DEVELOPMENT OF A STRATEGY TO ENHANCE HUMAN-CENTRED DESIGN FOR MAINTENANCE

RAeS Human Factors: Engineering Sub-Group Project

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A Royal Aeronautical Society Report

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Contact

For further information or to discuss the contents of this paper, please contact:

+44 (0)20 7670 4362
communications@aerosociety.com
https://www.aerosociety.com/news-expertise/policy-public-affairs
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Glossary

AAIB	Air Accidents Investigation Branch
AMC	Acceptable Means of Compliance
APU	Auxiliary Power Unit
ATSB	Australian Transportation Safety Board
CAA	Civil Aviation Authority
CIEHF	Chartered Institute of Ergonomics and Human Factors
CHIRP	Confidential Human factors Incident Reporting Programme
CS	Certification Specification
DFM	Design for Manufacture
DO	Design Organisation
EASA	European Union Aviation Safety Agency
FAA	Federal Aviation Administration (United States)
GM	Guidance Material
HFDS	Human Factors Design Standards
HFG:E	Change to Human Factors Group: Engineering Sub-Group
ICA	Instructions for Continued Airworthiness
MAA	Military Aviation Authority
MEMS	Maintenance Error Management System
MOR	Mandatory Occurrence Report
MRO	Maintenance, Repair or Overhaul Organisation
OEM	Original Equipment Manufacturer
RAeS	Royal Aeronautical Society
SSA	System Safety Assessment
TC	Type Certificate
TCH	Type Certificate Holder (usually, but not necessarily, the design organisation for the product which is the subject of the Type Certificate)
UK CAA	United Kingdom Civil Aviation Authority

STRUCTURE OF THIS REPORT.

This report comprises 12 chapters, and considers the experience of maintenance errors in aviation. The work already complete, and the initiatives taken to date, are reviewed and the impact that these have had are reviewed. The report then considers each of the key areas that are considered to be most relevant to human-centred design for maintenance, including education, training, professional and academic standards, design organisation practices, design organisation regulation, and certification standards. Where considered appropriate, further action is recommended based upon the findings and observations made.

To assist in the development of this report two Mind-Maps were generated. The first set out to identify the major issues to explore, while the second identifies the areas in which it is considered that action can be taken to help improve human-centred design for maintenance. These two mind-maps are included for reference in Appendix A.

Introduction

Maintenance error continues to be a root cause of aircraft accidents, incidents and many operational disruptions such as delays, air turn backs and diversions. In the five-year period between 2013 and 2018, 14% of the total number of worldwide aviation industry insurance claims were related to 'faulty workmanship/maintenance'.

While initiatives such as Maintenance Error Management Systems (MEMS) and mandatory human factors training for maintenance engineers have been introduced, it is clear that, on their own, they are not delivering the required improvement in safety performance: additional, more effective action is required. This additional action needs to focus on the initial design of the aircraft: ie human-centred design for maintenance. This could be interpreted to be understood that it should be easier to get it right than to get it wrong.

The importance of addressing the subject of human performance in aircraft design has already been recognised in the context of flight crew and much has been done in this area. Since the flight-deck design requirements have accepted that the design has to accommodate realistic human performance/error, it is incongruous that no similarly comprehensive design requirements exist for design to avoid maintenance error. It is readily accepted that aircraft design must account for other factors external to the aircraft, such as weather, atmospheric changes, and bird-strike, and there is clearly a need also to address human performance in maintenance activities.

This report summarises the work already completed, and assesses the impact that this has had by looking at recent accident and incident data. The report then reviews each of the key areas that are considered to be most relevant to human-centred design for maintenance, including education, training, professional and academic standards, design organisation practices, design organisation regulation, and certification standards. Where considered appropriate, further action is recommended based upon the findings and observations made.

Where the term 'maintenance error' is used in this report it should be read that the maintenance as actually conducted was different from the way in which it was intended for the task to be completed. That is to say that the 'work-as-done' deviated from the 'work-as-imagined' by the designer, maintenance organisation and indeed sometimes by the maintainers directly involved. In addition, the 'work-as-prescribed' (as set out in the technical manuals or procedures) may also have differed from the 'work-as-imagined'. It is recognised that maintenance is a dynamic environment and that error occurs due to weaknesses in the system of maintenance, not simply due to individual error by the maintenance engineer at the front line.

On this latter point, it is clear that there is a need to improve communication between design and maintenance organisations. There exists an opportunity to develop better mechanisms to ensure feedback from maintenance to design, and vice versa, that will help minimise the potential for maintenance error.

CHAPTER 1

Context and Problem Statement

CONTEXT

For over two decades studies have concluded that maintenance engineers can err in the course of their work, exploring the factors influencing their performance, the prevalence of such error and the consequences. The RAeS's Human Factors Group: Engineering conducted a review in 2011 which summarised the trends of these studies including the prevalence of error during installation and the finding that some areas of the aircraft including equipment and furnishings, powerplant, landing gear and flying controls appear especially vulnerable to error (Simmons, 2011). Since this study, analysis of UK CAA Mandatory Occurrence Reports, voluntary and mandatory reports in the European Central Repository, reports in the UK-MEMS database and in the Aviation Safety Network's Accident Database and Skybrary's Accidents and Incidents database shows that maintenance error still occurs and no significant change can be identified in either the prevalence of error or the influencing factors.

As awareness of maintenance human factors and maintenance error grew, action was taken by regulators, operators and Maintenance, Repair, and Overhaul Organisations (MRO) however, most of this action has been focussed on changes in the maintenance environment to improve maintenance engineer awareness such as *The Dirty Dozen* (UK CAA, 2002), *Training for Engineers* (EASA, 2014, 2015a, 2015b), *Just Culture* (Reason, 1997), and the Introduction of Maintenance Error Management Systems, or MEMS (UK CAA, 2020). However, detailed analyses of maintenance errors in civil accidents and incidents show that aircraft design, procedures, tooling and documentation are often found lacking.

These studies illustrate that the way that maintenance engineers actually conduct maintenance (so-called 'work-as-done') can deviate significantly from the assumptions made by the design engineers on how maintenance should be conducted ('work-as-imagined') and how the procedures are written by the OEM's technical authors ('work-as-prescribed'). This gap is all too often exposed only by accident and incident investigations following errors made by maintenance engineers, illustrating that there are currently no effective means to eliminate this gap. This gap, between design intent and maintenance practice, is often created both by a lack of awareness on the part of design engineers of the way maintenance is actually conducted, and by the need to maintain aircraft effectively and efficiently under time pressures, often in difficult environmental conditions. Understanding this gap can yield considerable value, identifying improvements which could be made and, when this is done pro-actively, we can learn much to help drive improvements in the system. This philosophy of learning from everyday work is becoming established as an important technique in safety practice (Hollnagel, 2018). In addition, the engineering System Safety Assessment (SSA) assumes that the human actions on the system are always performed correctly, and does not integrate the likelihood that human error will occur within a 'Total System' risk assessment. The safety analysis assumes human actions are always correct although the data tells us this is not so. Therefore, a gap exists between the OEM's assumed human reliability and the realistic human reliability that appears in the data (and is still likely a conservative picture).

Equally, action by the OEM can be the most effective means of addressing the risks associated with this gap, and changing design is the only means by which such risks can be prevented (Gill, 2009). If action cannot be taken to prevent the error (ie eliminate the error potential or the consequences), then it may be possible for the OEM to reduce the likelihood or consequences of the error or improve detection and recovery. Examples include making sure items can only be fitted one way, baulking similar electrical plugs that are in close proximity, and providing unambiguous fitting instructions, can be directed at areas of significant risk. This can be achieved using studies highlighting aircraft systems/areas that are at particular risk, or those systems which have an increased likelihood of hazardous consequences if errors occur[1]. Previous studies have shown there is economic justification for addressing those maintenance tasks which bear the greatest elements of risk to safety.

Aircraft are designed to meet a customer specification which can be hugely complex, but usually contains elements of safety, performance, fuel consumption,

(1) Note that CS-E already focuses on hazardous outcomes. However, other, 'Major' outcomes still occur too frequently.

weight, environmental impact, payload/range, cost etc. The final design will often be a compromise to meet all the elements of the specification, although safety is not negotiable. Maintainability is also in the specification, but it can appear lower down the priority list than other more fundamental elements such as initial cost and performance. Yet the cost of poor maintainability caused by inadequate design can be substantial, in terms of both safety performance and financial cost. Ideally, aircraft would be designed so that maintenance wasn't necessary ('Don't do maintenance'), and indeed, this is an approach taken by the space industry as their products are rarely accessible after launch. However, it is recognised that space and aviation operate in different environments and this may not be a practicable solution for aviation. It is therefore necessary to consider how best to minimise both the need for maintenance, and the potential for maintenance errors.

An analysis in 2010 by a large UK engine manufacturer of in-service safety and reliability data over a 15-year period covering circa 2000 engines determined that maintenance human factors were a causal factor in 12% of the reliability events and 9% of the safety related events on a large engine fleet, resulting in an estimated cost impact of $67m (Eccleston, 2010). This cost estimate was based on a set of standard costs for each type of event, such as in-flight shut down, diversion, aborted take-off etc. and took no account of the associated maintenance costs. Design changes were made to eliminate 35% of the safety related human factor maintenance events and manual wording changes made on 25% of those events.

Analysis performed by the UK CAA of thousands of audit findings of Part 145 organisations, gathered over 6 years, (UK CAA, 2019) showed 40% of findings were due to failure to follow a procedure or process, with a significant proportion down to ambiguous procedures. This represents a significant opportunity for improvement to technical publications.

Data from Statista show that, over the period from 2013 to 2018, 14% of the total number of worldwide aviation industry insurance claims were related to "faulty workmanship/maintenance" (Statista, 2021).

It was not possible to obtain accurate data related to the cost of this 'faulty workmanship/maintenance'. Such information, of the true cost to the aviation industry of failing to enhance human-centred design for maintenance, would be valuable in helping to quantify the magnitude of the problem and in setting the priority of appropriate remedial action.

Clearly a drive to raise awareness of these types of events in the design and technical publications communities, with an aim to eliminate them, will have measurable cost and safety benefits. However, being realistic, we should not expect any changes we propose to design activities will have instant results. Typically, aircraft have a 30-to-40-year service life and some aircraft have a 50-year production run, so changes to designs can take a long time to feed through to in-service statistics, unless they are safety related and mandated by airworthiness authorities on existing, in-service aircraft.

Unless a focus can be kept on the motive for changing the designers' priorities, and an emphasis placed on the safety and operational cost elements, there will be no reduction in occurrences of maintenance errors.

Figure 1

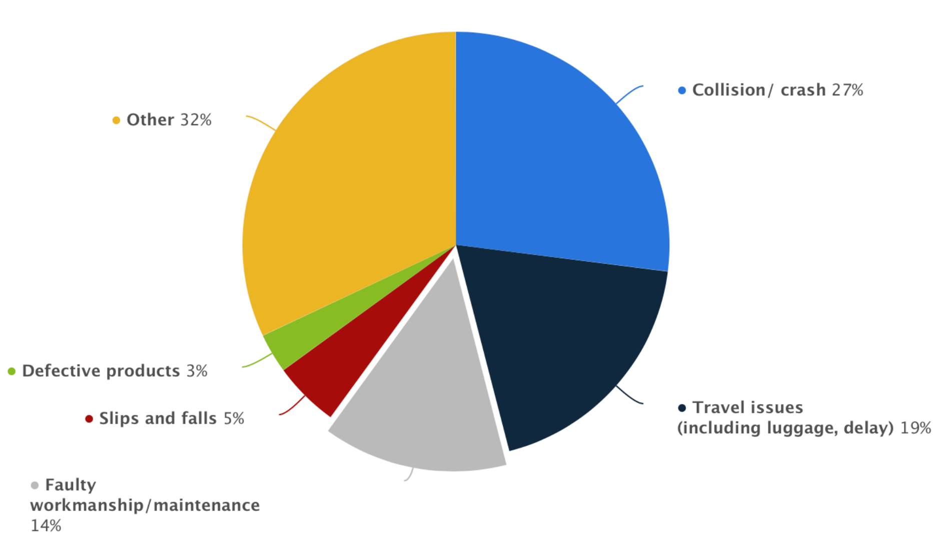


Figure 1. Distribution of aviation insurance industry claims worldwide from 2013 to 2018, by number of claims. (Statista 2021)

IMPACT ACROSS THE LIFECYCLE

Human-centred design for maintenance should be applied at all stages of an aircraft lifecycle from initial design of a new concept airframe, detailed design, changes during operational life, mid-life updates and so on. In practice the action taken by the design organisation is different according to the lifecycle stage:

● **Design Concept**
Maintenance human factors is most effectively integrated in early aircraft design. However, with limited awareness within the design community, it is necessary for human factors professionals, maintainability engineers or designers with HF training to champion HF in initial design stages. This is not always easy to achieve because HF, with a subjective output, is a difficult concept to communicate especially when compared to more quantitative concepts such as weight and aerodynamics. Flight Deck Human Factors specialists have had success here and their methods should be emulated. Support from senior management is critical at this stage.

Boeing appoints a Chief Mechanic to champion maintenance from initial stages of a new design. "Every mechanic – at Boeing and at the airline – has asked themselves at some point what the designers were thinking because they don't always make it easy to do required tasks… My job is to be the voice of the customer and the voice of the factory mechanic… I keep that voice present for our engineering team as they create new designs." (Radtke, 2020)

● **Detailed Design**
As the design progresses trade-offs become more acute and changes more expensive. Illustrating human factors weaknesses or opportunities to improve HF becomes ever more important.

Interrogation of the digital prototype by maintainability engineers, for example, allows quick changes to design concepts to optimise maintenance performance. In the design of the Bell Helicopters 525 Relentless, human factors software was used to model various maintenance scenarios for the 20th percentile female and 95th percentile male mechanic to perform common maintenance procedures to identify opportunities for improvement (Donner, 2015).

● **In-service Analysis**
While still in design it is obviously not possible to know exactly what maintaining the aircraft will be like. However, once in service, feeding back insights from those actually maintaining the aircraft is critical to identifying and rectifying unforeseen issues but also supporting continuous product improvement. Unfortunately, feedback of design, documentation and tooling issues to the OEM is not always easy.

HeliOffshore, the offshore helicopter safety body, runs workshops to share good practice and identify areas of potential improvement related to offshore helicopter maintenance. Engineers with direct experience of maintaining a particular aircraft work with the designers of that aircraft to learn from the everyday work of maintenance focussed specifically on safety-critical maintenance tasks.
(HHA-Standardised-Approach-v1.pdf (squarespace.com)

Good Practice

Boeing appoints a Chief Mechanic to champion maintenance from initial stages of a new design.

Consideration of human-centred design throughout the lifecycle is critical as many aircraft can be operating for up to 50 years. Emphasis must be placed on early design work but further initiatives throughout the lifecycle maximises our opportunities to optimise maintenance.

CONCLUSIONS

Maintenance error continues to occur in both civil and military aerospace, costing millions of pounds each year. The exact cost is difficult to determine and more accurate costs would help the industry focus on designing out the need for maintenance, or making it simpler and less error-prone.

Recommendations

1.1 It is recommended that the RAeS works with its corporate partners, and particularly those in the aviation insurance business, and other organisations as necessary, to establish the actual cost to the industry of 'maintenance errors'.

1.2 It is recommended that the RAeS works with its corporate partners to identify examples of good maintenance instructions and where improvements can be made to serve as illustrations for the industry discussion on improving documentation. Examples given for a specific OEM could be shared with that OEM including the maintenance engineer's comments on the nature of the difficulty.

PROBLEM STATEMENT

How do we improve aircraft human-centred design for maintenance?

(*How do we make it easier to get it right than to get it wrong?*)

CHAPTER 2

Body of Evidence

Since an early study by Graeber and Marx (1993, cited in UK CAA, 2002) into maintenance occurrences with a human factor element, over the past few decades a considerable body of evidence on maintenance error has been established. In 2011 the HFG:E commissioned an internal report (Simmons 2011) to summarise maintenance error data collected from multiple sources including the Confidential Human factors Incident Reporting Programme (CHIRP), the UK CAA, the Australian Transportation Safety Board (ATSB), Boeing, Airbus, the UK's Military Airworthiness Authority, MIRCE Akademy, NASA Air Safety Reporting System (ASRS), FAA 'Root Cause Analysis' and Defence Aviation Hazard Reporting & Tracking System (Australia).

