NORTH ATLANTIC TREATY ORGANISATION

RESEARCH AND TECHNOLOGY ORGANISATION

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RTO TECHNICAL REPORT **TR-AVT-144**

Enhanced Aircraft Platform Availability Through Advanced Maintenance Concepts and Technologies

(Amélioration de la disponibilité des plateformes d'aéronefs par l'utilisation des technologies et des concepts évolués de maintenance)

The Report of an investigation by the AVT-144 Technical Team, which includes information contributed during the Workshop documented in RTO-MP-AVT-144.

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The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Table of Contents

List of Figures

List of Tables

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Note:

This report includes information obtained from the following sources: papers by invited specialists at a three-day AVT-144 Workshop held in Vilnius, Lithuania in October 2006; discussions at the Workshop; supplementary papers by invited specialists; and research of the open literature. Information from papers has in most cases been substantially edited. All the known authors and co-authors of papers are listed above, and their contributions are acknowledged in the text of the report. Where there is no such acknowledgement, the Chairman is responsible for the content. All papers submitted by the authors are being published unedited in separate Workshop Proceedings. In addition to obtaining publication clearance for individual papers, an attempt was made to give all participants in the Workshop, as listed in Annex A, an opportunity to check the report before publication. Nevertheless, the Chairman remains responsible for any errors. All views expressed in this report and the separate proceedings are the private views of the authors and participants, and do not necessarily reflect the official policies of their governments.

Enhanced Aircraft Platform Availability Through Advanced Maintenance Concepts and Technologies

(RTO-TR-AVT-144)

Executive Summary

Aircraft platform availability is a key component of military capability and an important measure of the readiness and effectiveness of a force. Aircraft availability is generally viewed as average availability on the flight line. However, the continued availability of aircraft during missions – usually expressed as "mission reliability" – is an important component of overall availability. With the increasing involvement of NATO in expeditionary operations, there is now a need to place more emphasis on availability and mission reliability, together with an enduring ability to provide these in tactical deployments with a small logistics footprint. There has been a trend to concentrate more capability in fewer aircraft. This trend has heightened the importance of platform availability, while making it more difficult to achieve. The report identifies advanced maintenance/support concepts and technologies that could enhance aircraft availability.

To maximise aircraft availability it is necessary to minimise the need for maintenance and the associated downtime. The need for maintenance is minimised by optimising the inherent (design) reliability and mission reliability, achieving these inherent values in operational service, and performing only essential maintenance. Maintenance downtime is minimised by designing the aircraft for maintainability (ease of maintenance) and managing the maintenance/support system to minimise the downtime for needed maintenance. The attrition of aircraft during combat could have a devastating effect on aircraft availability and force capability. For this reason, special measures are needed to enable the rapid assessment and repair of battle damage.

Management concepts and technologies can have a large influence on progress towards these goals, and are constantly evolving. Systems engineering is the management concept that provides the structure and logic behind the design of an aircraft and its maintenance/support system, through processes such as Reliability Centred Maintenance (RCM), Integrated Logistics Support (ILS), and Reliability and Maintainability (R&M) management. It also provides the framework for maintenance/support and technology insertion throughout the life-cycle. Advanced systems engineering concepts must be blended with management concepts that promote efficiency. Fortunately, efficiency and availability are mutually supportive objectives.

There is a wide range of advanced aircraft and support equipment technologies that could be used to reduce the need for maintenance and the associated downtime. The mainstream of relevant R&D is in concepts and technologies to improve reliability, mission reliability, and the speed, scope, resolution, and accuracy of usage monitoring, inspections, and diagnostics. Part of this effort is directed at increasing the automation of maintenance functions by increasing the capabilities of on-board maintenance (health management) systems. The associated sensor and processing systems tend to increase complexity and cost, but technologies are being developed to mitigate these disadvantages by allowing greater integration with other aircraft avionics. Since considerable fleet downtime is caused by structural inspection and repair related to fatigue and corrosion, there continues to be considerable R&D effort to reduce this downtime. Important advances have been made.

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Amélioration de la disponibilité des plateformes d'aéronefs au moyen de concepts de maintenance et de technologies évolués

(RTO-TR-AVT-144)

Synthèse

La disponibilité des plateformes d'aéronefs est une composante clé de la capacité militaire et une mesure importante de l'état de préparation et de l'efficacité d'une force. La disponibilité d'un aéronef est généralement vue comme la disponibilité moyenne en ligne de vol. Cependant, la disponibilité continue d'un aéronef au cours d'une mission – sous l'expression usuelle de « fiabilité de mission » – est une composante importante de la disponibilité globale. Avec l'engagement croissant de l'OTAN dans des opérations expéditionnaires, le besoin se fait sentir actuellement de donner plus de place à la disponibilité et à la fiabilité de mission ainsi qu'à la capacité de fournir durablement celles-ci dans des déploiements tactiques avec une faible empreinte logistique. Une tendance a été de concentrer plus de capacités sur moins d'aéronefs. Cette tendance a augmenté l'importance de la disponibilité des plateformes tout en la rendant plus difficile à obtenir. Le compte-rendu identifie des concepts et des technologies de maintenance et de soutien évolués qui puissent améliorer la disponibilité des aéronefs.

