Maintenance errors in commercial aviation: contextualising an undefined systemic problem

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SUMMARY

In the commercial aviation sector, Maintenance Errors have resulted in several high-profile accidents and incidents and the annual cost to the industry is estimated to be some US$616M (Allianz, 2024). Despite an industry wide consensus from both regulators and operators alike that the problem of Maintenance Errors needs to be addressed, there remains no definition of what a Maintenance Error is. Using both literature reviews and data from interviews with airline safety professionals, this paper explores why there has been an issue in aviation with regards to understanding Maintenance Error and proposes the Aviation Maintenance System (AMS) as a model for contextualising the problem, as well as proposing a working definition for Aviation Maintenance Errors (AMEs).

KEYWORDS

Aviation Maintenance Error, Aviation Safety, Maintenance

Introduction

In the aviation sector there has been a growing awareness over the past few decades that Maintenance Errors have a significant impact on the safety (BASI, 1997), efficiency and profitability of airlines (RAeS, 2022). Despite a shared consensus from both the regulators and the industry that this issue should be addressed, there is still no industry wide definition of what a Maintenance Error is and consequentially there is no unified approach to address the problem. This paper explores why there has been an issue in aviation with regards to understanding Maintenance Error and proposes the Aviation Maintenance System (AMS) as a model for contextualising the problem before proposing a working definition for Aviation Maintenance Errors (AMEs).

Background

High profile events such as the Air China flight 120 incident of 2007 in Naha, Japan, show how critical maintenance can be to the safe operation of commercial aircraft. This event saw the total destruction by fire of a Boeing 737-800 after a single washer was not fitted during maintenance to the downstop of a wing slat (Japan Transport Safety Board, 2009). For reasons partially explored by this paper, getting accurate global safety data regarding Maintenance Error in aviation is difficult, so the scale of the problem can be difficult to quantify and contextualise. The UK Air Accident Investigation Branch (UK AAIB) conducted an analysis of the occurrences it investigated over a 12 year period and found that 55 events, some 2% of the total, involved some sort of maintenance error (RAeS, 2022). The UK AAIB only investigates those occurrences above a certain threshold but an Airbus internal study that looked at occurrences with a much wider range of severities placed the estimate in a similar order of magnitude, with some 5% of occurrences reported to the company in 2024 containing details that could be attributed to Maintenance Error. When compared to the number of safety related events involving flight operations, the number of Maintenance Errors that directly led to an accident might seem small but these figures do not account for safety related events in which a maintenance error was not the primary cause of the accident but still may have been a significant causal factor. An example of such an accident is the PenAir flight 3296 incident in 2019, when a Saab 200 overran the end of the runway at Unalaska Airport, Alaska resulting in the death of a passenger. In this accident the brake system was found to be cross wired and while this did not lead directly to the accident it was a significant contributing factor as to why the aircraft came off the runway (National Transportation Safety Board, 2021).

Maintenance Errors also come with a significant financial cost. Not only do errors in maintenance require the task to be redone, doubling the cost of the task in terms of wages and materials, they often have knock on effects to the airlines operational schedule which can result in expensive compensation pay-outs to customers who are impacted by delays, in-flight turn backs or flight rerouting. Over a five-year period “faulty workmanship” accounted for 22% of aviation insurance claims at a cost of more than US$3.08bn (Allianz, 2024). The cost of reworking maintenance errors is set to rise as the industry faces a number of challenges such a global shortage of mechanics, increasing costs for parts and next generation aircraft/engines being more expensive to service and repair (Allianz, 2024). In an industry with notoriously tight margins the ability to control such costs is the difference between success and failure for an airline.

Doing nothing to reduce the number of Maintenance Errors in aviation is no longer an option. The worldwide aviation fleet is set to double in the next 20 years (Airbus, 2024) and even if the rate of Maintenance Error remains the same the industry will still see in real terms a doubling of the number of safety related incidents attributable to maintenance, along with a doubling of the associated cost. So, with a strong rationale as to why the phenomenon of Maintenance Error needs to be addressed the question remains, what exactly is a Maintenance Error?