Common themes were identified in this report:

- Certain areas of the aircraft appear especially vulnerable to error – Equipment and furnishings (ATA 25), powerplant (combining ATA 71-80), Landing gear (ATA 32) and Flying controls (ATA 27) (CAA, 2009; CHIRP, 2011; MAA 2010, Owen, Nicholas & Gill, 2006);
- Installation errors are predominant, listed in the top three of the errors reported in all studies (Hobbs & Williamson, 2002; Airbus, 2008; CAA 2009; CHIRP, 2011, Hobbs & Kanki, 2008, Owen, Nicholas & Gill, 2006, Owen, Nicholas & Gill, 2006)
- Errors are dominated by knowledge-based and rule-based errors (Hobbs & Williamson 2002; Hobbs & Kanki, 2008)
- Some of the studies highlight the contribution of violations, accepting that this is not just an issue of personal culpability but are "often organisationally induced or even encouraged". FAA (1999) identified the impact of the pressure placed upon maintenance engineers to complete the task, resulting in well-intentioned violations, and their consequences.
- There are common contributing factors. Pressure; Equipment deficiencies; Training; Fatigue and circadian effects and co-ordination between workers (ATSB, 2001; Hobbs & Williamson 2002).
- The cost of maintenance error is publicly completely undocumented, although some studies do indicate the cost of events (eg inflight turn back) of which the origin could be maintenance error.

Within the period considered by the report, very few of the studies specifically consider issues related to design organisations. However, a few of note are:

- Patankar and Taylor (2001) found that of the 939 cases studied, 459 were due to organisational factors and the top two of these were: procedures or information quality and aircraft design/configuration of system or quality of parts.
- Hobbs & Kanki (2008) highlighted procedure problems as one of the most common contributing factors.
- Owen (2005) found task support (documents and parts/spares) and aircraft design to most frequently correlate with maintenance occurrences.
- The most frequent contributing factor reported in Owen, Gill and Nicholas (2006) was Task Support. Considering this in more detail, the most frequently reported were Aircraft and/or Aircraft system – Aircraft Maintainability, Procedure – Inadequate and Procedure – Ambiguous/confusing.

The HFG:E report of 2011 also contained a number of recommendations however, it appears that these have not been taken forward. See Appendix to Chapter 2 for these recommendations.

Case Study

Airbus A321-211, G-POWN, 26 FEB 2020. Both engines on the aircraft malfunctioned after the aircraft fuel system was overdosed with Biocide. The maintenance engineer did not understand the term 'ppm', meaning parts per million, and his calculations were not independently checked. The investigation concluded that a contributory factor was the Aircraft Maintenance Manual (AMM) did not provide enough information to enable maintenance engineers to reliably calculate the quantity of Kathon required. In addition, it was concluded that 'Subsequent troubleshooting used the wrong part of the manual'.

Air Accidents Investigation Branch, 2021

In the decade since this report was published a number of studies have continued to look at the issue. These include:

- Hieminga J and Turkoglu C (2018) analysed 1232 incidents from the European Central Repository (ECR) between January 2012 and December 2016 consisting both mandatory and voluntary reports.
- The UK CAA (2015) explores the maintenance error in 1896 large aircraft MORs between 2005 and 2011 and 584 MEDA events from the UK-MEMS database for 1998 to 2006.
- Insley J and Turkoglu C (2018) analysed 112 aircraft maintenance-related accidents and serious incidents for CAT category aeroplanes between 2003 and 2017 identified in the Aviation Safety Network's (ASN) Accident Database and SKYbrary's Accidents and Incidents database.
- UK CAA (2019) is a guide developed by the airworthiness industry which starts with an analysis of over 8,000 audit findings by CAA Surveyors on Part 145 Organisations between 2012 and 2018. The report focussed on how organisations can write better procedures.
- HeliOffshore (2020) is a unique study of gaps between 'maintenance-as-done' in offshore helicopter maintenance and 'maintenance-as-imagined' by designers in the OEM and 'maintenance-as-prescribed' by the support engineers writing procedures. This is a proactive analysis of critical maintenance tasks focusing specifically on design-related issues.
- Gill (2021) outlines a number of recent studies into decision-making in aviation maintenance.
- CHIRP (2021) outlines analysis of the General Aviation reports received in the first six months of 2021 including discussion of system design.

These studies show that some of the report's findings have not changed.

- Error during installation is still predominant.
  - ◊ In Hieminga J and Turkoglu C (2018) 361 incidents occurred during installation of components (29%) and 308 incidents were related to maintenance control (25%).
  - ◊ In UK CAA (2015) the most frequently reported error was installation error in the MOR dataset (44%) and in the UK-MEMS dataset (37%).
  - ◊ In HeliOffshore (2020) 59% of identified potential errors relate to installation and 39% relate to inspection.
- The same areas of the aircraft are showing as being vulnerable.
  - ◊ In UK CAA (2015) the most vulnerable ATAs in the MOR dataset were ATA 25 Equipment/ Furnishings (14%), ATA 71-80 Combined Powerplant (12%) and ATA 32 Landing Gear (8%).
- Documentation is still a significant contributing factor. In HeliOffshore (2020), documentation was the most frequently cited contributing factor, followed by special tooling.

However, studies are looking in new areas too. Deviation from procedures is one area which has received more detailed study. The UK CAA (2019) study found that 40% of the 8,000 audit findings on Part 145 Organisations undertaken by CAA surveyors between 2012 and 2018 were attributed to a failure to follow procedure or process. Looking at this more closely, almost a third of the CAA findings identified as failure to follow procedures were categorised with root causes in which the approved data was found to be ambiguous, incorrect, unavailable or where the incorrect version of data was being used for the task, suggesting that the approved documentation probably was followed, but it was incorrect (Evans, 2019). This suggests potential for improvements within the design organisation.

Case Study

Saab 340B, ES-NSD suffered a loss of control of engine RPM, which was found to be caused by a chafed cable near to the gear box. Investigation revealed that chafing protection was installed incorrectly and that the SB to relocate a chafing relief stand-off bracket wasn't embodied (this SB was not mandatory). The AAIB noted that there were a number of ways to install the chafing protection incorrectly.

Air Accidents Investigation Branch, 2021

Good Practice

A major UK engine manufacturer does not rely upon inspections or amended procedures to address safety related maintenance errors identified in service, but adopts a policy of changing the design to eliminate the problem.

Deviation from procedures by maintenance engineers has been recognised for many years:

- 80% of maintenance engineers reported doing a job a better way than in the manuals (Australian Transport Safety Bureau, 1997)
- 79% of maintenance engineers admitted to making errors that they picked up themselves, 50% to making errors that were detected by supervisors (Fogerty et al, 1999)
- 64% of maintenance engineers reported finding their own way of performing a procedure (McDonald et al, 2000)
- 34% of surveyed maintenance engineers had failed to perform official task procedures (Chaparro et al, 2002)
- 41% of respondents agreed that there are always better ways of doing a task than that described in the maintenance publications (Bannister-Tyrrell, 2020)
- 60% of participants indicated they had done a task a better way than that specified in maintenance documents within the past six months (Bannister-Tyrrell, 2020)

Many deviations can be viewed as positive, with a view to achieving a more efficient, effective or safer outcome. Bannister-Tyrrell (2020) concludes that in many cases the engineer does so without formal organisational approval, either because they believe they have the authority to do so or have the competency to make the judgment. Organisational and personal norms support this behaviour, enabled by a belief that their organisation values innovation. In addition, Bannister-Tyrrell (2020) found that maintenance engineers very often demonstrate innovation mindsets – 75% of engineers feel no conflict in approaching a technical maintenance task in an innovative way, 78% that they are an innovative maintainer and 90% having a strong belief in their technical ability enabling them to identify innovative maintenance solutions. The challenge for the industry is to harness such innovation without it impacting safety, developing a safe space for innovation, taking advantage of this but identifying and managing the resulting risk.

Exploring why maintenance engineers choose to deviate from procedures is critical. Maintenance is not a binary activity and engineers are subject to many factors which can influence their performance. However, research by Bannister-Tyrrell (2020) shows that contributing to such a decision is the belief that maintenance manuals are sometimes wrong and can be misleading. 'Concern was expressed by interviewees regarding errors and omissions and, cross-referencing anomalies when multiple publications were intended to contain the same information, and also language translation issues, incomplete amendment incorporation, and occurrences of too little, too much, or perceived irrelevant information.' (Bannister-Tyrrell, 2020, p.255). Further, although 82% of engineers agree that the process to amend manuals is clear to them, it was perceived as long, difficult and frustrating to achieve change by 51% and there is a lack of feedback during the process (Bannister-Tyrrell, 2020).

Case Study

Shortly after take-off the engine on the Breezer B600 stopped due to a loss of fuel pressure and the pilot made a forced landing which resulted in a heavy touchdown. The engine stoppage was probably caused by a fuel restriction when a placard blocked the fuel tank outlet. The fuel tank outlet was not fitted with a strainer or filter as none was required by the regulations for a 'Light Sport Aeroplane' (LSA). The AAIB recommended that EASA amend CS-LSA to require a fuel strainer and that the American Society for Testing and Materials (ASTM) amend the 'Standard Specification for Design and Performance of a Light Sport Airplane' (ASTM F2245) to require the installation of a strainer at the fuel tank outlet. Proactively, the aircraft manufacturer published a Safety Alert to check the fuel tank for foreign objects, has introduced checks in the assembly process to ensure that the placard on the fuel sender is removed prior to installation and has taken safety action to install a fuel strainer at the fuel tank outlet of all new aircraft and is offering the same modification for retrofit.

Air Accidents Investigation Branch, 2021

Good Practice

HeliOffshore (www.helioffshore.org) conducts Human Hazard Analysis workshops involving helicopter OEM design engineers and operator maintenance engineers to proactively identify gaps between maintenance-as-done, maintenance-as-prescribed and maintenance-as-imagined.

In the first six months covered by the latest General Aviation CHIRP reports, 7% had 'systems design' as a key factor in the report (CHIRP, 2021).

The authors of this report felt it valuable to explore the body of evidence since 2010 further, especially in relation to design- related issues. It was decided that the source of the data to be analysed would be events investigated by the Air Accidents Investigation Branch (AAIB). Although this focussed only on events where safety was compromised or threatened, the public availability and quality of the investigation reports

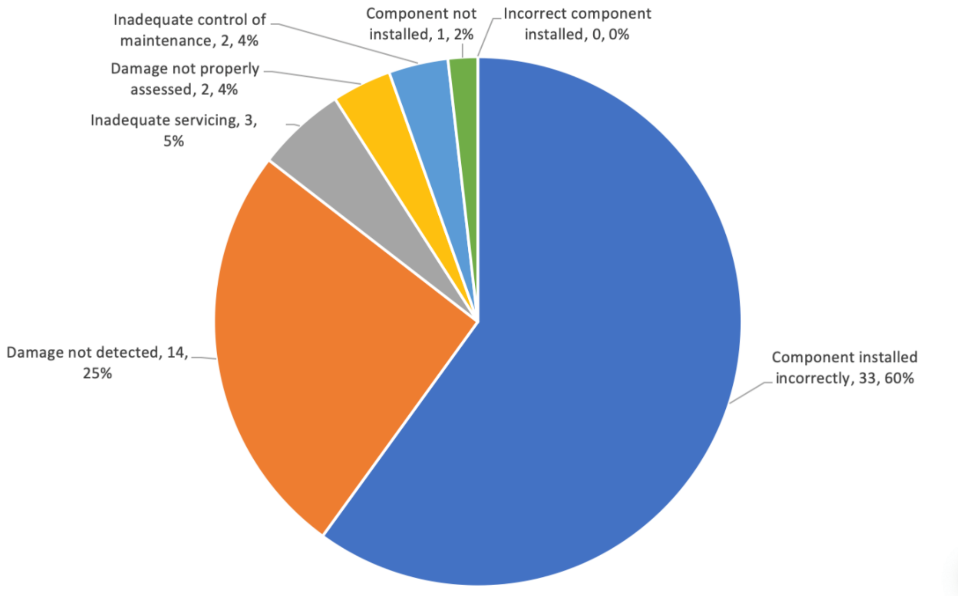


Figure 2 Type of Maintenance Error identified in the analysis of AAIB Reports.

would enable us to explore the issues and extrapolate results. Data from the AAIB's database were reviewed by an AAIB Inspector using the following criteria:

- Event date: On or after 01/01/2010
- AAIB report: already published
- AAIB report synopsis containing any of the following words/phrases:
  - ◊ Maintenance
  - ◊ Improperly assembled
  - ◊ Incorrectly assembled
  - ◊ Installed incorrectly
  - ◊ Incorrectly installed
  - ◊ Was not fitted
  - ◊ Overhaul

It should be noted that it cannot be guaranteed that the final analysis by the authors was conducted on an exhaustive list as some events may not have been captured under the keyword search. Equally the AAIB Inspector did also include some events which met the overall criteria but were not revealed in the keyword search. However, it is considered by the authors that this represents an indicative dataset which includes reports from all sectors of the industry, including general aviation, helicopters, small and large transport among others. Note that this excluded events involving uncrewed aircraft. The output included published reports from differing levels of AAIB investigation including: correspondence investigations (generally lower-level investigations for which limited information may be available); field investigations for which an AAIB team has generally deployed to undertake a complete investigation; and formal investigations, the highest level of investigation.

The authors used a common taxonomy of maintenance error to classify the events. They identified 55 events which involved maintenance error (with three events involving more than one error). During the period under review there were approximately 2,442 events investigated by the AAIB (excluding those involving uncrewed aircraft) for which the published reports were available. Events involving maintenance error therefore represent 2% of the total number of events in this period. Analysis of the event consequences reveal that on average, across the 2,442 events, 3% were classified by the AAIB as incidents (n=5), 15% as serious incidents (n=20) and 83% as accidents (n=32). For the 55 events involving maintenance error, 9% were incidents, 35% serious incidents and 56% accidents. This analysis therefore suggests that while maintenance error is a low contributor to aviation incidents and accidents in terms of overall numbers, when it does occur it leads to incidents and serious incidents at comparable rates. In addition, it is the authors' considered opinion that the event data significantly underestimates the frequency of maintenance error: the low number of events illustrates the success of the aviation system in detecting or mitigating their effects: eg, maintenance action detecting errors with potential safety consequences, and flight crew action in mitigating consequences. Finally, the events in question often represent situations in which more serious consequences were only narrowly avoided.

Of the 55 identified maintenance errors, 60% were 'Component installed incorrectly' with the next frequently reported being 'Damage not detected'

(25%). This is shown in Figure 2. Considering the aircraft category, 44 were fixed wing, 10 were rotary wing, 2 were microlights and 1 was in the lighter-than-air category. Figure 3 shows the frequency of maintenance error events by type of aircraft.

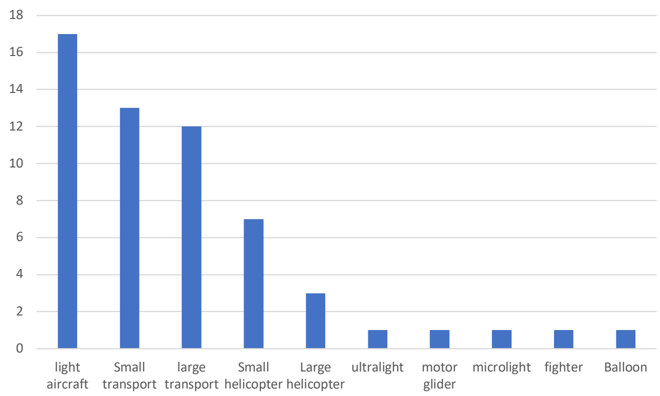


Figure 3. Frequency of maintenance error events by type of aircraft.

In the published reports for the 55 identified events, the AAIB made 33 maintenance-related recommendations (which were directed to the design organisation, the MRO, the operator, the regulator, or an industry body). Of these, to date 17 actions were taken by design organisations to address issues raised by these investigations (determined from either the investigation report itself or in a subsequent AAIB Annual Safety Review). Figure 4 presents an overview of this, showing the different types of organisations to which the recommendations were addressed.

