An overview of trends in aircraft maintenance program development: Past, present, and future

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ABSTRACT: The purpose of this paper is to describe the trends in aircraft maintenance program development during the last 50 years, including the reasons for the aircraft industry to change its view of maintenance. The major milestones and fundamental reasons for such development are also discussed and illustrated in relation to a flow diagram, which shows the logical and chronological order of the trends. Finally, the paper describes some possibilities and challenges as regards applying Information & Communication Technology (ICT) within the emerging approach of e-Maintenance in order to enhance the surveillance of aircraft maintenance program performance.

1 INTRODUCTION

Before 1950, technical items were mostly simple, which made them reliable and easy to maintain. The maintenance concept were mostly based on the belief that failures were mostly caused by wear and tear and the common maintenance strategy was Corrective Maintenance. By the late 1950s, the second generation of maintenance started, with the introduction of more complex items, mostly due to lack of labor and high performance requirements. With increasing complexity and criticality of items, the importance of a preventive maintenance program for failure management increased. However, one of today's major challenges remains how to determine the success of such maintenance programs.

The first part of this paper provides some background to the airlines' problems during the 1960s, with a short discussion on efforts leading to the publication of the first systematic review of aircraft systems, known as the MSG-1 and the MSG-2 methodologies. Next, the efforts of United Airlines, which led to the Reliability-Centered Maintenance (RCM) methodology are described, outlining how the preventive maintenance concept was influenced by system level thinking. The effect of RCM on the MSG methodology, which resulted in the publication of MSG-3, will also be described. All these developments and trends are discussed with the help of a flow diagram, which illustrates the developments in a logical and chronological order.

Finally, the possibilities and challenges related to e-Maintenance for the surveillance of an aircraft maintenance program's performance is discussed as a future development.

2 EARLY MAINTENANCE STRATEGIES AND RELATED PROBLEMS

Prior to World War II, maintenance was a skill learned through experience and rarely based on scientific theories. The maintenance requirements were determined by a few experienced technicians with assistance from the Original Equipment Manufacturer (OEM). The items were quite simple, which made them reliable and easy to maintain. In those days, the common maintenance strategy was Corrective Maintenance, based on the belief that the failures were mostly caused by wear and tear. Hence, the maintenance was applied in order to restore the functional capability of failed items. This was a reactive approach to maintenance since the action was done after the failure had occurred. This period of maintenance is known as 'Pre World War II'. (Moubray, 1997)

By the late 1950s, or 'Post World War II', the second generation of maintenance started to evolve. Industry became more competitive and a lack of manpower, improved design standards, and new performance requirements led to increasingly complex and mechanized items. Therefore, the maintenance of items required more downtime and resources. Hence, maintenance costs were high and availability became another problem. These changes, together with penalties associated with loss of production, forced industry to consider how to prevent the item from failing by applying Preventive Maintenance instead of relying on Corrective Maintenance.

In an effort to reduce the number of failures, industry concluded that, based on the accepted 'wear and tear' model of failure, every item had a 'fixed age' at which either complete overhaul or discard was necessary to ensure safety and operating reliability.

Based on these concepts, there was a widespread belief that all failures could be prevented by age-based overhaul. As a result, Time-Based Maintenance became the norm for Preventive Maintenance. This kind of approach motivated the indiscriminate use of overhaul or preventive replacement for all items included in a Preventive Maintenance program. (Tsang, 1995)

Consequently, the failure rate increased rapidly and maintenance costs grew accordingly. This prompted the airline industry to look for new preventive maintenance concepts. In addition, the Federal Aviation Administration (FAA) in the US was concerned that the reliability of some engines had not been improved by changing either the type or the frequency of overhaul. The available data indicated that although the frequency of some failures had been reduced, many more had remained unchanged or actually increased. These findings could not be explained by using the accepted model of failure. During this time, a new approach to maintenance evolved within the aircraft industry. Based on analysis of failure data, it was found that the probability of failure did not increase with operating age and the traditional time-based policies were found to be ineffective for controlling the failure rate of many items. (processonline, 2007)