Maintenance Error - the cross-sector view

The concept of Maintenance Error, as its name implies, exists at the intersection of two disciplines, that of engineering and that of Human Factors. When discussed by maintainability and reliability engineers, Maintenance Errors are usually dismissed as being the result of the wrong preventative or repair actions (Dhillon, 2006). This is because maintenance is seen by many engineers as merely being a set of actions required to maintain an item in a serviceable condition with the description of what maintenance people do often being mistaken for the intent of what those same actions are trying to achieve (Kinnison & Siddiqui, 2013).

The discipline of Human Factors takes a more systemic view of Maintenance Error and it does so in order to try and reduce the error rate by identifying the underlying causes. One of the largest explorations of the topic has been done by Reason and Hobbs (Reason & Hobbs, 2003) who discuss the various types of Human Error and how they may apply in a maintenance setting regardless of which sector the maintenance is occurring in. Despite considering many micro and macro factors that might influence Maintenance Error, at no point is a definition of a Maintenance Error given. Across the body of Human Factors and Ergonomics literature this tendency is repeated, a keyword search of "Maintenance Error” in four leading HFE Journals found a number of papers that discuss how Maintenance Errors can be investigated or reduced. Those few papers that used the term "Maintenance Error” do not provide a definition of what this phrase means but would discuss it in terms of Human Error in a maintenance environment and usually with reference to Rasmussen's Skill-rule-knowledge model (Rasmussen, 1983) and Reasons additional work on this framework describing slips, lapses etc (Reason, 1991).

Maintenance Error in Aviation

The regulatory perspective. The two largest and most influential regulators in commercial aviation around the world are the Federal Aviation Administration (FAA) in the USA and the European Union Aviation Safety Agency (EASA). Despite acknowledging the safety concerns that arise from Maintenance Errors (EASA, 2024) and repeatedly referring to Maintenance Error in the regulatory design requirements (EASA, 2023) neither organisation provides a definition of what a Maintenance Error is. How has such a situation arisen and why is it important?

EASA has very detailed and specific regulation regarding the impact of cockpit design on the performance of pilots (EASA, 2023). This regulation and the subsequent work of HF professionals to try and reduce pilot error as much as possible has widely been credited with making modern aviation as safe and reliable as it is today (Mathavara et al, 2022). While EASA, as part of its plan for aviation safety, is currently trying to emulate the success of HF in the cockpit by running an initiative to better explore how to mitigate against Maintenance Errors through design (EASA, 2024) there remains no single regulation that requires HF to be considered in the design of maintenance tasks in the same way that HF is considered in the operation of an aircraft (EASA, 2023). Instead within CS25, the rules for designing large aircraft, there are multiple references to maintenance errors and the need for the design of certain systems to be "tolerant" of them, for example the wiring systems around fuel tanks (EASA, 2023). This can be attributed to the regulation evolving over time and in response to specific safety related occurrences. While there is nothing intrinsically wrong with this approach it does result in the non-consistent application of HF best practice across the aviation maintenance domain. What's more, without an agreed upon working definition of Maintenance Error how can designs be made "tolerant"? A problem cannot be solved without knowing what the problem is, and as such the first step in tackling Maintenance Errors should be to define what they are.

The perspective of airline operators. Away from the regulatory sphere, there have been a few attempts in the past at defining what a Maintenance Error means in an aviation context, though there remains no industry wide consensus with no definition being adopted nor in common use. One example that is fairly typical comes from Marx and Graeber (Marx, 1997) who define a Maintenance Error in an aviation context as "*an unexpected aircraft discrepancy attributable to the actions of an Aviation Maintenance Technician*". This definition is problematic insofar as it places the responsibility for committing the error firmly on the actions of the individual and so ignores the systemic nature of Maintenance Error as identified by Reason and Hobbs (Reason & Hobbs, 2003). This emphasis on the actions of the Maintenance Technician is a recurring element in commercial aviation and one of reasons why the issue of Maintenance Error has not been addressed in a systemic way.