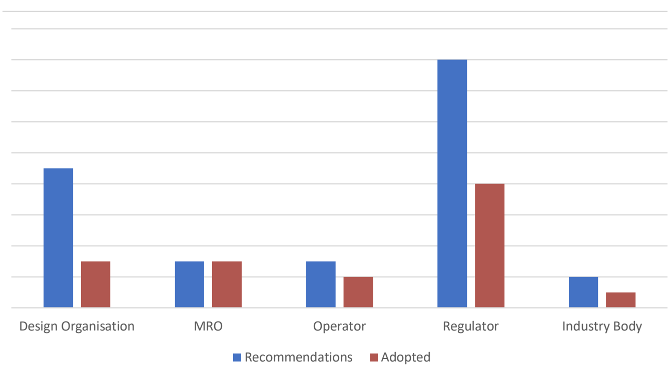
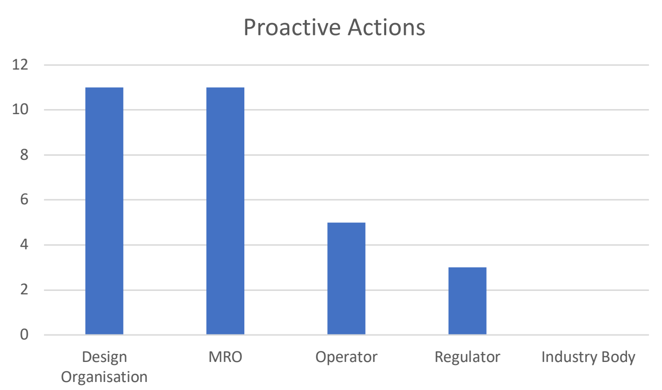


Figure 4. Comparison of maintenance-related recommendations *vs* those adopted.

Evident from Figure 4 is the large discrepancy between the adoption rate of both design organisations and regulators against recommendations addressed to these groups. Design organisations have a 33% adoption rate vs a 50% adoption rate for regulators. It should be noted however that this is a 'snapshot' in time and the process of accepting individual safety recommendations may not have been complete at the time this analysis was conducted.

This however, isn't the full story. It was noted that on many occasions, organisations proactively took action to address a safety issue when a recommendation wasn't made. Indeed, it may be because of this proactive action that the need for any safety recommendations was negated. The number of cases where proactive action was taken is shown in Figure 5.



Case Study

Shortly after take-off the aircraft (a Cessna 172M) exhibited a tendency to pitch nose down despite the application of NOSE UP trim. During the subsequent approach to land, the forces required to maintain the approach path increased to the point where the pilot could no longer control the glidepath and the aircraft struck the ground short of the runway. The investigation found that the drive chain for the elevator trim actuator had been fitted incorrectly, which resulted in the elevator trim tab moving in the opposite sense to the movement of the trim wheel. The maintenance organisation has introduced procedures to ensure that duplicate inspections of all flight critical systems are carried out following maintenance.

Air Accidents Investigation Branch, 2021

CONCLUSION

Studies of incidents and accidents over the past 30 years, and new analysis of AAIB reports for this report, consistently reveal weaknesses in the system of maintenance, and the prevalence of errors during installation. It is clear that the action taken by the industry focusing on the maintenance engineer has failed to address maintenance error nor the originating challenges. There remains a gap between maintenance-as-imagined, maintenance-as-prescribed and maintenance-as-done. Any remedial action taken is on a tactical, reactive basis and little is being done proactively by design organisations to address this strategically. Although such analyses provide useful data it is critically important that we move our attention from just looking back at what has failed (ie event data) and start to consider what can be learned from what has been successful (ie adaptation of maintenance practice). This so-called 'Safety-II' approach can help the industry to identify weaknesses of the system, support robust assessment of these issues and in the development of effective interventions.

Recommendations

2.1 Training on the EASA database should clarify how users should apply the 'Event Type' taxonomy. This appears to be used inconsistently, with users rarely selecting the more detailed fourth level of the taxonomy, severely restricting the level of detail available from the data (Hieminga J and Turkoglu C, 2018).

2.2 Users of the EASA database should be encouraged (or mandated) to use the narrative section of the database and use English as standard to increase the usefulness of the collected data (Hieminga J and Turkoglu C, 2018).

2.3 Analyses of maintenance events should be conducted at least every three years to identify trends and offer insight to the industry to allow appropriate remedial action to be taken.

2.4 The industry should consider the concept of 'innovative violation' in addition to the typical violation taxonomy, adding to the generally accepted routine, optimising, situational, exceptional, and unintentional violations (Bannister-Tyrrell, 2020).

2.5 Design organisations should be required to critically evaluate existing (and new) maintenance tasks, especially in critical areas of the aircraft or engine where failure could lead to hazardous or catastrophic effects (using processes like Human Hazard Analysis outlined in Gill (2021)).

2.6 Design organisations should consider where improvements may be made in the information feedback process so that potential improvements to maintenance and overhaul manuals may be readily reported, assessed and, where appropriate, implemented. The feedback process should include staff from the maintenance organisation(s), the OEM's design office, and the technical authors of the instructions for continued airworthiness. This should be driven by the senior management of the organisations to ensure that it is given due priority.

2.7 The industry should be encouraged to explore alternative feedback mechanisms to facilitate the efficient and effective sharing of ideas and innovations by maintenance personnel through their own organisations and to the OEM.

2.8 Research should be undertaken on how the industry can embrace a Safety-II approach to explore successful adaptation by maintenance engineers, why such adaptations are required and what interventions could be made to improve safety.

CHAPTER 3

Education

INTRODUCTION

Education is a formal learning process which, in the UK, takes place in Primary schools, Secondary schools, Colleges and Universities. Students are typically able to choose their own learning path at colleges and choose a specialist subject to study at college and University.

Professionals involved with the design and maintenance of aircraft typically take one of two routes into the profession:

1. An apprenticeship. Entry criteria are typically Secondary school or college level qualifications and apprentices undertake practical on the job training alongside formal education. An apprenticeship typically lasts for 3 years.
2. A graduate programme. Entry criteria is typically a Bachelors or Masters level university qualification. Graduates are typically integrated into the workplace over the course of a 1 or 2-year programme and are assigned a workplace mentor.

Both these routes into the profession could be via a broad-range of subjects – for example, a graduate could typically have studied Mechanical, Electrical or Aeronautical Engineering.

APPRENTICE EDUCATION

Professionals educated as apprentices will typically have their learning tailored around the job for which they are training. Apprenticeships are built around so called 'Apprenticeship Standards' of which there are 871 in the UK to date. There is limited scope for deviating from these agreed Apprenticeship Standards.

Thus, professionals educated as apprentices will typically have an in-depth knowledge of the 'hands on' practical aspects in which they were initially trained, but will have limited knowledge about other practical aspects of design.

GRADUATE EDUCATION

Professionals educated as graduates will typically have a learning programme which is heavily theoretical, and cover mechanical, structural, aerodynamic and avionic aspects but don't typically cover human factors as either compulsory or optional modules.

Thus, professionals educated as graduates will typically have a breadth of knowledge of these aircraft performance subjects, but not subjects related to human performance or maintainability.

PROFESSIONAL BODY ACCREDITATION

As well as being accredited by national standard bodies, apprenticeships and university programmes can be accredited by professional bodies such as the Engineering Council, the Royal Aeronautical Society, Institute for Engineers and Technicians, Institute for Mechanical Engineers and Chartered Institute of Ergonomics and Human Factors (CIEHF).

According to CIEHF there are just 9 Human Factors degrees currently accredited in the UK today, all MSc courses, none of which are currently (November 2021) accredited by the Engineering Council. This compares to 83 Aeronautical degrees and over 1000 Mechanical degrees accredited by the Engineering Council.
The Engineering Council publishes an accreditation handbook used by engineering education providers and engineering institutions all over the world. It focusses on learning outcomes and was compiled with stakeholders from the engineering profession and employers. The teaching of Human Factors is not required to meet the accreditation standard.

BLENDING SPECIALISMS INTO EDUCATION

There is plenty of evidence of educational institutions blending wider specialist subjects into their degree programs. Many universities now offer modules such as Availability, Reliability and Maintainability (ARMs), Risk Analysis and Flight Testing as optional modules.

To date, few universities offer Human Factors modules outside of a formal Human Factors degree programme. There are a few exceptions; for example, Cranfield University offers a Human System Engineering module as part of its Systems Engineering MSc and City University offers an optional Human Factors module in their Aviation masters programmes.

Good Practice

In 2012, the University of Twente (Netherlands) worked with industry to publish a 'Design for Maintenance Guidelines to enhance Maintainability, Reliability and Supportability for Industrial products.' Whilst not involving aviation, this is a good example of how industry and academia can work together to improve maintenance.

It should be noted that a recent article in the Journal for Petroleum Technology (JPT) shows that this problem is not just isolated to the aviation industry and makes the case for educational institutions to explore ways of promoting HF content into curriculums (Nazaruk, 2021).

CONCLUSIONS

Future generations of aviation professionals are fed into industry against defined curricula. Although some institutions have made efforts to educate the next generation with Human Factors awareness, there is no widespread effort to do so.

For professionals following the vocational route into industry, their parent companies have an opportunity to embed an awareness of HF issues relevant to their own niche industry, and to influence the academic side of the apprenticeship.

For professionals following the graduate route; only a select number of universities offer Human Factors modules as part of an engineering degree programme. While there is evidence that universities are blending specialisms into their curricula, more engagement is needed to encourage the integration of Human Factors into these degree programmes.

There is no widespread effort to incorporate Human Factors principles into graduate or apprentice education routes. If industry and academia want to contribute to improved human-centred design, there needs to be a more concerted effort to incorporate Human Factors principles at these levels.

Recommendations

3.1 It is recommended that Professional engineering bodies work together to highlight the importance of engineers having an awareness of human factors.

3.2 It is recommended that Professional engineering bodies actively encourage Universities offering engineering degrees to expand their curricula to include human factors. This could take the form of optional modules, but should be considered mandatory for aeronautical engineering courses.

3.3 It is recommended that Professional engineering bodies encourage and accredit engineering degrees with human factors content.

3.4 It is recommended that action be developed to ensure that apprenticeship programmes within aerospace design organisations include human factors within both the vocational and academic content.

3.5 It is recommended that Professional engineering bodies take steps actively to promote the need for engineering apprenticeship standards to include appropriate human factors within both the vocational and academic content/learning objectives.

3.6 It is recommended that Professional engineering bodies take steps actively to promote the need for college engineering courses to include human factors modules for students that may enter the engineering profession without undertaking an apprenticeship or graduate programme.

3.7 It is recommended that the RAeS HFG:E, in conjunction with the Society's Young Persons Network, produce some digestible 'bite size' human factors material, such as short videos or illustrations, aimed at university engineering students, and send links to university lecturers, inviting them to show the material.

CHAPTER 4

Training

While there are mandatory requirements in place for maintenance engineers to undertake initial and two-yearly refresher courses on human factors, there are no such provisions for design engineers. Consequently, there is almost a total absence of training material for design engineers on the subject of human-centred design for maintenance. While some companies may provide some training in this area, it is by no means common practice across the industry.

One of the biggest challenges related to the practical implementation of human-centred design for maintenance is the lack of awareness among engineers, health, safety, and environment (HSE) professionals, and front-line employees of Human Factors. HF is poorly understood and does not yet yield the full potential that the practical insights and actions can produce. There is a common misconception that HF skills are solely for frontline employees and once suitably trained their behaviour will change and performance will improve. This approach rests on the belief that the behaviour of frontline operators is the source of all problems, which it is not.

Human factors is a discipline that requires professional competency. It covers many topics from design to leadership to decision making and contains diverse schools of thought. To advance HF, the awareness of HF needs to be raised at every level, including supervisors and senior managers. However, there are several barriers which are slowing down progress:

TRAINING COURSES

Parts of Industry recognise the importance of HF and several organisations are advancing various HF topics. Those efforts undertaken by various bodies are being advanced in silos without industry-wide collaboration. Human factors is often seen as something separate from engineering work, education and even from safety activities. There is a clear need to integrate HF principles into the curricula of engineering and safety degrees and continuing professional development programmes.
It can be said that although all engineers should have some background in HF, some may need to have a deeper understanding while others may need to know the general principles and how to integrate the skills and knowledge of an HF professional into their work. Therefore, it is reasonable to assume that all engineering graduates should have a baseline of understanding regarding HF principles, methods, applications, and the risks associated with not considering HF when designing systems and interfaces. By knowing how people work and respond, engineers are able to come up with much better solutions. Teaching HF as a foundational part of engineering degrees would allow students to join companies well equipped to deal with the challenges ahead of them. Having a better understanding of human behaviour and the interaction among people, equipment, and processes will provide a more holistic approach to managing safety.

In principle, it would seem that requiring an introductory-level course in HF would suffice although the HF content of an engineering programme could be adjusted to the requirement of the graduate.

Specific HF training courses are available, such as those accredited by The Chartered Institute of Ergonomics and Human Factors. Their list of courses does not include any that are specifically targeted at engineers within a design organisation but as many are delivered by HF consultancies, it is likely that they would be able to customise the content. Other industry bodies are conducting training for designers including HeliOffshore, an international organisation with a remit to improve safety of offshore helicopters, with a membership of helicopter operators and manufacturers. In response to demand from the manufacturers they have run workshops bringing design engineers together with maintenance engineers, and developed and delivered training to designers, managers and maintainability engineers of four helicopter OEMs and other organisations with design approval.

The military is more proactive than civil regulators when it comes to training. In the UK the Military Aviation Authority (MAA) has a mandatory requirement for design organisations to put in place a Human Factors & Safety Management System training module for all its design staff (RA1440).

CONCLUSIONS

There is clearly an issue that 'human factors' means something different in different aviation domains. Pilots often refer to 'human factors' as their Crew Resource Management (CRM) training. This divergence of what HF means is one of the issues that doesn't help industry-wide integration, and undermines the associated training needs. It needs to be recognised that all these aspects spring from the same root, and should be considered as an integral part of the mainstream disciplines, and not as something separate: perhaps as part of the 'Total System' approach.

Recommendations

4.1 It is recommended that action be taken to introduce, in Part 21 subpart J, or other relevant regulation, requirements making initial and refresher human-centred design for maintenance training mandatory for all staff in design organisations.

4.2 It is recommended that design organisations produce some digestible 'bite size' human factors material, such as short videos or illustrations, aimed at design engineers, highlighting the impact and importance of effective human-centred design for maintenance.

CHAPTER 5

Professional Standards

INTRODUCTION

This section considers the UK's professional and educational standards and requirements for aerospace and aviation engineers. It explores the requirements for professional registration, and the educational learning objectives as they relate to understanding human factors, and how the risks associated with human errors may be mitigated through design considerations and maintenances practices.

Competence is the ability to carry out a task to an effective standard. To attain competence the individual needs to acquire the right level of knowledge, understanding and skill, and a professional attitude. Competence is developed by a combination of formal and informal learning, and training and experience, generally known as initial professional development. However, these elements are not necessarily separate or sequential and they may not always be formally structured.

This review therefore looks separately at the requirements for Professional Competence, and Occupational Competence.

PROFESSIONAL COMPETENCE, AND REGISTRATION

The Engineering Council is the regulatory body for the UK engineering profession, and is responsible for setting and maintaining internationally recognised standards of professional competence and commitment. Professional registration is open to all engineers and technicians who can demonstrate competence and commitment to perform professional work to the necessary standard.

The standards are published in the UK Standard for Professional Engineering Competence and Commitment (UK-SPEC), which sets out the competence and commitment required for registration as an Engineering Technician (Eng.Tech), Incorporated Engineer (I.Eng) or Chartered Engineer (C.Eng). It also includes examples of activities that demonstrate the required competence and commitment.

Anyone wishing to be registered must apply through one of the professional engineering institutions licensed by the Engineering Council. Institutions can provide advice about the process and typical timescales for the review. The assessment process is known as a professional review. The process starts with an application made in accordance with the requirements of the chosen institution. Any claim of qualifications, experience or training needs to be supported by formal, documented evidence. When submitting details, applicants will need to show how this relates to the required competences and commitment.

There are five generic areas of competence and commitment for all registrants, which broadly cover:

1. Knowledge and understanding
2. Design and development of processes, systems, services and products
3. Responsibility, management or leadership
4. Communication and inter-personal skills
5. Professional commitment

The Standard was most recently updated in 2020, with the fourth edition published in August 2020 for implementation by 31 December 2021. It must be acknowledged that the Standard covers the professional competence and commitment across all engineering sectors: eg civil, mechanical, nuclear, electrical, aerospace etc.

Nevertheless, it is notable that there is a complete absence of any requirements relating to the development of any awareness, appreciation, or an understanding of human factors. This would appear to suggest that human factors is not a significant issue in other engineering sectors (eg civil, mechanical and nuclear engineering), but it is considered that this is highly unlikely to be the case in reality. Further work is necessary to establish the extent to which human error is a concern in engineering disciplines other

than aerospace, and whether there is a case for the Standards to be revised accordingly.
In the context of reviewing human-centred design for maintenance, this report will only review the generic area of knowledge and understanding.