During 1960, FAA was surprised that, notwithstanding many previous efforts, it was not possible for airlines to control the failure rate of a certain type of engine, by changing the scheduled overhaul policy. Moreover, due to congested continuous maintenance activities, fleet availability dropped significantly, causing operation and maintenance costs to increase rapidly without equivalent improvements in reliability. The reasons for the problems mentioned above can be summarized in the following nine areas:

1. Risk analysis was not considered in maintenance analysis. The objective of the maintenance activities was mostly to retain the technical characteristics of the items, rather than reduce or mitigate the consequences of item failures.
2. The objectives of preventive maintenance were not recognized. Consequently, the applicability and effectiveness criteria for maintenance tasks were not defined either.
3. The operating context was not considered in maintenance analysis. Therefore, one maintenance program was applied to all aircraft fleets regardless of operating profile, weather, operator, etc. This approach was insufficient, since the operating context affects the failure characteristics and changes the failure rate. Hence, the maintenance task and its interval applicable to one operating context may not be applicable to another.
4. Maintenance was applied to control the degradation of functional performance and reliability of all items. It was believed that there was always an appropriate maintenance task to retain the inherent reliability or to restore the functional performance of the items. However, it is now known that, due to the nature of some failures, it might be impossible to retain or restore the item performance to the designated level. Hence, some of the maintenance tasks were inappropriate and contributed to anomalous maintenance effort and downtime without giving any benefits. It should be noted that inherent reliability is a function of design and cannot be improved without redesign or modification.
5. It was incorrectly assumed that all items had age-related failure characteristics and would benefit from age-based maintenance measures. Therefore, specific actions, mostly overhaul measures, were planned for every item. However, according to the reliability investigations conducted by United Airlines, no more than 11% of the items would benefit from a limited operating age or scheduled overhaul. Thus, for the remaining 89% of the items, these were inappropriate maintenance measures, which contributed to unnecessary maintenance efforts and non-beneficial downtime.
6. Prescribing hard-time actions for non-age-related failures had an adverse effect on the availability and reliability of the items, because it contradicted the actual failure characteristic and degradation processes. Therefore, serviceable items were unnecessarily removed from service and sent to shops for overhaul or other maintenance measures. This intrusive maintenance practice had a negative impact on manpower resources, spare parts, down time, total costs, and availability performance.
7. Since there is seldom any strong relationship between the items operating time and failure probability, many failure modes did not benefit from age-based shop visits. These failures were one of the main sources of unscheduled corrective maintenance, sudden aircraft unavailability, and disturbed operation. Even though many failure modes are not age-related, it is most often possible to identify and recognize the conditions that indicate an imminent functional failure. Hence, it is possible to apply On-Condition measures, i.e. scheduled inspections designed to detect a poten-

tial failure condition, in order to initiate preventive maintenance actions and thereby avoid the functional failure or its consequences. (Moubray, 1997)
8. All the items of systems were considered for maintenance regardless of the importance of their functions for system availability. Hence, limited maintenance budgets were not distributed in accordance with the importance of the items function for availability performance of the system.
9. Previous experience in the development of scheduled maintenance instructions had revealed that a program of effective maintenance measures could be developed through the use of logical analysis and decision-making processes. Hence, there was a need for a structured decision process to assess the maintenance requirements of the systems, and to develop an applicable and effective maintenance program.

In order to respond to the above-mentioned challenges and to find a proper solution, FAA formed a task force, including representatives from both FAA and American Airlines. The purpose was to evaluate the effectiveness of traditional time-based maintenance, investigate the capabilities of scheduled maintenance, and find the possible relationship between scheduled maintenance and reliability. These analyses gave rise to the following surprising discoveries (Kennedy, 2005; Equipment Links, 2007; processonline, 2007):

- Scheduled overhauls had little or no effect on the overall reliability of a complex item unless it had a dominant failure mode.
- There were many items for which there was no effective form of scheduled maintenance.
- Many types of failures could not be prevented or effectively reduced by 'right-age' overhauls, no matter how intensively they were performed.
- Cost reductions in maintenance could be achieved with no decrease in reliability.
- The intrusive nature of the overhauls was itself a major cause of unreliability.