Afin d'optimiser la disponibilité des aéronefs, il est nécessaire de réduire au minimum le besoin en maintenance et l'immobilisation au sol associée. Le besoin en maintenance est réduit au minimum en optimisant la fiabilité inhérente et la fiabilité en mission, en traitant ces paramètres pendant le service opérationnel, et en effectuant seulement la maintenance essentielle. L'immobilisation en maintenance est réduite au minimum en concevant l'aéronef en vue de sa maintenabilité (facilité de maintenance) et en gérant le système maintenance/soutien de façon à réduire au minimum l'immobilisation nécessaire à la maintenance. L'attrition des aéronefs au combat peut avoir un effet dévastateur sur la disponibilité et la capacité des forces. Pour cette raison, des mesures particulières doivent être prises pour permettre une évaluation rapide et une réparation des dommages causés au combat.

Les concepts et les technologies de gestion peuvent avoir une grande influence pour progresser vers ces objectifs, et sont en constante évolution. L'ingénierie des systèmes est le concept de gestion qui fournit la structure et la logique de conception d'un aéronef et de son système de maintenance/soutien, par des processus tels que la Maintenance centrée sur la fiabilité (MCF), le Soutien Logistique Intégré (ILS), et la gestion de la Fiabilité et Maintenabilité (R&M). Elle fournit aussi le cadre de la maintenance/soutien et l'intégration de la technologie sur le cycle de vie. Les concepts d'ingénierie des systèmes évolués doivent se fondre avec les concepts de gestion qui assurent l'efficacité. Heureusement, l'efficacité et la disponibilité sont des objectifs qui se soutiennent mutuellement.

Il existe une large gamme de technologies d'aéronefs évolués et d'équipements de soutien qui peuvent être utilisées pour réduire le besoin en maintenance et les immobilisations associées. Le courant dominant de la R&D en la matière repose sur des concepts et des technologies destinées à améliorer la fiabilité, la fiabilité en mission, ainsi que la vitesse, la portée, la résolution, et la précision de la surveillance de l'utilisation, des inspections, et des diagnostiques. Une partie de ces travaux est dédiée à l'augmentation de l'automatisation des fonctions de maintenance, en élargissant les capacités des systèmes de maintenance embarqués (gestion de l'état). Les systèmes de traitement et les capteurs associés tendent à augmenter la complexité et le coût, mais des technologies sont développées actuellement pour diminuer ces désavantages en permettant une plus grande intégration avec d'autres avioniques. Etant donné qu'une immobilisation importante de la flotte est due à des inspections et des réparations structurelles en relation avec la fatigue et la corrosion, les efforts R&D devront continuer à être considérables pour réduire cette immobilisation. Des progrès importants ont été faits.

The Workshop was held in Vilnius, Lithuania, from 3 to 5 October 2006. It was attended by over eighty invited specialists from thirteen NATO Nations and two Partner Nations (Sweden and Australia). Participation was by invitation only. Most of the participants were senior engineers and managers with relevant hands-on experience from industry, the Armed Forces, and other government organisations. A list of the participants is in Annex A. The Workshop was larger and wider in scope than is normally envisaged for RTO Workshops. Thirty-four authors made presentations and most of these submitted formal papers for the Workshop Proceedings. The Workshop Program is presented in Annex B. Some supplementary papers, which are also listed in Annex B, were invited after the Workshop to fill important gaps in information.

The report is based on the invited papers and discussions at the Workshop, the invited supplementary papers, and a review of the open literature. All submitted papers are being published in Workshop Proceedings separately from this report. The material from papers used in the report has been substantially edited, and in some cases divided into different sections of the report. The incorporation of material from papers has resulted in some variations in writing style and the use of English throughout the report.

In view of the wide scope of the investigation, the AVT-144 Technical Team decided to partition its investigation and the Workshop as follows:

a) National perspectives on the evolution of aircraft maintenance/support concepts with particular reference to their relevance to aircraft availability.

b) Metrics, key performance indicators, and modelling of aircraft availability/readiness.

c) Maintenance/support management concepts and technologies for improving aircraft availability and mission reliability.

d) Aircraft, support equipment and supply system technologies for improving aircraft availability and mission reliability.

This partitioning is preserved in Chapters 3 to 6 of the report, but the sections within these chapters do not necessarily follow the titles of Workshop papers. As mentioned earlier, Chapter 2 provides a philosophical and contextual framework for the report.

1.3 OTHER RELEVANT NATO RTO AVT PANEL INVESTIGATIONS

The RTO AVT Panel has a comprehensive program of activities related to aircraft availability. The following NATO RTO AVT Technical Teams have recently completed more detailed investigations of some of the technologies reviewed in the current report:

- AVT-125 “Future Airframe Lifing Methodologies”;
- AVT-126 “Improving Military Engine Reliability”; and
- AVT-128 “More Intelligent Gas Turbine Engines”.

In addition, the AVT-157 Technical Team organised a Symposium in Montréal, Québec, Canada, in October 2008 on “Military Platform Ensured Availability”.