Knowledge and understanding are important components of professional competence. Formal education is the usual, though not the only, way of demonstrating the necessary knowledge and understanding, and the following qualifications exemplify the required knowledge and understanding for Incorporated Engineers and Chartered Engineers:

- An accredited Bachelor's degree with honours in engineering or technology, plus either an appropriate Master's degree or Engineering Doctorate (EngD) accredited by a professional engineering institution, or appropriate further learning to Masters level (for CEng); or
- An accredited integrated MEng degree (for CEng); or
- An accredited Bachelors or honours degree in engineering or technology (for IEng), or
- a Higher National Diploma or a Foundation Degree in engineering, or technology, plus appropriate further learning to degree level (for IEng), or
- an NVQ4 or SVQ4 which has been approved for the purpose by a licensed professional engineering institution, plus appropriate further learning to degree level (for IEng).

Applicants without exemplifying qualifications may demonstrate the required knowledge and understanding in other ways, and increasingly, workplace learning is contributing to this. However, this route is not discussed any further here. This section will only review courses that are at Bachelor level and above. The Engineering Council website provides searchable databases of accredited programmes at this level, with over 7000 courses accredited. A small, random sample of courses was reviewed, and the results of this are provided in the table in the Appendix to Chapter 5.

As can be seen, this report only relates to research on courses that are accredited by the Institution of Engineering Designers (IED) and The Royal Aeronautical Society (RAeS) and concentrates in the subject areas of:

- Aerospace Engineering
- Mechanical Engineering
- Product Design

Within these courses, very few modules were found to cover the relationship between design and a maintenance error and even then, the relationship is tenuous.

When looking for a course with the title related to human factors in aviation maintenance, only one was located, that being a 5-day course at Cranfield.

OCCUPATIONAL COMPETENCE

The standards for occupational competence are set out by different organisations in a variety of documents. These include the apprenticeship standards, and the licensing requirement for a maintenance engineer's licence. For the purposes of this exercise the engineering apprenticeship standards, and the licensing requirements prescribed in the EASA's Part-66 were reviewed.

The apprenticeship standards are published by the Institute for Apprenticeships and Technical Education. The Institute is an employer-led organisation, sponsored by The Department for Education, and supports employer groups in the development of the apprenticeship standards. It maintains the occupational maps which underpin all technical education, and develops, approves, reviews and updates apprenticeships and technical qualifications with employers. This includes responsibility for implementing an approval process for higher technical qualifications.

The following apprentice standards were reviewed:

- ST0010 Aerospace Engineer – Degree (Level 6)
- ST0456 Post-Graduate Engineer (Level 7), and
- ST0457 Engineering Technician (Level 3)

In addition, it was noted that a new standard, ST0785, is currently under development by the Institute of Apprenticeships and Technical Education. This standard is for a Human Factors Specialist at Level 6 (Degree). A copy of the latest draft of this new standard was obtained and it was noted that the subject of human-centred design for maintenance was not included. Moreover, the subject of maintenance was not addressed at all. The fact that this standard is still underdevelopment provides an opportunity to influence its final content.

ST0010. This standard is designed and intended specifically for engineers 'Creating aircraft components and equipment, specialising in a specific engineering discipline (for example – airframe, design and stress, systems integration, support engineering or manufacturing engineering)'. It contains no requirements relating to human factors.

ST0456. This standard is for those 'Developing innovative solutions to complex technical engineering problems'. It contains no requirements relating to human factors.

ST0457. This standard is for engineering technicians 'Designing, building, servicing and repairing a range of engineering products and services'. It covers a range of roles, including for example, Engineering Technician, Aerospace Technician, Aviation Engineer, Maritime Engineering, Machinist, Mechatronics Engineer and Toolmaker, and identifies specific knowledge and skills for each of these roles. The standard does prescribe the need for skills enabling applicants 'to apply human factors in aviation – attitudes and behaviours to ensure aviation safety', however, these are set out as requirements for only two of the roles covered by the Standard, namely: Aircraft Maintenance Fitter/Technicians (Fixed and Rotary Wing), and Airworthiness, Planning, Quality and Safety Technicians. The first of these is clearly a maintenance only role. The second is primarily maintenance orientated but may exist to a limited extent in a design organisation.

It can therefore be seen that the apprentice occupational standards address the subject of human factors only (or primarily) in regard to aircraft maintenance activities. As with the professional standards, this would suggest that human factors is not seen as a significant issue in engineering disciplines outside of aerospace and aviation. Furthermore, it also strongly suggests that human factors in aviation is primarily regarded as an issue only for aircraft maintenance. Clearly these are false conclusions and there is a need to engage with other engineering disciplines to address human factors as a specific issue early on in the careers of apprentice engineers.

The requirements to obtain an aircraft maintenance engineer's licence are set out in Regulation (EU) No 1321/2014, Annex III, Part 66. These contain very detailed requirements with regard to maintenance engineers having a basic knowledge of human factors, with two learning modules (9A and 9B), depending upon the type of licence.

PROFESSIONAL ENGINEERING INSTITUTIONS

Issues that professional engineering institutions could become actively involved in are:

- The lack of standardisation across the industry related to HF. It would be beneficial if there were a common set of concepts, principles, practices, standards, and tools across all industries.
- The absence of guidance on what should be taught and how to teach it
- The need to explore how to integrate HF topics into existing accreditation frameworks.
- The need to provide a learning map to support engineering graduates to fulfil minimal requirements for HF.

INDUSTRY RECRUITMENT

At the moment, investing effort into developing HF knowledge does not appear to make a difference when searching for a job after graduation. Industry could incentivise the need for engineering students to learn a solid foundation of HF in their education. Engineering graduates should indicate HF knowledge on their curricula vitae, and employers should express interest in graduates having HF knowledge as a job prerequisite.

In the meantime, Industry can develop awareness of HF in practice (eg through learning modules to increase competence and capability).

CONCLUSIONS

This review has found that neither the engineering professional nor the occupational standards require any knowledge or skills in human factors for aerospace design engineers. It has also established that such requirements exist only for those involved directly in aircraft maintenance and, even then, it is occupational standards alone that prescribe a need for knowledge of human factors.

The review has also shown that the requirements applicable to the issue of an aircraft maintenance engineer's licence do require a detailed understanding of human factors and how these can affect the work being undertaken, and the safety of the aircraft.

Recommendations

Note: Recommendations on apprentice standards, university degrees and college courses are addressed in Chapter 3.

5.1 It is recommended that the RAeS engage with the Institute of Apprenticeships and Technical Education to ensure that the new apprentice standard, ST0785 “Human Factors Practitioner” contains appropriate requirements for human-centred design for maintenance.

5.2 It is recommended that the RAeS work with the Engineering Council to amend the UK Standard for Professional Engineering Competence and Commitment (UK-SPEC), so that it includes appropriate, relevant human factors standards.

5.3 It is recommended that the RAeS engage with other, non-aerospace, engineering disciplines to address human factors as a specific issue early on in the careers of apprentice engineers.

5.4 It is recommended that the RAeS consider taking a leading role in developing professional seminars on the subject of human-centred design for maintenance. Such seminars could be counted towards the continued professional development of design engineers.

CHAPTER 6

Design Organisations

INTRODUCTION

Design Organisations (DOs) are approved by civil certification bodies to design aircraft and their associated components. DOs can also act as Type Certificate Holders (TCHs) in which role they apply to the civil certification bodies to approve the design of an aircraft, engine or Auxiliary Power Unit (APU) against a set of airworthiness requirements (known in Europe as 'Certification Specifications' (CS)). These are typically CS-23 for small aircraft and CS-25 for large aircraft, and CSs 27 and 29 for small and large rotorcraft. These are explored in Chapter 7.

Design Organisations are approved against the requirements set out in Part 21 subpart J.

This section provides an overview of the certification process used by DOs along with the DO's responsibilities as written down in 21J. A brief exploration of other sectors is included for comparison.

DESIGN ORGANISATION APPROVAL

Design organisations in the UK are approved by the UK CAA. All European Union based design organisations are approved by the European Aviation Safety Agency (EASA). As of March 2021, the CAA had provided no guidance on design organisation approval however, the EASA has published and kept current Acceptable Means of Compliance (AMC) and Guidance Material (GM) to their Part 21. It should be noted that, in the United States there is a different approval regime whereby the FAA does not delegate approval to Design Organisations.

Most relevant to maintenance human factors is that part of Part 21 which prescribes the need for there to be a reporting system in place between the operators and maintainers of an aircraft, and the TC holder. This system enables operators and maintainers to feed-back safety issues to the TC holder (among these being maintenance issues). The TC holder then has the responsibility to analyse the reported issues and to act on the reports appropriately.

It is important to note that the in-service reporting system does not automatically go to the regulator for analysis, and the TC holder ultimately makes the decision about whether to implement corrective action.

In the introduction to its GM document (GM 21.A.3B(b)), when determining an 'unsafe condition' the EASA states that: 'the aircraft is assumed to be maintained in accordance with the prescribed instructions for continued airworthiness (or maintenance programme), etc.' This statement makes a precedent then for Design Organisations to be able to assume that the aircraft is maintained in accordance with the Instructions for Continued Airworthiness (ICA) and makes no allowance for systems failing safe, being error proofed or any human-centred design for maintenance.

In paragraph 2.5 of this section, preliminary guidance is provided for human centric design for maintenance, but it admits that 'human factors techniques are under development'.

Subpart J to Part 21 includes the AMC and GM for design organisations. In this, Section 3.15 presents the required considerations for maintenance. While it includes the requirement for ICAs, it does not specify what they should contain or indicate the required level of detail.

Good Practice

One manufacturer of small transport aircraft communicates to operators every six months 'Human Factors Induced Events in Maintenance'. This describes events which have been attributed to maintenance human factors issues along with cautions on how such events may be prevented. They also encourage the reporting of such events.

HUMAN FACTORS GUIDANCE FOR DESIGN ORGANISATIONS

The EASA and the FAA do not generally provide any detailed guidance on design for maintenance, although, a detailed AMC is provided for maintenance and checks of Thrust Reversers (Ref AMC 25.933). This is probably in response to the Lauda Air disaster (May 1991).

The FAA does provide a Human Factors Design Standard (HFDS), while this provides good guidance, its content covers the basic principles of ergonomics and anthropometry, but doesn't cover more advanced aspects such as training, fatigue, error proofing etc. In addition, the document doesn't specifically cover the human factors surrounding maintenance, but is more of a generic guide.

The UK CAA published CAP 715 and CAP 716 (in 2002 and 2003 respectively) as an introduction to, and as guidance for Part 145 maintenance organisations. While these two guides provide good guidance for Part 145 organisations, they are not written for design organisations, and don't provide guidance for avoiding human error through design.

IN SERVICE REPORTING AND ACTIONS

AMC No 2 to 21.A.3A(a) describes how a TC or STC holder can maintain a system where operators and maintainers of aircraft can report issues that may affect airworthiness. This AMC further lays out a defined risk profile in terms of probability of a catastrophic event within which TC and STC holders must put in place rectifying action:

1×10^{-7} for 2.5% of the aircraft's life; or

5×10^{-7} for 0.5% of the aircraft's life; or

1×10^{-6} for 0.25% of the aircraft's life; or

1×10^{-5} for 0.025% of the aircraft's life; or

Figure 6. AMC No 2 to 21.A.3A(a) defined catastrophic risk profiles.

AMC 20-8 lays out a taxonomy for reporting organisations to classify their reported incidents. Section II D of this taxonomy is specifically for Human Factors incidents. And Section III is for maintenance incident.

While this section of the taxonomy is good, the previous section described how the EASA advises DOs to assume that maintenance is carried out as described in the ICAs. Caution should be taken with this approach however, as it is implicit from the GM that it may be assumed that maintenance is carried out correctly with no apparent consideration of the potential for error: there is an inherent motivation for the DO to follow the GM advice and not investigate the incident thoroughly.

If a DO is allowed to assume that maintenance is performed correctly, this reduces the effectiveness of the defined risk profile of AMC No.2 to 21.A.3A(a). When an accident or incident occurs on an aircraft, the immediate response by the DO can often be a once around the fleet inspection to determine if an unsafe condition exists on other aircraft of the same or similar type. This is sometimes made mandatory by the airworthiness authorities.

This can be followed by regular, frequent, fleetwide inspections or parts changes which are required to maintain acceptable levels of safety. Each of these inspections or part changes represents a very small risk in terms of Human Factors Maintenance error, but cumulatively on a large worldwide fleet over a long time period can be a significant safety risk and maintenance burden.

One large engine manufacturer has had a safety policy for some time that prevents long term frequent inspections being used to manage a safety issue. The policy requires a modification to be developed that removes the need for those inspections, thus removing the human factors risk of repeated inspections.

HUMAN FACTORS IN OTHER SECTORS

Maintenance

AMC2 145.A.30(e) requires that Maintenance Organisations (MOs) provide both initial Human Factors training and ongoing training for its maintenance staff. In addition, the Guidance Material to this (GM 1 145.A.30(e)) defines a 10-part Human Factors training programme. While this 10-part programme may not be directly applicable to a design organisation, it is notable that EASA mandates it for a Part 145 applicant, but NOT for a Part 21J applicant.

Manufacturing

The manufacturing sector in general has good guidance on 'Design for Manufacture' (DFM). For example, 'Product Design for Manufacture and Assembly' (Boothroyd, 1994) provides detailed design guidelines for manual assembly, assembly efficiency and minimising handling time, among others. (See Figure 7 for an example)

While the driving factor of DFM is reducing cost through:

(i) Improving quality
(ii) Reducing rework
(iii) Reducing complexity
(iv) Reducing time to build

The first three principles are directly related to improving aircraft human-centred design.

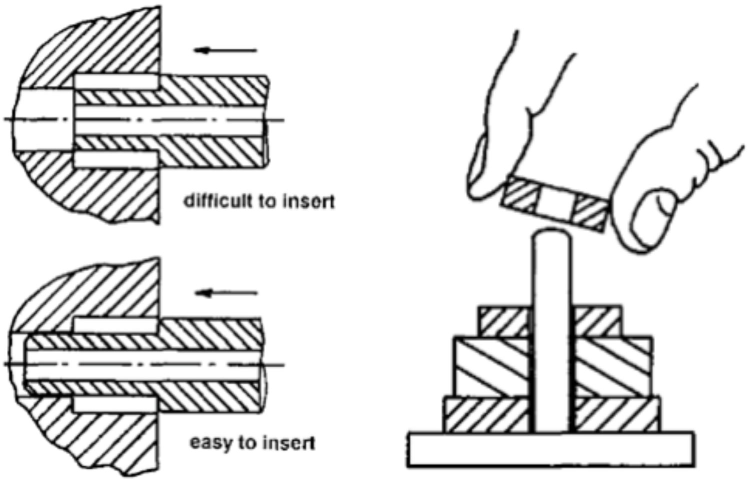


Figure 7. Tapered shafts and pyramid assembly, just two examples of the principles presented in *Product Design for Manufacture and Assembly*.

2.01	**Accessibility**
2.02	**Fasteners**
2.03	**Human Factors**
2.04	**Mating and Connections**
2.05	**Standardization and Interchangeability**
2.06	**Simplification**
2.07	**Modularization**
2.08	**Testability and Diagnostics Technique**
2.08.01	System Testability Design
2.08.02	System/Subsystem BIT/BITE
2.08.03	Module Level Testability Guidelines
2.09	**Module BIT/BITE**
2.09.01	General BIT
2.09.02	General BIT Techniques
2.10	**Inherent Testability Design Checklist**
2.11	**Preventive Maintenance**
2.11.01	Environmental Factors
3.01	**Connections**
3.01.01	Plumbing, Hoses, Fittings, & Quick Disconnects
3.01.02	Wiring, Connectors, & Fiber Optics
3.01.03	Coaxial Connectors & Wave Guides
3.01.04	Control Rods, Cables, & Controlex Concept
3.02	**Power**
3.02.01	Engines (Gasoline & Diesel)
3.02.02	Engines (Turbine-driven)
3.02.03	Transmissions, Clutches, & Rotors
3.02.04	Auxiliary, Secondary, & Emergency Power
3.02.05	Gear Boxes & Drives
3.02.06	Exhaust Exits, Nozzles, & Outlets
3.02.07	Inlets & Inlet Ducts
3.02.08	Electrical
3.03	**Structure**
3.03.01	Radomes
3.03.02	Drains & Vents
3.06	**Avionics & Electronics**
3.06.01	Antennas, Apertures, & Sensors
3.06.02	Communications, Command & Control
3.06.03	Computers
3.06.04	Power Supply
3.06.05	Information Systems
3.07	**Environmental Control, Air Conditioning, and Pressurization**
3.07.01	Oxygen Systems
3.08	**Armament & Explosives**
3.08.01	Armor
3.08.02	Weapons, Guns, Flares, Chaff, & Cannon
3.08.03	Cartridge Actuated Devices, Shaped Charges, Detonating Cord, & Pyrotechnic Devices
3.09	**Fluid Systems**
3.09.01	Fuel Systems, Tanks, Containers, Pumps, Trucks, & Bladders
3.09.02	Pneumatic Systems & Pumps
3.09.03	Hydraulic Systems, Tanks, Pumps, Accumulators, & Reservoirs
3.10	**Wheels & Related**
3.10.01	Tracks
3.10.02	Wheels, Tires, & Brakes
3.10.03	Landing Gear & Alighting Gear
3.10.04	Skids & Floats
3.10.05	Hooks & Catapults
3.11	**Personnel Equipment**
3.11.01	Oxygen Systems, Masks, Controls, & Containers
3.11.02	Personnel Protective Garments & Equip
3.11.03	Flotation Equipment
3.11.04	Parachutes

Figure 8. Part of the taxonomy for design guidelines presented in MIL-HDBK-470A.