The outcomes of the efforts mentioned above led to the first formal "FAA - Airlines Reliability Program" being issued in November 1961. The program was developed to improve the control of reliability through an analysis of the factors that affect reliability and to provide a set of actions to improve low reliability levels when necessary. As the propulsion system had been the area of greatest concern, and since power plant data was readily available for study, programs were developed for the propulsion system first. The introduction to that program stated that (Nowlan & Heap, 1978):

"…in the past, a great deal of emphasis has been placed on the control of overhaul periods to provide a satisfactory level of reliability. After careful study, the Committee is convinced that: reliability and overhaul time control are not necessarily directly associated topics; therefore, these subjects are dealt with separately."

3 THE FIRST STRUCTURED MAINTENANCE PROGRAM PROCEDURES: MSG-1 & MSG-2

United Airlines started a research program in 1965, to substantiate the outcomes of the FAA task force and to provide a generally applicable systematic review of the aircraft design. Hence, in the absence of operational experience, the best maintenance process should still be utilized through a structured logical decision tree. In June of 1967, T.D. Matteson and F.S. Nowlan presented a paper on the use of this methodology at an aircraft design and operations meeting of the American Institute of Aeronautics and Astronautics (AIAA). As a result, rudimentary decision logic was created and over the next few years, it was developed with the cooperation of airlines, manufacturers, and FAA. The methodology was used to develop the Boeing-747 initial maintenance program document. This document was published on 10 July 1968 by ATA under the title "Boeing-747 Maintenance Steering Group (MSG) Handbook: Maintenance Evaluation and Program Development (MSG-1)" (Nowlan & Heap, 1978). This was the first attempt at applying reliability-centered maintenance concepts when developing an aircraft maintenance program.

MSG-1 was a 'bottom-up' approach to the Boeing-747 systems, in which components were the highest level to be considered. Hence, MSG-1 focused on a component such as the Fuel Control Unit (FCU) in a system and analyzed which part of that component might fail. Then, it was determined what kind of maintenance action was required to prevent the failure. Through MSG-1, the potential maintenance measures for each maintenance strategy were selected and evaluated from criteria based on operating safety or essential hidden function protection. The remaining potential maintenance tasks were evaluated to determine if they were economically viable.

MSG-1 introduced three broad processes to classify the scheduled maintenance requirements, i.e. Hard Time (HT), On-Condition (OC), and Condition Monitoring (CM). OC requires an item to be periodically checked, or tested, against an appropriate physical standard to determine whether the item can continue in service or not (Nakata, 1984).

The efficacy of the systematic MSG-1 methodology applied to Boeing-747 was considered to justify a generic solution, which could be applied to other new aircraft. This resulted in the publication of a second document by ATA in 1970 as MSG-2: "Airline manufacturer maintenance program planning document". This document was used to develop the maintenance programs for aircraft such as the L-1011 and DC-10. (Smith & Hinchcliffe, 2004)

The objective of the two MSG methodologies was to develop scheduled maintenance programs that assured maximum safety and reliability of the item, at the lowest possible cost. MSG-1 and MSG-2 both followed the same process, but MSG-2 was a generic document, and non-aircraft type-related (Nowlan & Heap, 1978) .

Subsequently, in 1972, United Airlines used the idea of MSG-2 under the US Department of Defense (DOD) contract to develop the P-3A and S-3A maintenance programs, and the F-4J program in 1974. (Smith & Hinchcliffe, 2004)

An enhanced document was also prepared in Europe, called EMSG-2. It was used to develop maintenance program requirements for such aircraft as the Airbus A-300 and Concorde.