The Boeing Maintenance Error Decision Aid (MEDA) model is the most ubiquitous model in use in aviation that is used solely for the analysis of Maintenance Error. While MEDA acknowledges the systemic nature of Maintenance Errors (Boeing, 1995) its classification system lends itself towards misunderstanding by users and toward an emphasis on the actions of the Maintenance Technician. By way of example, MEDA defines Maintenance Error as "*the error that directly leads to the event*" and specifies seven different error types including, Installation Error, Servicing Error and Repair Error. All of these error types create a framing that creates a causal link between the actions of the individual and the unintended event/occurrence and so detracts the organisation from looking for systemic solutions to their recurrent issues.

To better understand the issues faced by airlines when conducting analysis of in-service events that involve maintenance error, Airbus engaged with stakeholders and safety investigation professionals from six different major airlines that had a combined fleet of over 800 passenger planes. As part of this research 24 semi-structured interviews were conducted by videoconference and lasted between 1.30hr and 2hrs each with the results being analysed using Thematic Analysis (Braun & Clarke, 2006). It was found that airlines often struggled to mitigate against maintenance error recurring. Tools such as MEDA and HFACS would cause them to confound the symptoms of what went wrong (i.e. that the item was incorrectly repaired) with what the actual failing was within the socio-technical system that allowed such a symptom to manifest (i.e. why the item was incorrectly repaired). These findings would then be represented in the metrics of the airlines since the trend analysis of error was found to be closely linked to the classification methodology being used. By way of example, every airline reported that the most common maintenance error that they experienced was some variation on "component not installed correctly". This finding is a common one within the literature as well, with similar observations being made by Rankin & Sogg (2003) who were also analysing MEDA data. Knowing that the most common maintenance error in their organisation was parts being misinstalled was found to not be very useful to the Airlines as there are many Performance Shaping Factors (Kirwan, 1994) that could lead to a misinstallation and as such it was extremely difficult to implement effective mitigations to avoid repeat occurrences.

It should be reiterated that the MEDA methodology does take a systemic approach to addressing maintenance errors, unfortunately the evidence shows that many organisations across aviation struggle to apply MEDA in a way that allows them to effectively mitigate against repeat maintenance errors. Part of this problem is that these organisations do not understand the systemic nature of maintenance errors and/or do not have analytical tools that match their needs.

The systemic context

This paper has referred several times to the systemic nature of Maintenance Error, but what is this system that is being alluded to? Before attempting to provide a definition for Maintenance Errors in the aviation domain we must first consider the socio-technical system in which that maintenance is being conducted. This will help with contextualising the problem and help with understanding why it is valid to refer to Aviation Maintenance Errors (AME's) as their own phenomenon, with their own definition, rather than referring to Maintenance Errors that just so happen to be occurring in an Aviation environment.

If an attempt was made to describe in detail the systems-of-systems that covers the topic of maintenance, regardless of which domain that activity is occurring in, it is clear that the size of the system being described would be vast. Such a description would have to cover all maintenance activities on all human inventions that currently exist and would include everything from the domestic goods in a home to the International Space Station. The description of such an open system would either be so large as to be impractical, or so generic as to not give any useful insights. In contrast, aviation maintenance is a highly regulated field and as such it is a much more closed system that can be better defined and bounded. Such a well-defined boundary allows for the possible identification of common Performance Shaping Factors within that system that could contribute to Maintenance Errors occurring. Additionally, these Performance Shaping Factors could be of sufficient specificity and granularity to facilitate organisations with the identification of trends and the development of robust mitigations. In the aviation maintenance environment, a model depicting such a system-of-systems can be usefully thought of as an Aviation Maintenance System (AMS).

Figure 1 illustrates the AMS that governs how aviation maintenance is conducted in an organisation bound by EASA regulations. It shows that an AMS truly is a system-of-systems as it meets all five of the basic criteria proposed by Maier (1998); independence, evolutionary development, possessing emergent behaviour and being geographically distributed. This model shows that despite the complexity of the AMS, the system is very well defined with regulations setting standards in all three categories of Performance Shaping Factor as suggested by Galyean (2006); the individual, the organization, and the environment. For the individual PSF's we can see that not only are there standards for the training of mechanics and licenced engineers (Part 147 and Part 66) but also responsibilities laid upon the Part 145 organisation around how these standards are monitored and assured. For the organisational PSFs there are standards for the production of procedures (Part 145 and Part M) and how effectively these procedures are applied (Part M). For environmental PSFs, maintenance personnel can expect themselves to be working in a hangar of sufficient quality (Part 145) or on an aircraft built to a known standard (Part 21) and using standardised tools and spares (Part 145 and Part 21). While this AMS only covers maintenance conducted in the regulatory sphere of EASA, similar AMS's could be produced for organisations in other regulatory areas such as those covered by the FAA. Due to international agreements between regulators, such as the bilateral Aviation Safety Agreement between EASA and the FAA, it can reasonably be expected that models of other AMS's will just as comprehensively cover the Performance Shaping Factors that influence a maintainer conducting aviation maintenance.