A technique developed by Shigeo Shingo, in post-war Japanese car manufacturer Toyota, Poka Yoke is defined as 'mistake-proofing' or 'inadvertent error prevention'. It is a popular technique in lean manufacturing as it aims to prevent incorrect operation and hence reduce waste and time to manufacture. Examples include the colour coding of connectors, keying of components, supplying a kit of parts, interchangeability of common parts, standardised units of measurement, special tools to standardise processes.

DEFENCE

In the UK, the Military Aviation Authority (MAA) issues design organisation approvals to organisations in a similar manner to the CAA and the EASA in the civil sector. As part of the MAA's approval process, there is a mandatory requirement for a design organisation to put in place a Human Factors & Safety Management System training module for all its design staff (RA1440). From personal experience these sessions are good, and do embed a 'design for the human' mindset.

Good Practice

The MAA requires design organisations to put in place a Human Factors and Safety Management System training module for all their design staff

That said, the Defence Standards of the UK provide no guidance on Design for Maintenance; although Def-Stan 00-45 advocates for a Maintenance Analysis team to review the proposed maintenance schedule, not only in terms of timeliness, but also the entire content including logistics, technical content and human factors.

In the US, MIL-HDBK-470A (See Figure 8 for an extract) acknowledges that there is a knowledge gap in the Design for Maintenance. It advocates for Design Organisations to set up so called 'Expert Systems' – essentially a knowledge base of design best practice. In addition, Appendix C provides detailed guidance for Design for Maintenance. While this guidance is good, it is defence focussed and wouldn't be directly applicable to civil aviation.

MIL-HDBK-759 & 1472 provide guidance for Design for Maintainability, but the focus is on ease and speed of maintenance, rather than minimising error, again defence focussed.

In the UK, Def Stan 00-251 and associated technical guides (UK MOD, 2016) cover issues regarding the physical aspects of design, eg Handle size, Access panel shape, Positioning of gauges, Accessibility etc.

CONCLUSIONS

There is a lack of rigour in the civil aviation design sector when considering human-centred design for maintenance. There is no widely used, accepted or known guidance for designers to use when designing for maintenance, and no training is required to inform them of even the basic principles of human factors.

The current development process and ongoing monitoring for maintenance programmes assumes that no errors are introduced during maintenance. There is no widely used, accepted or known guidance for designers to use when designing for maintenance, and no training is required to inform them of even the basic principles of human factors.

The EASA's AMC 20-8, 'Occurrence Reporting' requires TC holders to implement an in-service reporting system. While it includes a section dedicated to maintenance and human factors there is no detailed guidance as to how that system should be designed or operated. It is ultimately the TC holder's responsibility to decide whether or not reported issues require further action.

The EASA has put in place a defined human factors curriculum for maintenance organisations to implement while the manufacturing sector has detailed guidance around DFM which could be applicable to the design sector. Lastly the defence sector is cogniscent of the problem, and is making an effort to address it through the use of mandatory training and design handbooks. While the efforts put in place by defence organisations is not directly applicable to the civil sector, they represent an opportunity for learning.

Recommendations

6.1 It is recommended that action be taken to initiate rule-making activity for Approved Design, Production, Maintenance and Training Organisations, so that these organisations are required to:

(a) Ensure all relevant staff undertake training in human-centred design for maintenance,

(b) Incorporate human-centred design for maintenance in their safety reporting systems

(c) Report human-centred design for maintenance related events to the responsible Design Organisation (ie Type Certificate Holder), and ensure that suitable, effective corrective action is taken to prevent recurrence of such events.

6.2 It is recommended that action be taken to develop specific guidance for Approved Design Organisations on the subject of human-centred design for maintenance.

6.3 It is recommended that action be initiated to develop and publish specific guidance (ie a human-centred design handbook) for designers within design organisations. This guidance should include human-centred design for maintenance. The guidance could use, and build upon principles already contained in Design for Manufacture or the Mil-HDBKs.

6.4 It is recommended that guidance be created for, or by design organisations to support the introduction of systems and processes which ensure human-centred design for maintenance is included in aircraft design.

6.5 It is recommended that Regulators review the implicit assumption that aircraft maintenance is carried out with no allowance for error.

6.6 It is recommended that Regulators further develop the human-centred guidance material for Paragraph 2.5 of GM 21.A.3B(b).

6.7 It is recommended that Regulators provide more detailed guidance for the in- service safety reporting system described in AMC 20-8.

6.8 It is recommended that Design Organisations be required to incorporate human-centred design for maintenance in their in-service safety reporting systems.

6.9 It is recommended that Design Organisations be required to train staff in relevant human factors, and design for maintenance.

6.10 It is recommended that Regulators consider introducing mandatory requirements for human factors and design for maintenance training for approved design organisations.

6.11 It is recommended that Regulators audit the in-service reporting systems in place at TCHs, thus checking the correctness of action taken against human factors and maintenance issues.

6.12 It is recommended that a candidate issue paper be raised against MSG-3 to introduce a human-centred design analysis step in the process.

CHAPTER 7

Certification Requirements

INTRODUCTION

Within the European civil aviation sector, the design requirements for products and appliances are set out by the European Aviation Safety Agency in their *Certification Specifications*, (CS). The CS for Large Aeroplanes (CS-25), Normal-Category Aeroplanes (CS-23), Large and Small rotorcraft (CS-29 and CS-27 respectively) and Engines (CS-E) were reviewed to establish whether, and to what extent, these certification requirements recognised and addressed the need to minimise or eliminate the potential for maintenance error in the design considerations.

For each certification project, the EASA establishes teams of certification experts, grouped into 'Panels'. The composition of, and specialist knowledge required for these panels were also reviewed with regard to human factors in design.

Finally in this section, the EASA's 'European Aviation Safety Action Plan (EPAS)' sets out the current and emerging issues (risks) to aviation safety, and the interventions being taken to address these issues. The current EPAS was reviewed to determine whether any interventions have been initiated to address the potential threats posed by maintenance error and how these might be mitigated through design practice.

The findings from this review are summarised below.

CERTIFICATION SPECIFICATIONS FOR ENGINES: CS-E

There are a number of requirements in CS-E which address the subject of maintenance errors and the need to address this through appropriate design. These are:

CS-E 110 (d) "Turbine Engine parts, the incorrect assembly of which could result in Hazardous Engine Effects, must be designed so as to minimise the risk of incorrect assembly or, where this is not practical, permanently marked so as to indicate their correct position when assembled."

CS-E 110 (e) "As part of the system safety assessment of CS-E 50(d), the possibility and subsequent effect of incorrect fitment of instruments, sensors or connectors must be assessed. Where necessary, design precautions must be taken to prevent incorrect configuration of the system."

CS-E 250 (e) "Design precautions must be taken against the possibility of errors and inadvertent or unauthorised changes in setting of all fuel control adjusting means."

CS-E 510 (e)(1) "If the acceptability of the safety analysis is dependent on one or more of the following items, they must be identified in the analysis and appropriately substantiated.

(1) Maintenance actions being carried out at stated intervals. This includes the verification of the serviceability of items which could fail in a dormant manner. When necessary for preventing the occurrence of Hazardous Engine Effects at a rate in excess of Extremely Remote, the maintenance intervals must be published in the airworthiness limitations section of the instructions for continued airworthiness required under CS-E 25. If errors in maintenance of the Engine, including the Engine Control System, could lead to Hazardous Engine Effects, appropriate procedures must be included in the relevant Engine manuals."

AMC E 510 (3)(h) "Reliance on maintenance actions.

For compliance with CS-E 510(e)(1) it is acceptable to have general statements in the analysis summary that refer to regular maintenance in a shop as well as on the line. If specific Failure rates rely on special or unique maintenance checks, those should be explicitly stated in the analysis.

In showing compliance with the maintenance error element of CS-E 510(e)(1), the Engine maintenance manual, overhaul manual, or other relevant manuals may serve as the appropriate substantiation. A listing of all possible incorrect maintenance actions is not required in showing compliance with CS-E 510(e)(1). Maintenance errors have contributed to hazardous or catastrophic effects at the aircraft level. Many of these events have arisen due to similar incorrect maintenance actions being performed on multiple engines during the same maintenance availability by one maintenance crew, and are thus primarily an aircraft-level concern. Nevertheless, precautions should be taken in the Engine design to minimise the likelihood of maintenance errors. However, completely eliminating sources of maintenance error during design is not possible; therefore, consideration should also be given to mitigating the effects in the Engine design.

If appropriate, consideration should be given to communicating strategies against performing contemporaneous maintenance of multiple engines.

Components undergoing frequent maintenance should be designed to facilitate the maintenance and correct re-assembly.

The following list of Engine maintenance errors was constructed from situations that have occurred in service and have caused one or more serious events:

◊. Failure to restore oil system or borescope access integrity after routine maintenance (oil chip detector or filter check). Similar consideration should be given to other systems.
◊. Mis-installation of, or failure to refit, O-rings,
◊. Servicing with incorrect fluids,
◊. Failure to install, omitting to torque, under-torquing, or over-torquing nuts.

Improper maintenance on parts such as discs, hubs, and spacers has led to failures resulting in hazardous engine effects. Examples of this which have occurred in service are overlooking existing cracks or damage during inspection and failure to apply or incorrect application of protective coatings (eg anti-gallant, anti-corrosive)."

CS-E 560 (g) "Design precautions must be taken against the possibility of errors and inadvertent or unauthorised changes in setting of all fuel control adjusting means."

AMC E 560 (5) "In complying with CS-E 110(d), because a fuel leakage is considered as a potential fire hazard, design precautions should be taken to minimise the possibilities of incorrect assembly of fuel system components, including pipes and fittings, especially if parts of the system have to be removed during the routine maintenance procedures."

AMC E 560 (9) "CS-E 560(g) is intended to cover any likely changes in settings caused by vibrations, incorrect maintenance, mechanical interference when installed or during handling, etc. Examples of design precautions are: locking devices, sealing, inaccessible installation."

OBSERVATIONS ABOUT CURRENT CS-E PROVISIONS

1. There are no requirements relating to design considerations for maintenance error for piston engines, aside from CS-E 110 (e) (and by reference, CS-E 50 (d) which relates only to the control system).
2. There is a particular focus on preventing Hazardous Engine Effects as a result of maintenance errors, which is of course highly desirable. However, this may lead to other failure effects being overlooked or being given insufficient attention.

CERTIFICATION SPECIFICATIONS FOR LARGE AEROPLANES: CS-25

There is very little by way of requirements addressing the subject of design for maintenance in CS-25, although there are many references to the need to minimise the potential for flight crew errors. Indeed, there is nothing in the requirements themselves, any reference to the potential for maintenance error appear only in the Acceptable Means of Compliance (AMC). These are as follows:

AMC 25.783 (5) "Service history has shown that to prevent doors from becoming a hazard by opening in flight, it is necessary to provide multiple layers of protection against failures, malfunctions, and human error. Paragraph 25.783 addresses these multiple layers of protection by requiring:

◊. a latching system;
◊. a locking system;
◊. indication systems;
◊. a pressure prevention means.

These features provide a high degree of tolerance to failures, malfunctions, and human error."

Note however that this relates to fuselage doors and the reference to 'human error' appears to be mainly focused upon cabin and ground crew operatives, aside from the following, "CS 25.783(a) General Design Considerations… Failures that should be considered when safeguarding the door against opening as a result of mechanical failure or failure of any single structural element include those caused by incorrect assembly."

AMC 25.1302 This is a very comprehensive AMC on the subject of human performance/error, but is targeted solely at the flight crew/flight deck interface. It is clearly based upon a lot of research and investigative work. It is recommended that this be considered as a model for a new AMC to address human-centred design for maintenance.

Other references to maintenance error include:

AMC 25.933 (a)(1) 4b and 12 c(1)(iii) (Thrust reversers)
Qualitative assessments should be done, taking into account potential human errors (maintenance, aeroplane operation).

12.c.(1)(iii) Minimisation of errors: Minimisation of errors during maintenance activity should be addressed during the design process. Examples include physical design features, installation orientation markings, dissimilar connections, etc. The use of a formal lessons learned based review early and often during design development may help avoid repeating previous errors.

AMC 25.1309 definitions, and 9b (1)(v), and Appendix 1 f(1) (Zonal safety analysis)
(xi) Error-Tolerance that considers adverse effects of foreseeable errors during the aeroplane's design, test, manufacture, operation, and maintenance.

(1) General.

(iii) The possibility of requirement, design and implementation errors.

(v) The effect of reasonably anticipated errors when performing maintenance actions.

(5) Crew and Maintenance Actions.

(i) Where an analysis identifies some indication to, and/or action by, the flight crew, cabin crew, or maintenance personnel, the following activities should be accomplished:

1 Verify that any identified indications are actually provided by the system.

2 Verify that any identified indications will, in fact, be recognised.

3 (i) Verify that any actions required have a reasonable expectation of being accomplished successfully and in a timely manner.

(ii) These verification activities should be accomplished by consulting with engineers, pilots, flight attendants, maintenance personnel and human factors specialists as appropriate, taking due consideration of the consequences if the assumed action is not performed or mis-performed.

(iii) In complex situations, the results of the review by specialists may need to be confirmed by simulator or flight tests. However, quantitative assessments of the probabilities of crew or maintenance errors are not currently considered feasible. If the failure indications are considered to be recognisable and the required actions do not cause an excessive workload, then for the purposes of the analysis, the probability that the corrective action will be accomplished, can be considered to be one. If the necessary actions cannot be satisfactorily accomplished, the tasks and/or the systems need to be modified.

(1) Zonal Safety Analysis. This analysis has the objective of ensuring that the equipment installations within each zone of the aeroplane are at an adequate safety standard with respect to design and installation standards, interference between systems, and maintenance errors. In those areas of the aeroplane where multiple systems and components are installed in close proximity, it should be ensured that the zonal analysis would identify any failure or malfunction which by itself is considered sustainable but which could have more serious effects when adversely affecting other adjacent systems or components.

(3) Common Mode Analysis. This analysis is performed to confirm the assumed independence of the events, which were considered in combination for a given Failure Condition. The effects of specification, design, implementation, installation, maintenance, and manufacturing errors, environmental factors other than those already considered in the particular risk analysis, and failures of system components should be considered.

AMC 25.1707 2a (EWIS – 'electrical wiring interconnect system')
While these make reference to the need to consider maintenance error, they do not provide any specific guidance on how this may best be achieved. In addition, it would appear that the references to maintenance error here are all based upon historical events (eg the Lauda Air accident resulting from an un-commanded thrust reverser deployment).

OBSERVATIONS ABOUT CURRENT CS-25 PROVISIONS

In summary, there is no strategic approach within CS-25 to the address the issue of maintenance error, nor any specific advice or guidance on how designs should take account of the need to minimise or eliminate the potential for maintenance errors. The existing material within CS-25 appears to be solely reactive to past accidents and significant incidents.

Certification Specifications for Large Rotorcraft: CS-29

AMC 29.802(9) Emergency Flotation "Maintenance errors may also lead to a flotation unit failing to inflate."

AMC 29.917(a) Rotor drive system design. "The safety assessment should also consider potential assembly or maintenance errors that cannot be readily detected during specified functional checks."

OBSERVATIONS ABOUT CURRENT CS-29 PROVISIONS

There are only two references to maintenance error, and these point to the need to take account of the possibility of error in analyses, without there being any guidance or other information as to how the potential for such errors may be minimised or eliminated. It seems to be 'accepted' that errors will occur and that due account should be taken of this in the safety analyses.

Certification Specifications for Small Rotorcraft: CS-27

There are no references to maintenance error in CS-27.