MSG-2 and EMSG-2 continued to use a 'bottom-up' approach to aircraft systems and were 'maintenance process oriented', whereby the integrity of components in sub-systems was considered before those of the overall system

The most important advantage of MSG-1 and MSG-2 was the application of On-Condition (OC) maintenance, which made them unique. The introduction of OC began an era of new thinking. It was permissable to let an aircraft pass an immediate maintenance check with known deterioration, degradation or wear, and postpone the required maintenance action until the next earliest opportunity, as long as the appropriate physical standard and prescribed limitations were met. This approach helped the operators to have fleets that were more available and made planning more flexible. Moreover, since the cost of correcting potential failures is often far less than the cost of correcting functional failures, OC maintenance reduced the maintenance costs. Furthermore, OC maintenance strongly reduced the number of irrelevant scheduled overhauls, which was the main source of 'infant mortality' and unreliability. In addition, by avoiding premature removals of items that were still in a satisfactory condition, required spare part volumes were reduced.

Depending on the operating context of the asset, warning of incipient failure enables the users of an item to reduce or avoid consequences in a number of ways (Moubray, 1997):

1. Down time: corrective action can be planned at a time that does not disrupt operations.
2. Maintenance costs: the user may be able to take actions to eliminate the secondary damage, which would be caused by unanticipated failures. This would reduce the downtime and the maintenance costs associated with the failure.
3. Safety: warning of failure provides time to either shut down an item before the situation becomes dangerous, or to move people out of harm's way.

Today, OC tasks are well known because the inspected items are allowed to be left in service 'on condition' that they continue to meet specified performance standards (Moubray, 1997), until a potential failure is detected. For example, as many as 400 items that might have required scheduled overhaul prior to MSG-1/MSG-2/EMSG-2 were reduced to about 10 afterwards (ATE&M, 2001) .

In 1975, NAVAIR rewrote the MSG-2 procedures, to apply an 'analytical maintenance program' to naval aircraft and engine programs, which resulted in "NAVAIR Systems Command (NAVAIR 00-25-400)". This was applied to in-service naval aircraft and the manual was utilized to revise the preventive maintenance requirements for most of the Navy's in-service aircraft. (MIL-STD-2173)

The MSG-2 methodology revolutionized Navy procedures for developing preventive maintenance programs; but there were still aspects to consider for further development of both MSG-2 and NAVAIR 00-25- 400 documents. For example, they did not cover the procedures for developing inspections intervals and for refining the initial analysis. (MIL-STD-2173)

Moreover, the effectiveness criteria for different maintenance strategies and failure consequences were not considered and there was still a problem of balancing the requirements of cost and dependability. In addition, there was still pressure to decrease maintenance costs. In fact, the incentives to reduce the cost were changed from technical and engineering issues during design to economical issues and cost-effective maintenance during operation. As a result, the industry was expected to construct a framework that incorporated cost-effective maintenance strategies.

4 INTRODUCTION OF RELIABILITY-CENTERED MAINTENANCE

The US Department of Defense (DOD) sponsored United Airlines to write a comprehensive report, entitled "Reliability-Centered Maintenance (RCM)" (MIL-STD-2173). Stanley Nowlan and Howard Heap of United Airlines wrote this report in 1978 as the initial RCM Bible (DOD report AD-A0665791). The report gave a detailed rationale and analytical logic, which required a fundamental shift in the current methodology for maintenance program development (i.e. MSG-2).

RCM is a methodology that supports a well-structured, logical decision process used to identify the policies needed to manage failure modes that could cause the functional failure of any physical item in a given operating context. These policies will reduce the risk of function loss and are: Preventive Maintenance, Predictive Maintenance, or Redesign. Hence, RCM can be considered as an overall risk management program, to effectively manage the risk of function losses through effective maintenance.

As one of the major elements in risk management is reliability, the RCM methodology is used to develop and optimize the preventive maintenance and inspection requirements of an item in its operating context to achieve its inherent reliability, where inherent reliability can be achieved by using an effective maintenance program.

Any RCM methodology shall ensure that all the following seven questions are answered satisfactory in the order given below (Rausand, 1998):

1. What are the functions and associated performance standards of the item in its present operating context (function)?
2. In what ways does it fail to fulfill its functions (functional failures)?
3. What are the causes of each functional failure (failure modes)?
4. What happens when each functional failure occurs (failure effects)?
5. In what way does each failure matter (failure consequences)?
6. What can be done to prevent each failure (proactive tasks and task intervals)?
7. What should be done if a suitable preventive task cannot be found (default actions)?