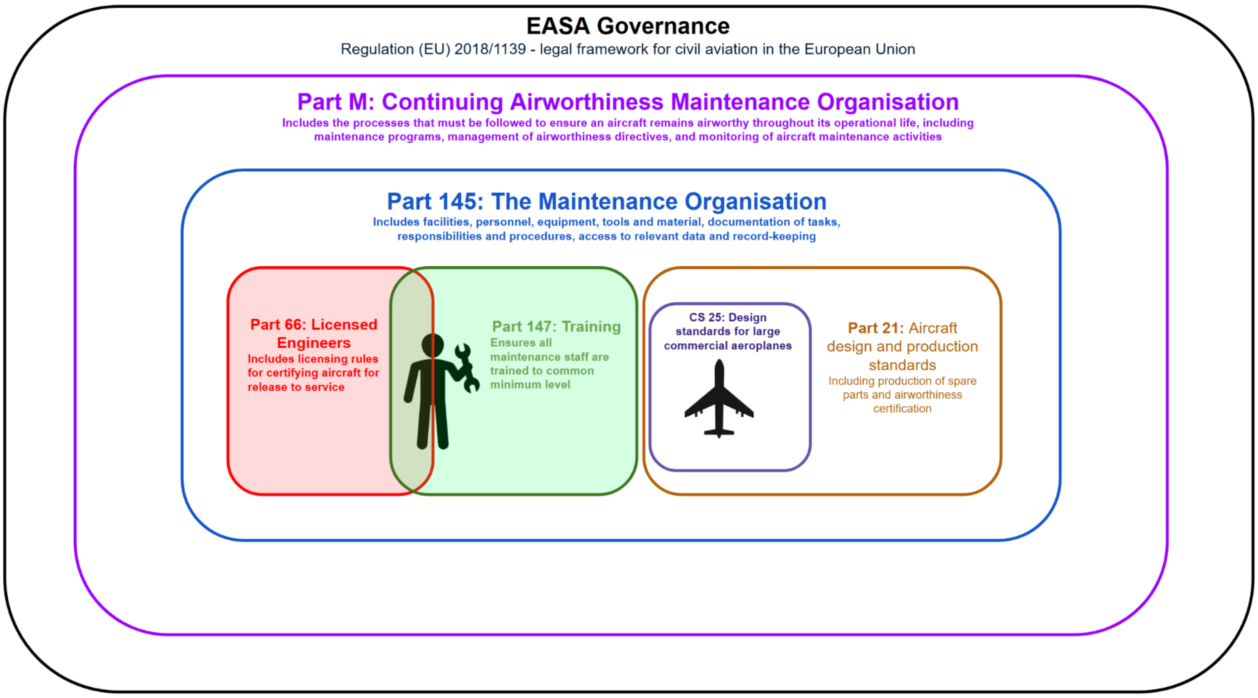

Figure 1**:** The Aviation Maintenance System (AMS) for an EASA approved maintenance organisation