The EASA has published a Notice of Proposed Amendment (NPA), 2019-11 (https://www.easa.europa.eu/sites/default/files/dfu/NPA%202019-11.pdf) containing proposals to amend both CS-27 and CS-29. While this NPA recognises the need to 'reduce the risk of design-related human factors (HFs) errors that may lead or contribute to an accident or incident,' it focusses exclusively on flight crew and the design of the flight crew environment. This NPA was adopted and included in Amendment 8 of CS-27 in June 2021 and in Amendment 9 of CS-29 in August 2021.

It is considered that the recognition of 'design-related human factors' in relation to flight crew performance in this recent amendment of CS-27 and CS-29 should now be extended so that attention is now given to addressing human-centred design for maintenance.

Certification Specifications for Normal-Category Aeroplanes: CS-23

There are no references to maintenance error in CS-23.

EASA CERTIFICATION PANELS

In conducting the certification of an aircraft, the European Aviation Safety Agency (EASA) uses a team of 'Certification Panels', each panel focussing on specific areas of the certification programme. In all there are 20 (Numbered from 0 to 19), though not all are necessarily used on each certification. Of these panels only one (Panel No. 1, 'Flight and Human Factors') includes a responsibility for 'Human Factors' and this focusses primarily on flight crew aspects.

European Plan for Aviation Safety (EPAS) 2021 – 2025

The EASA's current EPAS features the following human factor related activities:

(1) RMT.0713. Human Factors in rotorcraft design. The objective of this rule-making task (RMT) is to introduce into CS-29 requirements for the consideration of human factors/performance in the design of rotorcraft flight decks. This will be based upon existing requirements in CS-25. It does not however address any design requirements to eliminate the potential for maintenance errors.

(2) SPT.0104. Safety Promotion material on high-profile maintenance safety issues. This activity has the objective of increasing the reach and effectiveness of materials sharing maintenance safety issues. While commendable, it serves only the reactive aspect of maintenance errors: it does not address the issue of seeking to eliminate the potential for such errors through design.

The EPAS has a whole chapter, 'Chapter 22 Human Factors' which covers a range of HF topics. One of these, Error mitigation by design (maintenance and production) (SI-3017), states, "Incorrect assembly in production or maintenance may lead to an unsafe condition for the aircraft. It is inappropriate to rely solely on warnings in maintenance instructions, markings and independent inspections to detect mis-assembly, when the hazard can be eliminated by careful design in most cases." This activity is currently in the 'Assess' category of the European Safety Risk Management process, meaning that it requires further analysis to identify contributory factors and proposed mitigations.

Within this same Chapter 22, activity SI-3007 addresses the subject of the design and use of procedures, stating, "Procedures are used throughout the aviation industry to describe the correct actions and sequence of actions to perform a task. Out of necessity, procedures are designed using assumptions about the circumstances in which they will be applied. While this frequently produces well-designed procedures, the complex nature of the aviation working environment means that not every circumstance can reasonably be accounted for. Regardless of whether the procedure has been designed well or badly, rapid changes in the aviation system can mean that a procedure becomes more difficult to use over time." Further work is required to understand the current status of this activity (currently shown in the 'Mitigate' section of the European Safety Risk Management process).

PREVIOUS RULEMAKING ACTIVITY

In 2000, the UK CAA developed a Preliminary Notice of Proposed Amendment (P-NPA) to JAR 25 (now

CS 25) to address human centred design (UK CAA, 2000). A primary driver of this is that although 25.1309 shows a clear intent to address human performance in the system safety requirements for large aircraft, these are limited and incomplete (Lawrence and Gill, 2007). P-NPA 25-310 had two objectives:

- To make designers more aware of the need for 'human-centred design';
- To identify potential error on safety critical tasks and, wherever possible, prevent them, preferably by design. Where this cannot be achieved the potential for safety critical failures arising from human error should be minimised.

The key requirement in the P-NPA is:

"It must be shown by analysis, substantiated where necessary by test, that as far as reasonably practicable all design precautions have been taken to prevent human errors in production, maintenance and operation causing Hazardous or Catastrophic effect. Where the potential cannot realistically be eliminated, then the remaining safety critical tasks should be sufficiently understood and the potential for Human Error mitigated." Unfortunately, this P-NPA was never incorporated into CS 25. While the reasons for this are not known, it's possible that it was lost in the transition from the Joint Aviation Authorities to the EASA.

CONCLUSIONS

Within the current European certification requirements, the subject of designing to minimise or eliminate maintenance error is either addressed by some very specific material (usually in response to an accident or serious incident), or ignored completely.

CS-E has the most comprehensive set of certification requirements however, as noted above, these tend to focus on ensuring that maintenance errors cannot lead to hazardous engine failures. There are no requirements at all in CS-23 or CS-27, despite there being a long and continuing history of maintenance errors causing accidents for the smaller ('Normal Category') aeroplanes and rotorcraft.

By contrast, there are some comprehensive and focussed requirements (with supporting acceptable means of compliance, and guidance material) which address the need to consider, in the design, human factors for flight crew, notably in CS-25 (Large Aeroplanes). Indeed, this is where the significant majority of design requirements for human factors may be found.

It is reasonable to conclude that previous 'maintenance-error' related activities/rule changes have been undertaken in response to accidents or serious incidents, some involving heavy loss of life. Furthermore, in addition to being reactive, all of these activities have focussed purely upon the specific issues relating to the accidents themselves – there has not yet been a more strategic, holistic and pro-active review of the root causes, at least none that has gained any traction to address this issue.

In addition, since the cockpit design requirements have accepted that the design has to accommodate realistic human performance/error, it is incongruous that no similarly comprehensive rules exist for design to avoid maintenance error.

Recommendations

7.1 It is recommended that rule-making activity is initiated to develop requirements for Part 21, and the EASA certification specifications, and associated AMC and GM, so as to put human-centred design for maintenance at the heart of the design process, and to ensure appropriate consideration of the maintenance environment, and potential for maintenance errors, when designing aircraft and engines.

7.2 It is recommended that the EASA be encouraged to consider revising its certification panel arrangements so as to ensure that it has the capacity and capability to assess human-centred design for maintenance as part of its aircraft and engine certification activities.

CHAPTER 8

Impact of Covid-19

INTRODUCTION

The Covid-19 pandemic has had a significant impact on the aviation industry due to travel restrictions and a slump in demand among travellers. This has resulted in reduced revenues for airlines and has forced many airlines to lay off employees and to either ground their aircraft and /or place in long-term storage.

A summary of the impact of the pandemic on the industry generally, has been produced by the EASA and some key points from their published document, *EASA Review of Aviation Safety Issues Arising from the Covid-19 Pandemic*, are included here.

IMPACT ON MAINTENANCE WORKFORCE

The impact of Covid-19 on the Aerospace Design, manufacture and maintenance workforce has been substantial. A number of companies have introduced early retirement and/ or redundancy programmes, resulting in significant loss of experienced personnel. The resulting loss of expertise could be significant. However, even before the Covid-19 pandemic the airline industry was concerned about maintaining an adequate supply of aircraft mechanics, and technicians. The industry has been projecting severe labour shortages over the next 20 years due to expansion in the airline industry combined with workforce retirements and attrition. While the reduction in flights has eliminated immediate concerns about labour shortage, in the long term the pandemic could undermine airlines' ability to attract highly skilled workers. The aviation maintenance field, pre-Covid-19, had faced recruitment and retention challenges. Furloughs and layoffs attributable to the Covid-19 pandemic would continue to make aviation maintenance work a less attractive alternative for workers.

If the pool of skilled mechanics and technicians in the future is to become an issue then avionic equipment and its maintenance may have to be designed to account for this by reducing the maintenance burden and repair complexity of new build systems.

IMPACT ON AIRCRAFT MAINTENANCE

Aircraft are designed to fly daily, with routine ramp and overnight maintenance. Because of Covid-19, a number of commercial aircraft have been grounded and/or put in storage for longer periods

This situation has caused a number of maintenance and repair challenges. Aircraft maintenance is primarily driven by flight hours and cycles and if aircraft are not active then the parked/stored aircraft will be subjected to a basic service schedule (that includes covering intakes and exhaust points, and greasing and cleaning the landing gear), with non-essential maintenance being delayed and required maintenance events deferred into the future. Stored aircraft face hazards such as increased corrosion, pest and insect infestation, extremes of temperature and humidity. When they are returned to service, they will need to be thoroughly checked and rescheduled maintenance events carried out before flying can restart.

The next generation of aircraft would need to consider this possibility of long storage and that the design of future aircraft and its avionic equipment should require less maintenance and fewer replacement parts.

IMPACT ON MAINTENANCE PROCEDURES

Although the aviation industry is experiencing a decrease in capacity and maintaining a reduced maintenance workforce, those who are still employed are working in very different environments.

Social distancing prevents exposure to Covid-19. However, social distancing in aviation maintenance can be difficult. Particularly within confined workspaces like fuel tanks, avionics bays, landing gear wells, cockpits, etc. Organisations are having to schedule work tasks to maximise social distancing. This may mean sequencing tasks, assigning solo work activities, implementing new work schedules (ie, staggering shifts or shorter shifts) to reduce the number of individuals in the workspace at once. Where tasks have to be carried out by more than one person then changes to the working routine such as work side-by-side, or facing away from each other, rather than face to face if possible. Where face-to-face contact is essential, this should be for a short a time as possible and a face covering worn by all involved.

The Covid-19 challenge is forcing organisations to find new ways of doing business such as 'going virtual' with inspections and certifications and providing access to human expertise for advice. There may be need for special tools and equipment to be introduced to allow tasks that were originally performed by more than one person, to be now carried out by an individual. Maintenance procedures may have to be rethought or rewritten to cope with Covid guidelines on distancing, working face to face, masks etc. Such actions will promote social distancing to the extent possible.

IMPACT ON OFFICE WORKING

With Covid-19, many office workers have been successfully working from home. As a result, some companies are asking if their companies need workplaces at all, or at least introducing a working routine where time is spent between the home and the office. In the aviation industry some companies are looking into the practice of introducing a 'Smart Desk' working model, where you no longer have your own desk in an office. If you need to come into work to carry out an activity you are unable to undertake at home you will need to book a desk on a given day. Finding ways to maximise staff productivity in such a situation may be key for organisations maintaining a 'work from home' working practice, post Covid-19.

People tend to spend more time working when at home especially if the work involves desk-based activities. Then there is speculation that if people are not out there mingling because they are not in a physical setting (as opposed to a virtual community), then productivity suffers. Sometimes just sharing ideas, communicating with each other can help optimise productivity. Finding ways to staying connected while away from the office as we emerge from Covid-19 is key for organisations: eg by introducing a 'virtual watercooler', using video conferencing software where quick chats can be conducted on a communal thread, and sharing photos.

It may be necessary to accelerate digital adoption. If there are constraints around staff and cost, it will be important to automate as many tasks as possible. Therefore, technologies like artificial intelligence (AI), machine learning (ML), will come into play.

New hazards to aircraft safety could emerge resulting from the Covid-19 pandemic that will require changes to Safety Management Systems, as the system is not the same as before.

The focus on Covid-19 could result in a reduced focus on safety. The different ways of working in the Covid-19 environment could change team behaviours, increasing stress levels and fatigue.

VIRTUAL DESIGN REVIEWS

A product of the UK government's directive to work at home where possible has led to a phenomenon whereby design reviews are being carried out virtually rather than in person. These virtual design reviews are significantly different to in-person reviews, and, anecdotally, both benefits and drawbacks have been identified from a human-centred design viewpoint.

Benefits

- Conversation is focussed, and no 'sidebar' discussions can take place in a virtual setting. This helps keep participants focussed and on task.

- The gravitas effect is reduced, and there is a tendency for participants to receive equal screen time. This helps specialisms (including human factors) to have a greater impact in design reviews.

- As there is no commute required, people are less likely to be tired or stressed from this commute. Leading to a more attentive audience during the review.

Drawbacks

- There is less scope to use physical prototypes or mock-ups during these reviews. This can make it harder to objectively assess different candidate design options, which could have a knock-on effect on users.

- People can become distracted by 'home life'. Particularly those who are in House shares, or have dependents.

- The 'water cooler' moments prior to the meeting are lost, which can lead to longer discussions around design details.

OPPORTUNITIES POST Covid-19

Digital innovations such as predictive analytics, and machine learning are already making inroads into aftermarket services. Aircraft Health Management (AHM) and Maintenance Planning/Predictive Maintenance (PM) have evolved the most to date, and these capabilities are expected to provide the most benefit in the next three years – particularly for operators. PM involves the use of information such as sensor data and maintenance logs to predict maintenance needs in advance, helping airlines carry out better maintenance planning and determining the right moment to replace a part. This is critical because replacing too late can lead to unexpected failures, flight delays, cancellations, and reduced asset availability. Replacing too soon, on the other hand, means forfeiting the benefits of the extended use.

AHM/PM is particularly impacting the material supply chain, as an MRO shop getting a replaced component may not receive a fault code or failure mode with the part – only a shop note, such as 'removed per AHM programme'. Diagnosing the problem with the component off aircraft is more time consuming and challenging for MROs, which typically have fixed-rate repair contracts with operators – in which they must diagnose, correctly repair, and return a part to the operator within contractual turn times. Would improving the detail within error codes or increasing the number of distinct faults that can be identified, expedite fault finding?

Augmented Reality (AR) and Virtual Reality (VR) are visualisation technologies that have been marketed as being useful to the MRO industry, especially with regard to maintenance engineer training and support for conducting tasks. Users wear goggles to enable them to look around a 3D model of an aircraft and its parts and systems. The goggles can be connected to enable each user to see the same thing and with AR, they can also see through the glasses to observe the physical environment. Digitised models of engine and aircraft parts facilitate the ability to remove and expand areas of an engine or part, collaborative discussion, and have the potential to significantly improve maintenance, design, manufacture and assembly tasks as a new generation of engineers are recruited into the industry. Airbus Helicopters for example uses AR to conduct gearbox inspections, to show the engineer documentation and pictures hands-free. This has been demonstrated to shorten the inspection time by 41% (Teamviewer, 2021). Airbus has also collaborated with a university to use VR technology to train aviation maintenance students. This showed that they had an improved understanding of the maintenance task compared to traditional lectures (Bernard et al 2021). Immersive technologies can also provide designers with the ability to interact with the design and stress test the maintenance requirements before designs are finalised. Berg & Vance (2017) for example found 18 examples of VR being employed in design organisations throughout the design process. Research in institutions such as the University of Sheffield Advanced Manufacturing Research Centre are pushing the boundaries of what these technologies can do for design organisations and, although not yet widely used, there is likely to be a significant impact on human-centred design as the cost reduces and adoption increases.

The desire to automate maintenance activities will also likely to have a significant impact on the human factors of maintenance. Although robotics are in widespread use in manufacturing, robotic maintenance has not reached the front-line of aviation. Inevitably this will be achieved in time, and the human factors issues to be considered by designers will need to a evolve accordingly.

CONCLUSIONS

The 'Covid-19 challenge' is forcing organisations to find new ways of working, including the need to conduct more business in a virtual environment. The loss of experienced personnel as a result of Covid-19 will undoubtedly have an affect both on maintenance and design teams, and this is likely to be far-reaching. The risks when returning large fleets of aircraft to service after extra-long periods of storage will need to be managed carefully.

Recommendations

8.1 In order to ensure that home working and social distancing do not disrupt teamwork, and to maintain staff productivity while working as a virtual community, it is recommended that the RAeS give consideration to leading an activity to identify and promote 'good practice' across the aerospace and aviation sectors (eg Introducing a 'virtual watercooler', video conferencing feature where quick, informal chats can be conducted on a communal thread).

8.2 It is recommended that the opportunities to accelerate the introduction of new technologies, such as Augmented Reality, be examined. This may, in particular, help designers 'see' what impact their designs have on required maintenance activity.

8.3 It is recommended that the RAeS give consideration to promoting the need for the development of design guidance for mechanical and avionic equipment and its maintenance, to minimise the maintenance burden and repair complexity of new systems. This may help to minimise the impacts of any need for future long-term storage, or any future reduction in the pool of skilled mechanics and technicians.

8.4 It is recommended that the RAeS consider ways in which the benefits of Aircraft Health Management (AHM) and Maintenance Planning/Predictive Maintenance (PM) can be promoted and further developed.

8.5 It is recommended that the RAeS consider the potential merits of a detailed review of the impact of the Covid-19 pandemic on the aerospace and aviation workforce, with the aim of identifying future recruitment and training needs, and any impact on knowledge and skills. The outcome of such a review may also help inform future design considerations.