In order to answer the questions above, RCM uses a structured decision diagram, and encompasses the well-known Failure Mode & Effects Analysis (FMEA) methodology to identify functions, functional failures, and failure modes of an item. Furthermore, FMEA classifies the severity of each failure effect according to severity classification criteria established by each program. Hence, the quality of the RCM analysis strongly depends on the quality of the FMEA execution.

The RCM logic requires an age exploration program for all maintenance tasks where reliable historical information is not available. It also requires an independent auditing of all performed analyses, see Nowlan & Heap (1978) and Moubray (1997). In contrast to earlier methodologies supporting maintenance program development (e.g. MSG-1 and MSG-2), the RCM methodology was based on:

- System level instead of component level.
- Top-down instead of bottom-up approach.
- Function preservation instead of failure prevention.
- Task-oriented instead of maintenance process oriented.
- Consequence-driven, where the consequences of failures are far more important than their technical characteristics.

In an RCM process, the consequences of every failure have to be analyzed. It should clearly separate hidden failures from evident failure modes, and distinguish events that have safety, environmental, operational and or economic consequences.

By using an approach based on system level and function preservation, RCM treats components differently in terms of relative importance according to the correlation between the equipment and system function. Huge benefits can be derived by implementing RCM. These achievements include higher safety and operating performance, better understanding of the failure modes, and reduction of operation and maintenance costs (Tsang, 1995). Figure 1 illustrates how the maintenance concept has changed in a

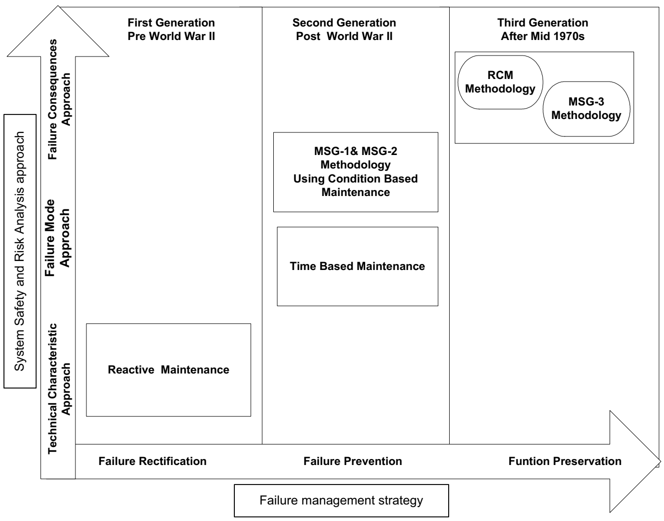

Figure 1: Changes and milestones in maintenance methodology development with regard to risk and failure management.

logical and chronological order.

Since Nowlan and Heap's report, RCM has been widely used by different industries, such as the nuclear and power generation industries, offshore oil and gas industries, and has been refined, developed, and customized to their specific requirements.

5 PUBLICATION OF MSG-3

A decade after MSG-2 was published and subsequent to Nowlan and Heap's report, US Association of Air Transport (ATA) formed another task force to review MSG-2 experience in 1979. In this review, it became obvious that there were some areas for improvement (Overman et al., 2003; ATA, 2005):

- The rigor of the decision logic.
- The clarity of the distinction between economics and safety.
- The adequacy of treatment of hidden functional failures.

The high fuel price increased the total operating cost of aircraft, and the pressure to decrease maintenance costs was still present. In addition, the development of new-generation aircraft, new regulations and new damage tolerance rules for structures, which had a heavy influence on maintenance program development including the new premises of Nowlan and Heap's RCM methodology, provided in the basis for the development of a new, improved "Airline/Manufacturer Maintenance Program Planning Document MSG-3", published by ATA in 1980. (Transport Canada, 2003; ATA, 2005)

This methodology was a combined effort by the manufacturers, regulatory authorities, operators, and ATA. The MSG-3 methodology implicitly incorporated the principles of RCM to justify task development, but stopped short of fully implementing reliability-centered maintenance criteria to audit and substantiate the initial tasks being defined (Transport Canada, 2003).