Aviation Maintenance Error

Through the model of an AMS it now becomes easier to define Maintenance Error, but before doing so we must first consider what is maintenance and what is its purpose? *Maintenance* is defined as the *process* of ensuring that a system continually performs its intended function and at its designed-in level of reliability and safety (Kinnison & Siddiqui, 2013). Defining maintenance as a process shows that there is a difference between the word when meant in an engineering or technical sense versus when the same word is colloquially or commonly used to describe the act of what a maintainer does when carrying out their job role. An AMS *is the process* by which an aircraft is ensured to perform with both high safety and reliability. The AMS covers all aspects from when the aircraft was designed through to how it is maintained, who does the maintenance and where that maintenance is conducted. It includes all interdependencies and complexities that are required as part of that process occurring within a socio-technical system. It therefore becomes clear that when a Maintenance Error occurs in an aviation environment that something beyond the actions of the individual must also have contributed to the error occurring since the goal of the entire AMS is to avoid such a degradation of performance. It therefore follows that if it is useful to discuss the system which governs aviation maintenance in terms of an AMS, it becomes equally useful to discuss failures within that system-of-systems as Aviation Maintenance Errors (AMEs). This also helps to distinguish the concept of AMEs from the concept of maintainer error or from the term Maintenance Error when applied to non-aviation domains, which tend to be more open systems.

Based upon this reasoning, the following definition of an Aviation Maintenance Error (AME) within the context of the commercial aviation sector is therefore proposed: *When the Aviation Maintenance System (which includes people) allows, or could have allowed, a maintenance activity to be completed in a way that* ***does not*** *fully meet the* ***intended outcome*** *of the task as per the design intent or the regulatory requirements.*

Application of the definition

As previously described, many airlines struggle to mitigate against repeat occurrences of AMEs because the *symptom* of the error is often considered to be the *actual* error. By looking at a simple case study it is possible to see why this misperception is an issue and how the model of an AMS can be used as a tool to develop better solutions.

Use case. The misinstallation of components is continuously identified as the largest category of Maintenance Error identified by analysis (RAeS, 2022 and Rankin & Sogg, 2003). There are many different ways in which a misinstallation can occur, but one of the most common is through a configuration control issue. Configuration control refers to the process of ensuring that the aircraft always operates with the intended and approved configuration of components installed, so as to avoid unexpected system behaviors which could affect the safety of the aircraft. With an aircraft being made up of thousands of different parts this can be a complex task as different modifications are introduced over time and different combinations of components becomes possible.

On one occasion, an Airbus customer identified that one of their aircraft had been operating for some time with a component fitted that was not compatible with the current aircraft configuration as mandated by the approved Aircraft Technical Configuration document. The customer made a request to Airbus asking whether there was a safety concern with having this component fitted and, if not, would it be possible to add the item to the approved Aircraft Technical Configuration so as to avoid the nugatory replacement of the item. In this instance there was no safety concern and Airbus was able to approve the customer's request that the item remain fitted for the current configuration of the aircraft.

At the time, this sequence of events was not considered by the customer to constitute a Maintenance Error. As far as the customer was concerned the component was not misinstalled as there was no operational impact to the operator and consequently no further investigative action was taken. What this approach did not consider was that, despite the final outcome, there was still a latent error (Ramanujam & Goodman, 2003) within the systems-of-systems that allowed the aircraft to fly in a configuration that, at the time, was unapproved. By only focusing on the outcome, rather than on the error mechanism, there was no acknowledgement that it was only by pure luck that the aircraft could be approved to remain in this configuration. This also meant that without further action there remained the possibility that another incompatible component could be fitted to an aircraft, and that the checks and balances within the organisation may not be robust enough to immediately identify such an issue, as had previously happened. Had the operator understood the concept of AME in the context of an AMS then they would have been more likely to try and identify the contributing factors that led to this occurrence so that appropriate mitigating actions could have been put in place to prevent a similar event happening again in the future.

This use case therefore shows how the lack of an agreed definition for Maintenance Error within the aviation domain perpetrates misconceptions and contributes towards the issue not being systemically addressed.

Conclusion

This paper has attempted to provide a definition of Aviation Maintenance Errors that places the phenomenon within the systemic context of an Aviation Maintenance System. For regulators, airlines and manufacturers to effectively address AME such a definition, or something similar, must be adopted across the industry so that the issue can be properly discussed, analysed and mitigated against. Future work that would capitalise on this systemic approach would be the development of a taxonomy that allows for the identification and trending of Performance Shaping Factors at a sufficient level of granularity to allow organisations to identify the best way to mitigate against repeat occurrences of Aviation Maintenance Errors.

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