ROYAL AERONAUTICAL SOCIETY

CHAPTER 9

Summary and Conclusions

This review has revealed that while initiatives have been introduced to minimise maintenance error, one of the significant root causes of such errors has largely been ignored. Much remains to be done in order to ensure that human-centred design for maintenance is given the attention and priority it needs in order significantly to reduce the potential for maintenance errors. This area needs to be given as much attention as has been previously dedicated to the design of flight decks to help minimise the potential for crew error. The fact that 42 recommendations are made perhaps reflects the scale of effort required.

In addition to a review of current educational, professional, and industry standards, requirements and practice, a selection of recently published work has also been considered to help guide our conclusions and recommendations. In this regard, key pieces of work include:

1. The RAeS's HFG:E report on Maintenance Error Data from July 2011 (Simmons, 2011). Data were collected from a number of aerospace sources, including civil and military operators, regulators and OEM's. The common themes identified were:

(a) Maintenance Error Reports make up a significant proportion of all engineering related Air Safety Reports.

(b) Certain ATA Chapters are especially vulnerable, such as engines, landing gear and flight controls.

(c) There are predominant error types, eg installation errors.

(d) Errors are dominated by knowledge based and rule-based errors.

(e) Certain error types are associated with high-risk outcomes

(f) There are common Performance Shaping Factors.

2. One of the report's recommendations was that 'Aircraft Design should embody error prevention and detection mechanisms such as forcing functions to reduce criticality and facilitate error recovery'.

3. First Eleven Paper (Owen, 2012). Entitled 'Design Organisation Guidance for Delivering In-Service Human Performance in Maintenance', it covers eleven steps for aircraft and design supplier organisations to deliver safer, more effective and reliable aircraft through improved design for maintenance.

4. RAeS's Human Factors Group in Engineering (HFG:E) conferences for the last decade, including one in 2019 at Cranfield and the recent Maintenance Engineer Wellbeing Conference. Conference proceedings are available on the RAeS website.

WHAT HAS CHANGED?

Since the previous RAeS HFG:E report on Maintenance Error Data from July 2011, it is considered that very little has changed. The evidence for this statement includes:

1. Recent studies by Hieminga & Turkoglu (2018) and UK CAA (2015) conclude that maintenance errors on engine, landing gear and flight controls are predominant, reflecting the conclusion of Simmons (2011).

2. Hieminga J and Turkoglu C (2018), UK CAA (2015) and HeliOffshore (2020) have found that errors during installation are still most common, confirming the conclusions of Simmons (2011).

3. Analysis for this report of 55 events investigated by the AAIB over the last decade (covered in the Body of Evidence section) reinforces these conclusions with 60% of maintenance errors identified as incorrect installation.

4. Anecdotally, root causes identified in two recent AAIB investigations regarding engine-related maintenance errors, were familiar to one of the authors of this report from their past experience in the engine side of the Aerospace business, including fumes in cabin post engine wash, and an event of a Variable Inlet Guide Vane unison ring not being connected resulting in compressor blade failure.

Despite there being an awareness of the continued occurrence of maintenance errors, the service experience continues to show that there has been little effective action to address this threat to safety. Perhaps even more notably, the introduction of maintenance error management systems (MEMS) appears to have had little impact. While recognising that this is potentially a controversial position to take, it must be noted that MEMS do not address the root cause of the majority of cases where the maintenance conducted deviates from the maintenance intended, and that the actions arising from MEMS most usually target areas where the operator (eg MRO or airline) has control.

The key themes emerging from this review are, therefore:

- Maintenance errors are still prevalent despite action such as the introduction of MEMS;
- There is a large, hidden cost to industry;
- There remains an underlying safety risk, possibly enhanced owing to recent and on-going changes in industry resulting from reaction to Covid-19 (eg loss of skilled staff);
- Human-centred design for maintenance can play a key role in future error prevention and reduction;
- There is a need to recognise and accept that human adaptability is a core asset of the system of maintenance and we cannot rely on procedures being followed each and every time. Further to this we must accept that errors will occur and that such errors are a failure of the system of maintenance, not of individual engineers;
- There is a need to recognise that maintenance engineers are end users of the system so design of maintenance tasks should be human-centred as has been achieved for flight crew. Since the cockpit design requirements have accepted that the design has to accommodate realistic human performance/error, it is incongruous that no similarly comprehensive rules exist for design to avoid maintenance error;
- There is a general failure to adopt processes to ensure consistency between maintenance-as-done, maintenance-as-prescribed and maintenance-as-imagined

CHAPTER 10

Summary of All Recommendations

1.1 It is recommended that the RAeS works with its corporate partners, and particularly those in the aviation insurance business, and other organisations as necessary, to establish the actual cost to the industry of 'maintenance errors'.

1.2 It is recommended that the RAeS works with its corporate partners to identify examples of good maintenance instructions and where improvements can be made to serve as illustrations for the industry discussion on improving documentation. Examples given for a specific OEM could be shared with that OEM including the maintenance engineer's comments on the nature of the difficulty.

2.1 Training on the EASA database should clarify how users should apply the 'Event Type' taxonomy. This appears to be used inconsistently, with users rarely selecting the more detailed fourth level of the taxonomy, severely restricting the level of detail available from the data (Hieminga J and Turkoglu C, 2018).

2.2 Users of the EASA database should be encouraged (or mandated) to use the narrative section of the database and use English as standard to increase the usefulness of the collected data (Hieminga J and Turkoglu C, 2018).

2.3 Analyses of maintenance events should be conducted at least every three years to identify trends and offer insight to the industry to allow appropriate remedial action to be taken.

2.4 The concept of 'innovative violation' should be added to the typical violation taxonomy, adding to the generally accepted routine, optimising, situational, exceptional, and unintentional (Bannister-Tyrrell, 2020).

2.5 Design organisations should be required to critically evaluate existing (and new) maintenance tasks, especially in critical areas of the aircraft or engine where failure could lead to hazardous or catastrophic effects (using processes like Human Hazard Analysis outlined in Gill (2021)).

2.6 Design organisations should consider where improvements may be made in the information feedback process so that potential improvements to maintenance and overhaul manuals may be readily reported, assessed and, where appropriate, implemented. The feedback process should include staff from the maintenance organisation(s), the OEM's design office, and the technical authors of the instructions for continued airworthiness. This should be driven by the senior management of the organisations to ensure that it is given due priority.

2.7 The industry should explore alternative feedback mechanisms which could be built into the fabric of the maintenance system to facilitate the efficient and effective sharing of ideas and innovations by maintenance personnel through their own organisations and to the OEM.

2.8 Research should be undertaken on how the industry can embrace a Safety-II approach to explore successful adaptation by maintenance engineers, why such adaptations are required and what interventions could be made to improve safety.

3.1 It is recommended that Professional engineering bodies work together to highlight the importance of engineers having an awareness of human factors.

3.2 It is recommended that Professional engineering bodies actively encourage Universities offering engineering degrees to expand their curricula to include human factors. This could take the form of optional modules, but should be considered mandatory for aeronautical engineering courses.

3.3 It is recommended that Professional engineering bodies encourage and accredit engineering degrees with human factors content.

3.4 It is recommended that action be developed to ensure that apprenticeship programmes within aerospace design organisations include human factors within both the vocational and academic content.

3.5 It is recommended that Professional engineering bodies take steps actively to promote the need for engineering apprenticeship standards to include appropriate human factors within both the vocational and academic content/learning objectives.

3.6 It is recommended that Professional engineering bodies take steps actively to promote the need for college engineering courses to include human factors modules for students that may enter the engineering profession without undertaking an apprenticeship or graduate programme

3.7 It is recommended that the RAeS HFG:E, in conjunction with the Society's Young Persons Network, produce some digestible 'bite size' human factors material, such as short videos or illustrations, aimed at university engineering students, and send links to university lecturers, inviting them to show the material.

4.1 It is recommended that action be taken to introduce, in Part 21 subpart J, or other relevant regulation, requirements making initial and refresher human-centred design for maintenance training mandatory for all staff in design organisations.

4.2 It is recommended that design organisations produce some digestible 'bite size' human factors material, such as short videos or illustrations, aimed at design engineers, highlighting the impact and importance of effective human-centred design for maintenance.

5.1 It is recommended that the RAeS engage with the Institute of Apprenticeships and Technical Education to ensure that the new apprentice standard, ST0785 'Human Factors Practitioner' contains appropriate requirements for human-centred design for maintenance.

5.2 It is recommended that the RAeS work with the Engineering Council to amend the UK Standard for Professional Engineering Competence and Commitment (UK-SPEC), so that it includes appropriate, relevant human factors standards.

5.3 It is recommended that the RAeS engage with other, non-aerospace, engineering disciplines to address human factors as a specific issue early on in the careers of apprentice engineers.

5.4 It is recommended that the RAeS consider taking a leading role in developing professional seminars on the subject of human-centred design for maintenance. Such seminars could be counted towards the continued professional development of design engineers.

6.1 It is recommended that action be taken to initiate rule-making activity for Approved Design, Production, Maintenance and Training Organisations, so that these organisations are required to:

(a) Ensure all relevant staff undertake training in human-centred design for maintenance,

(b) Incorporate human-centred design for maintenance in their safety reporting systems

(c) Report human-centred design for maintenance related events to the responsible Design Organisation (ie Type Certificate Holder), and ensure that suitable, effective corrective action is taken to prevent recurrence of such events.

6.2 It is recommended that action be taken to develop specific guidance for Approved Design Organisations on the subject of human-centred design for maintenance.

6.3 It is recommended that action be initiated to develop and publish specific guidance (ie a human-centred design handbook) for designers within design organisations. This guidance should include human-centred design for maintenance. The guidance could use, and build upon principles already contained in Design for Manufacture or the Mil-HDBKs.

6.4 It is recommended that guidance (eg, a human-centred design plan) be created for, or by design organisations to support the introduction of systems and processes which ensure human-centred design for maintenance is included in aircraft design.

6.5 It is recommended that Regulators review the implicit assumption that aircraft maintenance is carried out with no allowance for error.

6.6 It is recommended that Regulators further develop the human-centred guidance material for Paragraph 2.5 of GM 21.A.3B(b).

6.7 It is recommended that Regulators provide more detailed guidance for the in- service safety reporting system described in AMC 20-8.

6.8 It is recommended that Design Organisations be required to incorporate human-centred design for maintenance in their in-service safety reporting systems.

6.9 It is recommended that Design Organisations be required to train staff in relevant human factors, and design for maintenance.

6.10 It is recommended that Regulators consider introducing mandatory requirements for human factors and design for maintenance training for approved design organisations.

6.11 It is recommended that Regulators audit the in-service reporting systems in place at TCHs, thus checking the correctness of action taken against human factors and maintenance issues.

6.12 It is recommended that a candidate issue paper be raised against MSG-3 to introduce a human-centred design analysis step in the process.

7.1 It is recommended that rule-making activity is initiated to develop requirements for Part 21, and the EASA certification specifications, and associated AMC and GM, so as to put human-centred design for maintenance at the heart of the design process, and to ensure appropriate consideration of the maintenance environment, and potential for maintenance errors, when designing aircraft and engines.

7.2 It is recommended that the EASA be encouraged to consider revising its certification panel arrangements so as to ensure that it has the capacity and capability thoroughly to assess human-centred design for maintenance as part of its aircraft and engine certification activities.

8.1 In order to ensure that home working and social distancing do not disrupt teamwork, and to maintain staff productivity while working as a virtual community, it is recommended that the RAeS give consideration to leading and activity to identify and promote 'good practice' across the aerospace and aviation sectors (eg Introducing a 'virtual watercooler', video conferencing feature where quick, informal chats can be conducted on a communal thread).

8.2 It is recommended that the opportunities to accelerate the introduction of new technologies, such as Augmented Reality, be examined. This may, in particular, help designers 'see' what impact their designs have on required maintenance activity.

8.3 It is recommended that the RAeS give consideration to promoting the need for the development of design guidance for mechanical and avionic equipment and its maintenance, to minimise the maintenance burden and repair complexity of new systems. This may help to minimise the impacts of any need for future long-term storage, or any future reduction in the pool of skilled mechanics and technicians.

8.4 It is recommended that the RAeS consider ways in which the benefits of Aircraft Health Management (AHM) and Maintenance Planning/Predictive Maintenance (PM) can be promoted and further developed.

8.5 It is recommended that the RAeS consider the potential merits of a detailed review of the impact of the Covid-19 pandemic on the aerospace and aviation workforce, with the aim of identifying future recruitment and training needs, and any impact on knowledge and skills. The outcome of such a review may also help inform future design considerations.

CHAPTER 11

A Proposed Strategy for Engagement

This chapter outlines a high-level strategy for the RAeS to consider with the objective of ensuring recommendations from the report are accepted, adopted by the appropriate stakeholders, and actioned.

The strategy is in three parts:

(1) Identifying the key messages which show that the prevalence of maintenance errors cannot be allowed to continue, and that one of the root causes of such error should be addressed by focusing on human-centred design for maintenance.

(2) Identifying key stakeholders and, among these, who are likely to be advocates for the key messages and recommendations that need to be communicated.

(3) Selecting the most appropriate form of communication for the delivery of the key messages and recommendations.

KEY MESSAGES

- Maintenance errors are still prevalent despite action such as the introduction of MEMS;
- There is a large, hidden cost to industry;
- There remains an underlying safety risk, possibly enhanced owing to recent and on-going changes in industry resulting from reaction to Covid-19 (eg loss of skilled staff);
- Human-centred design for maintenance can play a key role in future error prevention and reduction;
- There is a need to recognise and accept that human adaptability is a core asset of the system of maintenance and we cannot rely on procedures being followed each and every time. Further to this we must accept that errors will occur and that such errors are a failure of the system of maintenance, not of individual engineers;
- There is a need to recognise that maintenance engineers are end users of the system so design of maintenance tasks should be human-centred as has been achieved for flight crew. Since the cockpit design requirements have accepted that the design has to accommodate realistic human performance/error, it is incongruous that no similarly comprehensive rules exist for design to avoid maintenance error;
- There is a general failure to adopt processes to ensure consistency between maintenance-as-done, maintenance-as-prescribed and maintenance-as-imagined.

KEY STAKEHOLDERS

- EASA
- UK CAA
- Military Aviation Authority
- Engineering Council
- ADS (and for Europe, ASD)
- Universities
- ICAO
- AAIB
- Design Organisations
- Maintenance Repair and Overhaul Organisations

COMMUNICATION CHANNELS

The findings of the report can be promulgated and promoted by a variety of means, including:

- Lobbying the DfT and/or the CAA
- Identifying and working with potential advocate organisations
- Seminar(s)/workshop(s)
- Lecture(s)
- Article in Aerospace magazine
- Letters to stakeholders
- Short (3-5 min) videos and illustrations
- Social media, eg LinkedIn

APPENDICES

APPENDIX TO CHAPTER 2

Recommendations from HFG:E report of 2011

- Controls to mitigate risks should be reviewed and strengthened when work is being carried out in vulnerable ATA Chapters. Those ATA Chapters (27, 32 and 71-80) identified where errors are both frequent and lead to high-risk events, should receive priority consideration.
- Tasks which are rule-based or knowledge-based should be supported adequately by the internal (Planning and Quality) and external (Design Authority, Regulatory) functions.
- Performance Shaping Factors should be evaluated for high-risk tasks, and where human performance is predicted to be reduced, mitigations should be devised and applied.
- Aircraft design should embody error prevention and detection mechanisms such as forcing functions to reduce criticality and facilitate error recovery.