Since Nowlan and Heap's report served as the basis for MSG-3, it made major departures from MSG-2. Hence, MSG-3 involves a top-down, system-level, and consequence-driven approach, to classify failure effects in one of the failure consequences categories, see Figure 2. Since its original publication, MSG-3 has been revised five times. Revision 1 was issued in 1988 and revision 2 in 1993. MSG3-2001 and MSG-3.2002 were issued in 2001 and 2002 respectively and the latest revision was made in 2005. (ATA, 2005)

Methodology	Characteristics
MSG-1 **(1968)**	• Bottom-up approach • Component level • Maintenance process oriented • Aircraft type-related (Boeing-747) • Using On-Condition and Condition-Based Maintenance
MSG-2 **(1970)**	• Same as MSG-1 • Generic document, non-aircraft typerelated
MSG-3 **(1980)**	• Generic document • Top-down approach • System level • Maintenance task oriented • Emphasis on structural inspection programs • More rigorous decision logic diagram • Distinction between safety and economy • Hidden functional failure treatment

Figure 2: Summary of some of the major conceptual differences and improvements between MSG-3 and previous versions of the methodology.

6 FURTHER DEVELOPMENTS OF RELIABILITY-CENTERED MAINTENANCE

One of the most valuable efforts to develop RCM methodologies was performed by the US Department of Defense (DOD), and was initiated by the AD-A066579 report published in 1978. This report was based on the principles of MSG-logic and was the foundation of the most modern RCM methodologies. Based on that report, DOD issued several documents related to RCM analysis; most notably, Military Handbook (MIL-HDBK) 266, "RCM Requirements for Naval Air-craft, Weapons Systems and Support Equipment" in 1981, which superseded NAVAIR 00-25-400 for all applications of RCM-decision logic. It also applied the principles of RCM (as covered by the DOD report and MSG-3) to Naval aircraft, weapons systems and support equipment. (Leverette et al., 2005)

In 1985, as another effort, US Air Force (USAF) issued MIL-STD-1843: "RCM Requirements for Aircraft, Engines and Equipment". This standard was similar to MSG-3, which was cancelled without replacement in 1995. In 1986, DOD issued MIL-STD-2173, "RCM Requirements for Naval Aircraft, Weapons Systems and Support Equipment" (MIL-STD-2173; Leverette et al., 2005).

In the early 1990s the DOD decided that new acquisitions should rely, as much as possible, on commercial or performance standards, instead of using Military Standards. As a result, a group called

“Reliability, Maintainability and Supportability (RMS) Partnership”, began coordinating the efforts of various other organizations involved in developing related standards. Since no equivalent commercial standard existed at that time, the RMS Partnership requested the Society of Automotive Engineers (SAE) to lead the development of an RCM standard (Leverette et al., 2005).

The SAE RCM subcommittee initially consisted of representatives from the US Navy and some DOD contractors. As the group was supposed to find out more about the lessons learned through commercial industry efforts, John Moubray and some of his colleagues became involved in late 1997. With new participation and a clearer direction, the group was able to complete the SAE JA1011 standard in 1999.

7 AIRCRAFT MAINTENANCE PROGRAM SURVEILLANCE

The main objective of an aircraft maintenance program is to ensure that the aircraft meets and continues to meet the designed function to serve dependable and airworthy services. Hence, it is important for operators to determine any deviation from this objective and to assess the success of the program after bringing the aircraft into operation.

Today, it is known that an aircraft’s reliability and safety will be strongly affected by its operating context, e.g. operator organization, humidity, temperature, utilization load, and so on. Hence, the original assumption of effectiveness criteria made during the design of the initial aircraft maintenance program will probably change and the surveillance of the aircraft maintenance program will be important. In order to manage this surveillance, the operators normally follow a defined surveillance program, which has been approved by the authorities.

