officially reported.

A growing trend around the world is to encourage incident reporting in maintenance by giving reporters limited immunity from disciplinary action or prosecution. David Marx, an aeronautical engineer and lawyer, has promoted the idea of a "just culture" in which some unsafe acts will result in discipline, however most will not. Marx divides unsafe actions of people into four overlapping categories: (1) Human error, (2) Negligence, (3) Recklessness, and (4) Intentional rule violations. Negligence is a failure to recognize a risk that should have been recognized. Recklessness is a conscious disregard for a visible significant risk.

Part 145 of the EASA regulations requires maintenance organizations to have an internal occurrence reporting scheme that enables occurrences, including those related to human error, to be reported and analyzed.

In the United States, the FAA encourages airlines and repair stations to introduce Aviation Safety Action Programs (ASAP) that allow employees to report safety issues with an emphasis on corrective action rather than discipline. Incident reports are passed to an event review committee comprising representatives of the FAA, management, and unions.

Several investigation techniques have been developed specifically for airline maintenance events. The best known is Boeing's Maintenance Event Decision Aid (MEDA) which includes a comprehensive list of event descriptors, such as "access panel not closed" and then guides the investigator in identifying the contributing factors that led to the event. Over 70 contributing factors are listed, including fatigue, inadequate knowledge, and time constraints.

Investigators typically find that major accidents are preceded by numerous minor events. Minor everyday close-calls or incidents can serve as raw materials for a safety evaluation system. An example of such an approach is the 38-item Maintenance Environment Questionnaire (MEQ) (Hobbs, 2005).

The MEQ assesses the extent of seven error-producing conditions in maintenance workplaces: Fatigue, coordination, time pressure, knowledge, supervision, availability of parts and equipment, and procedures. The MEQ can supplement incident investigations by providing a large amount of information on workplace human factors to enable comparisons with industry norms (Fig. 4).

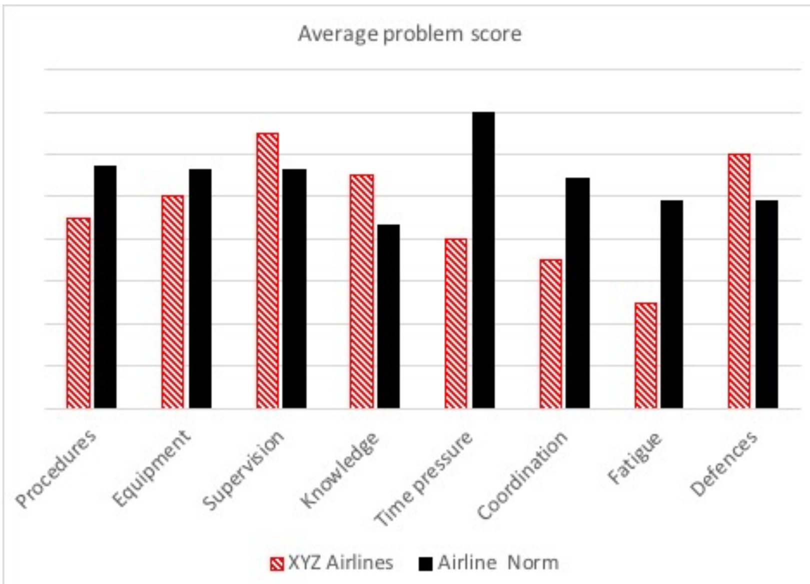

Figure 4. Example of a maintenance environment questionnaire profile.

The Future of Maintenance and Inspection

Emerging technologies have the potential to significantly change the processes involved in aircraft maintenance and inspection. Today, airline maintenance personnel routinely receive performance data from aircraft in-flight. This enables emerging problems with engines or other systems to be anticipated and diagnosed before the aircraft arrives at the gate, thereby reducing schedule disruptions.

For inspection, developments include more effective nondestructive inspection (NDI) techniques, smart materials with the ability to indicate damage through observable “bruising,” and structural health monitoring (SHM). The ability to readily transmit information over the web is enabling NDI results to be interpreted in real-time by personnel remote from the structure being examined. Several airlines are currently testing drones to assist in structural inspections. Data from permanently-placed sensors can be used as part of an SHM program. Benefits include reduced inspection times and the ability to monitor difficult-to-access areas of the airframe without the need to create access for a technician.

Despite advances in technology, the airline industry will continue to rely on the perceptual capabilities, judgment, teamwork, and communication skills of maintenance personnel. Airline travel is now the safest mode of transport. Part of the reason for this is that the industry has continuously learned and applied knowledge from the field of human factors to maximize the performance of maintenance personnel and drive down the rate of maintenance error.

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