APPENDIX TO CHAPTER 5

Engineering Institution	Accredited Course	University	Course Duration	User-centred Design /Maintenance / Human Factors Content
IED[3] /RAeS[4]	BEng (Hons) Aerospace Engineering MEng Aerospace Engineering	Swansea	3 Yrs FT 4 Yrs FT	http://www.swan.ac.uk/engineering/ Engineering Design 2 module in year 2. 100hrs over 6 months. Within this module, students will be expected to complete a series of exercises that will the form the basis of a 'major' design. One of Intended Learning Outcomes - on successful completion of this unit students will be expected, to be able to: Ensure fitness for purpose for all aspects of the problem including production, operation, maintenance & disposal.
IED / RAeS	MSc Aerospace Engineering	Swansea	1 Yrs FT 2 Yrs PT	http://www.swan.ac.uk/engineering/ None Course prepares you in the theory and operation of aeronautical vehicles, from propeller-driven and jet-powered planes, to helicopters and gliders. This covers design, analysis, testing and flight.
RAeS	BEng (Hons) Aero-Mechanical Engineering	University of Strathclyde		http://www.strath.ac.uk/ None Course is to learn how to design aircraft engines, control systems, landing gear and about the many complex parts which sustain flight.
RAeS	MEng Aero-Mechanical Engineering	University of Strathclyde	5 Yrs FT	http://www.strath.ac.uk/ None
RAeS	MEng (Hons) Aerospace Engineering	University of Bath	4 Yrs FT	http://www.bath.ac.uk/ Design 4: One compulsory unit in year 2 Design for: safety, ergonomics, life cycle design, automatic assembly, reliability. Material selection and applications and finishes. Costing, quality assurance and design development.
RAeS	BEng (Hons) Aerospace Engineering	The university of Nottingham,	3yrs FT	http://www.engineering.nottingham.ac.uk/ None
RAeS	MEng (Hons) Aerospace Engineering	The university of Nottingham,	4 Yrs FT	http://www.engineering.nottingham.ac.uk/ None
IED / RAeS	MEng Aerospace Engineering	The university of Bristol	4 Yrs FT	http://www.bris.ac.uk/engineering/ None
RAeS	BEng Aerospace Engineering	The university of Bristol	3 Yrs FT	http://www.bris.ac.uk/engineering/ None

[3] Institution of Engineering Designers (IED) represents those who work in the fields of Engineering and Product Design. The members of the institution work in a diverse range of industries that include: product design and manufacturing; architectural design and construction; mechanical, automotive and aircraft design, design education, IT and computing.

[4] The objectives of The Royal Aeronautical Society (RAeS) include: to support and maintain high professional standards in aerospace disciplines; to provide a unique source of specialist information and a local forum for the exchange of ideas; and to exert influence in the interests of aerospace in the public and industrial arenas.

Engineering Institution	Accredited Course	University	Course Duration	User-centred Design /Maintenance / Human Factors Content
IED	MEng (Hons) Mechanical Engineering	The university of Nottingham,	4 Yrs FT	http://www.engineering.nottingham.ac.uk/ Module: Simulation, Virtual Reality and Advanced Human-Machine Interface. In yr 4 This module will provide you with the knowledge and skills required to understand and utilise computers as human factors tools for understanding peoples' interactions with new technology.
IED	BEng (Hons) Mechanical Engineering	The university of Nottingham,	4 Yrs FT	http://www.engineering.nottingham.ac.uk/ None
IED	MSc Mechanical Engineering Design	Bournemouth University	1 Yr FT 2 Yrs PT	http://www.bournemouth.ac.uk/ None
IED	MEng Product Design Engineering BEng (Hons) Product Design Engineering	University of Strathclyde	5 Yrs FT 4 Yrs FT	http://www.strath.ac.uk/ Total Design 2: One compulsory unit in year 2 Amongst other subjects, the module covers: • user centred design techniques
IED	MSc Product Design	University of Strathclyde	1 Yr FT 2 Yrs PT	http://www.strath.ac.uk/ 180 credits for the award of MSc. 10 Credits to compulsory module: Human Centred Design. The module covers: • the evolution of HCD and its various approaches including ergonomics, cognition, user-centered design, people-centered design, design emotion, participatory design, co-design, design ethnography and design anthropology • ontological and epistemological perspectives and assumptions in HCD such as different 'world-views' of people, objects and interaction • research methods for HCD including interviews, focus groups, lab experiments, participant and non-participant observation, critical making/'provotyping'
IED	MSc Design Engineering with Sustainability	University of Strathclyde	1 Yr FT 2 Yrs PT	http://www.strath.ac.uk/ None Course is to learn how to design aircraft engines, control systems, landing gear and about the many complex parts which sustain flight.
IED	BSc (Hons) Design Engineering	Bournemouth University	3 Yrs FT	http://www.bournemouth.ac.uk/ None
	Human Factors in Aviation Maintenance	Cranfield University	5 days	https://www.cranfield.ac.uk/ Course Content includes: Designing for human factors: what can be done by the designer to reduce and mitigate human error? Design philosophies and human-centred design. Human error management in maintenance: the benefits and challenges associated with the use and application of reporting systems and safety tools. A compulsory module in Safety & Human Factors in Aviation MSc offered by Cranfield.

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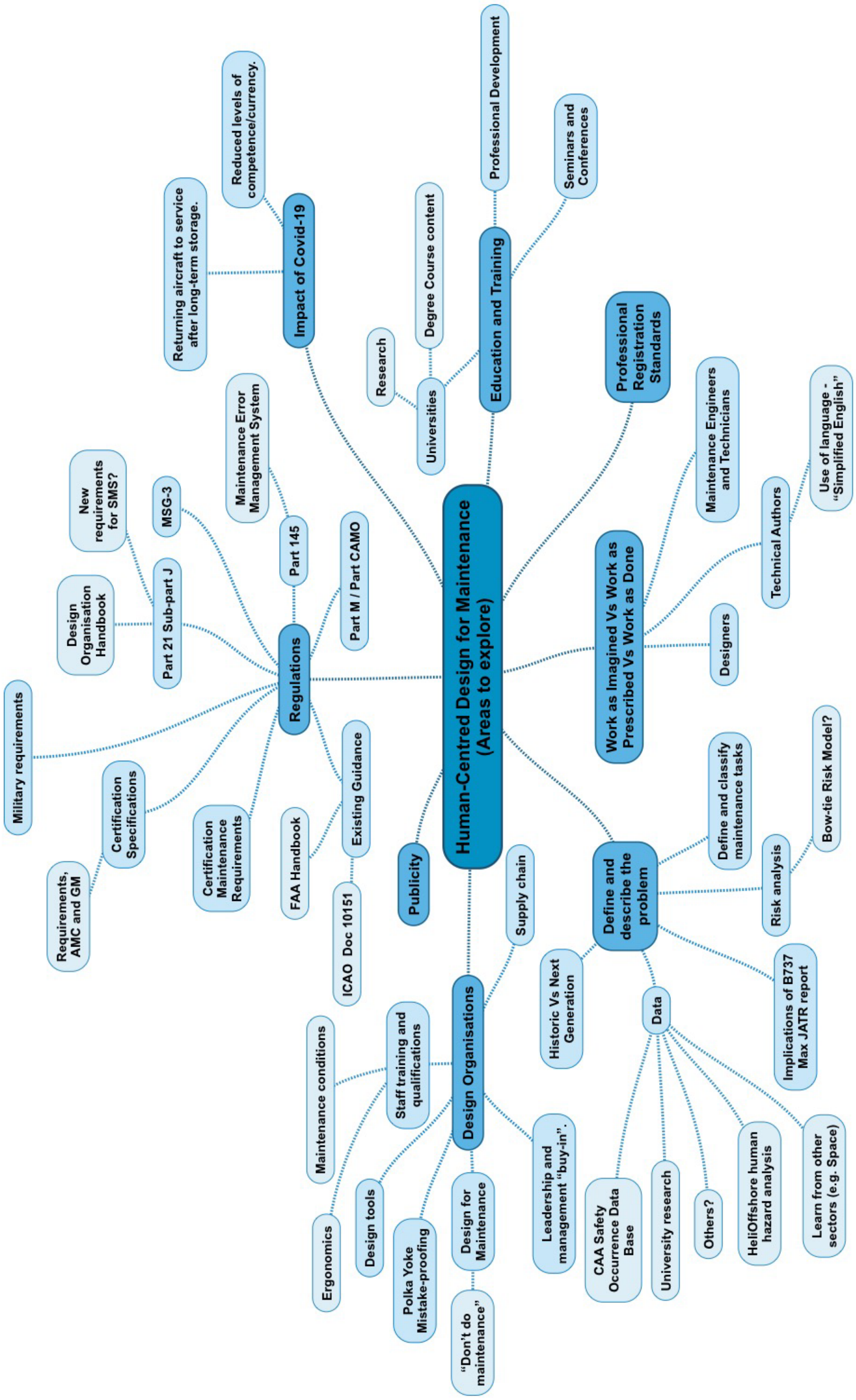
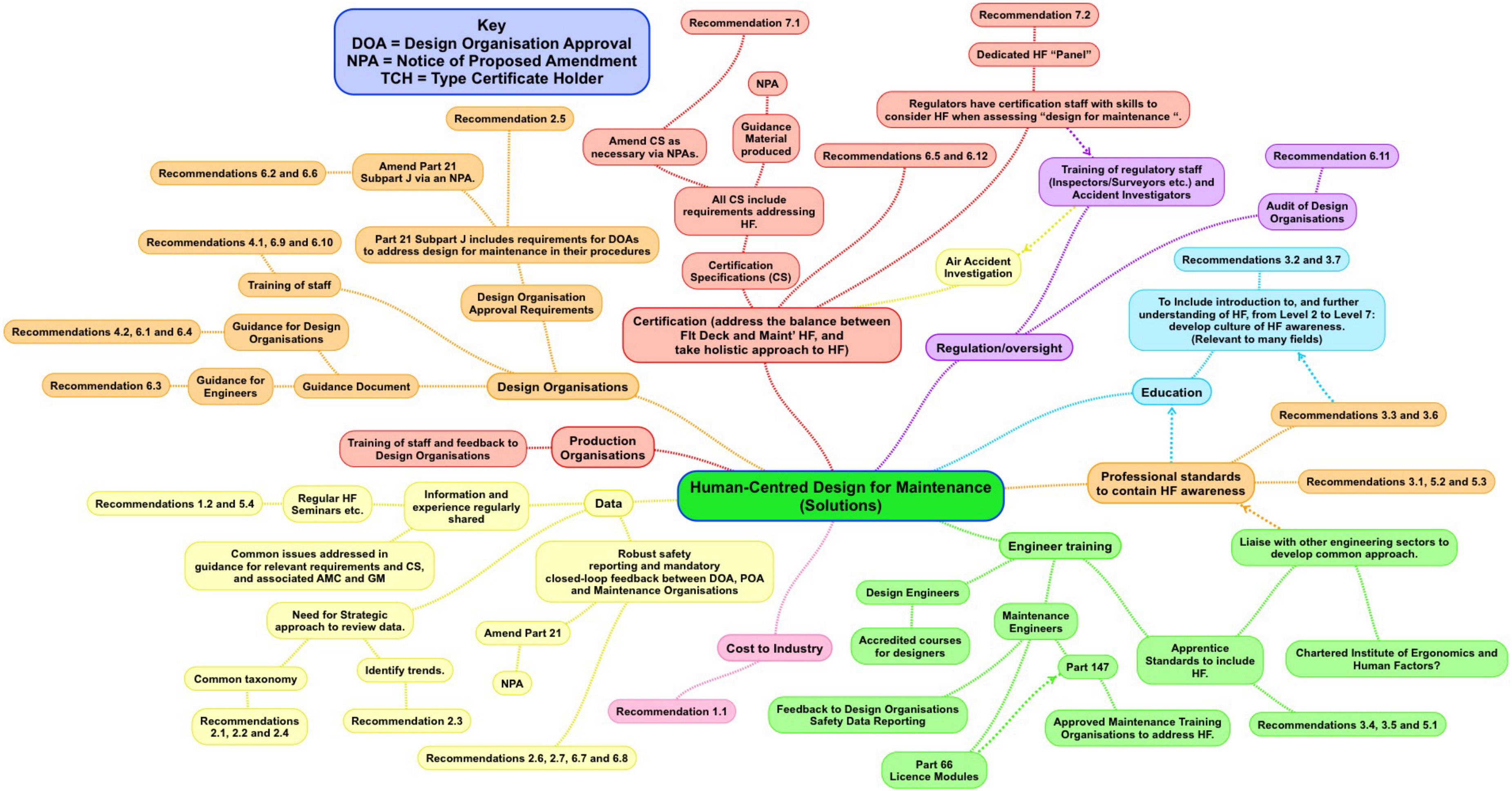
APPENDIX A

Mind Maps




Key
DOA = Design Organisation Approval
NPA = Notice of Proposed Amendment
TCH = Type Certificate Holder
Human-Centred Design for Maintenance (Solutions)
Design Organisations
Guidance Document
Guidance for Engineers
Recommendation 6.3
Guidance for Design Organisations
Recommendations 4.2, 6.1 and 6.4
Training of staff
Recommendations 4.1, 6.9 and 6.10
Design Organisation Approval Requirements
Part 21 Subpart J includes requirements for DOAs to address design for maintenance in their procedures
Amend Part 21 Subpart J via an NPA.
Recommendations 6.2 and 6.6
Recommendation 2.5
Production Organisations
Training of staff and feedback to Design Organisations
Data
Information and experience regularly shared
Regular HF Seminars etc.
Recommendations 1.2 and 5.4
Common issues addressed in guidance for relevant requirements and CS, and associated AMC and GM
Need for Strategic approach to review data.
Common taxonomy
Recommendations 2.1, 2.2 and 2.4
Identify trends.
Recommendation 2.3
Robust safety reporting and mandatory closed-loop feedback between DOA, POA and Maintenance Organisations
Amend Part 21
NPA
Recommendations 2.6, 2.7, 6.7 and 6.8
Cost to Industry
Recommendation 1.1
Certification (address the balance between Flt Deck and Maint' HF, and take holistic approach to HF)
Certification Specifications (CS)
All CS include requirements addressing HF.
Amend CS as necessary via NPAs.
Recommendation 7.1
Guidance Material produced
NPA
Recommendations 6.5 and 6.12
Regulators have certification staff with skills to consider HF when assessing “design for maintenance “.
Dedicated HF “Panel”
Recommendation 7.2
Air Accident Investigation
Regulation/oversight
Training of regulatory staff (Inspectors/Surveyors etc.) and Accident Investigators
Audit of Design Organisations
Recommendation 6.11
Education
To Include introduction to, and further understanding of HF, from Level 2 to Level 7: develop culture of HF awareness. (Relevant to many fields)
Recommendations 3.2 and 3.7
Professional standards to contain HF awareness
Recommendations 3.3 and 3.6
Recommendations 3.1, 5.2 and 5.3
Liaise with other engineering sectors to develop common approach.
Chartered Institute of Ergonomics and Human Factors?
Engineer training
Design Engineers
Accredited courses for designers
Maintenance Engineers
Feedback to Design Organisations Safety Data Reporting
Part 66 Licence Modules
Part 147
Approved Maintenance Training Organisations to address HF.
Apprentice Standards to include HF.
Recommendations 3.4, 3.5 and 5.1

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Authors and Contributors

Authors

Alan Eccleston Alan worked for Rolls-Royce for 37 years in a number of roles, including Director of Engineering for Repair and Overhaul, and Chief Airworthiness Engineer. He retired in 2011 and has since been Maintenance Manager and trained as a miller at the local windmill. He has previously been vice-chair of the RAeS HFG:E.

Ray Elgy C.Eng, FRAeS Ray started his career as an undergraduate apprentice with British Airways, gaining aircraft maintenance engineer licences for airframe and engines, and an Honours degree in Air Transport Engineering. In 1989, he joined the UK Civil Aviation Authority holding a number of posts including Head of the Propulsion Department, and Head of the Aerodrome Standards Department. During this time he was also appointed Chairman of the European Group of Aerodrome Safety Regulators (GASR). His last role in the CAA was as Head of the Licensing & Training Standards Division. He now works as an independent aviation safety consultant.

Dr Simon Gill PhD C.Eng MRAeS Simon started his career as a design engineer in Airbus Fixed Wing but recognising the impact of human variability in maintenance, he completed a part-time PhD in human factors. He set up the Airbus Maintenance Human Factors team, developing and implementing safety improvement processes, analysing safety events, co-ordinating research and training airlines, maintenance organisations and aviation regulators worldwide. He now works as a researcher, lecturer and consultant working on risk, resilience, safety and human factors in aviation, health and social care and critical infrastructure.

Martin Lambert Martin joined the Royal Navy in 1974, training as an Air Engineering Artificer. He maintained, serviced and repaired avionic equipment in a variety of roles and locations, on Fleet Air Arm Helicopters, until leaving in 1998. Since then he has been working as a Systems Safety Engineer, and is currently employed at Leonardo Helicopters conducting safety assessments on the Merlin Helicopter.

Karl Southern MRAeS Karl is a Senior Mechanical Systems Engineer at Raytheon Technologies. He started his career as an engineering apprentice with Airbus UK, before working as a member of the Manufacturing Engineering team for several years. He has spent the past 6 years working as a member of the Design Engineering team at Raytheon, and has worked within both civil and defence design and manufacturing sectors.

Contributors

Dr Hazel Courteney Chief Executive Officer, State Safety Global.

Andy Ebdon: Managing Director, Spot On Consulting Ltd.

Andy Evans: Director, Aerossurance.

Lisa Fitzsimons Senior Inspector of Air Accidents (Engineering) Air Accidents Investigation Branch.

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