In an ideal world, an applicable and effective maintenance program would ensure that there were no failure events between scheduled aircraft maintenance tasks. However, due to differences between design assumptions and actual operational conditions, each maintenance program must be adjusted to achieve this ideal situation. (Moubray, 1997)

According to official FAA research “Continuing Analysis and Surveillance System (CASS)” , an effective continuous airworthiness maintenance program should identify elements that are detrimental to the overall effectiveness of the air carrier’s maintenance program, and correct any deficiencies before they become systematic problems. Therefore, the operators should develop indicators to determine possible deviations from defined objectives and to measure the effectiveness of an aircraft maintenance program. These objectives might be based on risks related to health, business, safety, environment, property, and on-time services.

According to MIL-STD-2173, ‘effectiveness’ is a measure of the result of the task objectives, which is dependent on the failure consequences. Therefore, the effectiveness of applicable tasks in preventing the failure consequences must be determined. Hence, for each failure consequence, it is possible to develop indicators according the effectiveness criteria as follows:

- Safety: the task must reduce the risk of failure to assure safe operation.
- Operation: the task must reduce the risk of failure to an acceptable level from an operational point of view, or remove the operational consequences.
- Economics: the task must be cost-effective.

In order to measure the performance of an aircraft maintenance program, actual operational and support data are necessary. This data can be obtained from sources such as aircraft inspections, pilot reports, air safety reports, scheduled maintenance findings, reliability programs, unscheduled maintenance actions, deferred maintenance actions, teardown reports, recorded flight data, and so on.

However, gathering data and converting it to information is very time-consuming. In addition, the effectiveness of these analyses will decrease with time. To mange these difficulties, e-Maintenance is one promising approach.

8 E-MAINTENANCE AND MAINTENANCE PROGRAM SURVEILLANCE

Information resources are critical to maintenance and maintenance support, for example to support surveillance of an aircraft maintenance program’s performance. Hence, technological opportunities to improve the surveillance, such as innovative design features in the aircraft or its support system utilizing new technology applications can help to improve the maintenance program. The inclusion of developing technologies can also avoid early obsolescence and extend the useful life of the aircraft at the same time as availability performance and Life Cycle Costs (LCC) are improved. One example of new technology is Information & Communication Technology (ICT), which to an increasing degree is included in both the aircraft and its support system and that also integrates the two. The application of ICT within maintenance and maintenance support enables the emerging approach of e-Maintenance. (IEC 60300-3-14; Candell et al., 2007)

e-Maintenance is the application of ICT for remote maintenance (i.e. maintenance of an item performed without the maintenance personnel having physical access to the item) and for representing the physical world in an digital model aimed at supplying tailored information such as decision support regarding appropriate maintenance activities for all stakeholders independent of time, geographical location, or organizational affinity. Hence, the e-Maintenance approach is not limited to the management of condition monitoring data, explicit technologies, or any specific support service solution. (Candell et al., 2007)

One important source of information that supports maintenance program surveillance is the maintenance database, which should be structured so that it facilitates the seamless transfer of data to other databases (e.g. the maintenance work order system) and analysis tools (e.g. RCM software) used by stakeholders involved in maintenance program development. However, it is also important that the maintenance database is kept under configuration control to ensure that it reflects the latest design standard of the aircraft and its indenture levels, to provide an audit trail and to ensure the integrity and consistent use of support data. The database should also be kept up-to-date to reflect changes in customers' use and requirements and thereby provide the guidance necessary for future maintenance program development. In this context, e-Maintenance facilitates the use of one single maintenance database that is shared by all involved stakeholders, which in turn decreases the risk of redundant, contradictory, and obsolete data (IEC 60300-3-14; Söderholm, 2007).

Another important source of information for maintenance program surveillance is the maintenance work order system, which is used to initiate, control and document specific maintenance tasks. As stated in the maintenance program, a maintenance task is either triggered by a predetermined time measure (e.g. calendar time, number of flights, or flight hours) or the item's actual condition. The work order is used to identify and plan required resources and to schedule execution of the work. Finally, it is used to record results, observations, and resources actually used, which all provide the basis for assessment and improvement of the aircraft maintenance program. An appropriate e-Maintenance solution should enable easy access to the maintenance work order system and also integration with other maintenance systems. (IEC 60300-3-14; Candell et al., 2007)

Another important part of an e-Maintenance solution, which also is valuable for maintenance program surveillance, is Built-in-Test (BIT) systems included in the aircraft. Using BIT systems it is possible to analyze the failures at the exact point in time when they occur at a specific indenture level of the aircraft during operation. Operational data that should be monitored and recorded include data on bus inputs, strain gauge and other dynamic data, propulsion parameters, BIT failure data, and environmental data. Continuous monitoring of the aircraft's condition helps to identify the nature of intermittent faults and the stresses imposed on an item during operation. Hence, it is possible to obtain an enhanced understanding of failures, failure modes, failure mechanism, and failure effects. However, in addition to digitally monitored parameters, relevant operator and maintainer observations, which cannot be digitally recorded, such as decisions based upon various circumstances, should also be recorded. All this data can act as input to the surveillance of the maintenance program's performance and update the engineering judgments made during initial aircraft maintenance program development. (Söderholm, 2007)

As described above, one important aspect of e-Maintenance is the combination of maintenance and ICT. Hence, it is necessary to have expertise in both areas in order to achieve a good e-Maintenance solution that satisfies the requirements for aircraft maintenance program surveillance. Thereby, maintenance and maintenance support may be seen as the problem domain to which selected and adapted ICT is used as a solution. (Candell et al., 2007)

Some of the obstacles related to e-Maintenance, which have to be overcome in order to achieve effective and efficient maintenance program surveillance, are (Karim & Söderholm, 2007):

- Heterogeneous organizations: there are different structures in the organizations involved in providing and receiving maintenance and maintenance support.
- Heterogeneous ICT-environments: there are differences in technology in systems that are normally used for different purposes, but are needed to exchange information in order to support maintenance program surveillance.
- Information integration strategy: it is necessary to have a strategy to integrate a number of different types of hardware and software in a seamless manner. The content type has an impact on the overall ICT strategy.
- Documentation and archiving strategies: it is essential to provide and manage documentation of different types. The context requires different types of strategies for storage, distribution, safety, security, accessibility, availability, reliability, archiving, and destruction.

One example of a civil aircraft with on-board technologies that support an e-Maintenance solution for aircraft maintenance program surveillance is the Boeing-787, which will be certified during 2008. The aircraft's on-board technologies will also be integrated with off-board technologies within the support system. Another similar example is the intelligent software Airman, which is provided by Airbus. This software can connect the different sources of maintenance information in a seamless manner and also provide tailored information to different stakeholders. In military aviation, the Joint Strike Fighter (JSF) program is one example where on-board and off-board technologies are integrated in order to achieve an autonomic logistics system. Another military example is the Maintenance Work Station (MWS) efforts connected to the Swedish combat aircraft JAS 39 Gripen. These aircraft systems are examples where e-Maintenance will be very beneficial to aircraft maintenance program surveillance. The reason is that e-Maintenance enables measures supporting surveillance of aircraft maintenance program effectiveness to be more or less automatically collected, analyzed into indicators, and distributed to concerned stakeholders independent of the maintenance echelon.

9 CONCLUSIONS

This paper describes the trends in aircraft maintenance program development during the last 50 years, including milestones such as different versions of MSG and RCM.

Examples of fundamental changes described are: from failure correction to failure prevention; from time-based to condition-based maintenance, from bottom-up to top-down analysis; from component level to system level analysis; from technical characteristics to failure consequences; and from item rectification to function preservation.

Furthermore, the paper describes some of the reasons for these changes, e.g.: item complexity, system dependence, competition, and failure consequences, but also increasingly stringent requirements related to: dependability, costs, airworthiness, sustainability, and safety.

The paper ends with a description of challenges and possibilities related to e-Maintenance, which is believed to promote effective and efficient surveillance of an aircraft maintenance program in a near future.

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