1.4 TERMINOLOGY

With regard to the theme and objective of AVT-144, “maintenance” is defined in NATO’s manual of Reliability and Maintainability Terminology, ARMP-7 [2], as “all action taken to retain materiel in a serviceable condition or to restore it to serviceability, and all supply and repair action taken to keep a force in condition to carry out its mission". This and other definitions do not generally draw a line between "maintenance" and other elements of "in-service support". The term "in-service support" is not defined in any relevant documents. Therefore, for the purposes of AVT-144, the terms "maintenance" and "in-service support" are regarded as synonymous. The dual term "maintenance/support" is frequently used in this report to reinforce this perspective.

"Logistics" is defined in AAP-6 NATO Glossary of Terms and Definitions [3] as the science of planning and carrying out the movement and maintenance of forces. It includes aircraft maintenance/support, but is a broader term.

In this report, the acquisition and delivery of materiel, including repaired/restored components, for the handling, storage, inspection, testing, repair, and restoration of aircraft is generally referred to as "supply". As such, "supply" is part of "maintenance/support". Organisations that manufacture components and perform the 2^{nd}, 3^{rd} and 4^{th} Line repair/restoration of components are regarded as part of the "supply chain" to the aircraft platform.

In interpreting the theme and objective of AVT-144, the Technical Team decided to define the term "advanced" as implying that the maintenance concept or technology in question had recently resulted in improvements in the availability and/or life-cycle cost of military aircraft in one or more NATO or PfP Air Forces, or that it offered potential improvements. All Technology Readiness Levels (TRL) were of interest, but the focus was on technologies that exist or might mature within ten years.

There are several different definitions of "availability". NATO manual ARMP-7 [2] defines "availability" as the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided. Most other definitions are broadly similar to this one. There is more discussion of the definitions and metrics of availability in Chapters 2 and 4.

In view of the variety of definitions of terms used in aircraft maintenance/support, and in some cases the absence of clear definitions, a "List of Definitions" for several hundreds of terms relevant to this report has been included as Annex C. None of the definitions in this list are stated as preferred or mandatory. The list is intended to be an aid to communication and understanding. To keep the report readable, we have attempted to communicate in a way that most aircraft engineers would understand without recourse to a list of definitions. We have included definitions in the main text only where necessary. Uncommon acronyms are defined repeatedly near most points of use, to avoid the need to refer to a list.

Chapter 2 – THE IMPORTANCE OF AIRCRAFT PLATFORM AVAILABILITY

2.1 INTRODUCTION

Aircraft availability is a key component of military capability and an important measure of the readiness and effectiveness of a force. “The most powerful weapon in the world is useless if we can’t deploy and use it effectively in the fight…” (Louis A. Kratz, US Assistant Deputy Under Secretary of Defense – Logistics Plans and Programs 2002 [4]).

The overall availability/readiness of military forces and the associated availability/readiness of aircraft and other military equipment to meet operational demands are high profile issues in several NATO countries. One reason for this is that the high cost of military forces keeps them constantly in the budget spotlight. Secondly, there have been changes in the perceived threat environment following the end of the Cold War in 1992, the terrorist attacks on the World Trade Centre in 2001, and subsequent terrorist attacks and regional conflicts around the world. For years, NATO accepted trade-offs between reliability and technical performance in tactical systems because it was compelled to pursue technological superiority over the Soviet Union during the Cold War. There is now a need to place more emphasis on availability and mission reliability, together with an enduring ability to provide these in tactical deployments with a small logistics footprint. Thirdly, there has been a trend to concentrate more capability in fewer aircraft. This trend has heightened the importance of aircraft availability, while making it more difficult to achieve.

This chapter explains the relationship between aircraft availability and military capability, and reviews public information on the availability of military aircraft in some NATO Air Forces. It concludes by outlining strategies that are being used or could be used to optimise aircraft availability. The chapter provides a philosophical and contextual framework for the more detailed discussion in later chapters of maintenance concepts and technologies that can be used to enhance aircraft platform availability.

2.2 THE CONTRIBUTION OF AVAILABILITY TO MILITARY CAPABILITY

2.2.1 Military Capability

In recent USA DoD and UK MOD policy documents [5]-[6], military capability is defined as the ability to generate or achieve a desired effect under defined operational and environmental conditions. It is implicit in the US and UK definitions that a capability must endure and survive. Capability in this sense is delivered by means of force elements, such as an armoured brigade, an infantry battalion, a missile battery, a frigate, a carrier task force, a squadron of aircraft, or smaller elements. These force elements are used singly or in groups to form an overall force to achieve a particular objective or to apply a particular strategy. Under DoD policy, the development of a capability includes joint doctrine, organization, training, materiel, leadership and education, personnel, and facilities. Under MOD UK policy, the development of a capability includes the following “Defence Lines Of Development (DLOD)”: training, equipment, personnel, information, concepts and doctrine, organisation, infrastructure, logistics, and interoperability. Capability may be integrated between Services and between Allies.

2.2.2 Force Effectiveness and Readiness

“Effectiveness” is not formally defined except in some US DoD documents, but is a widely used term. In DoD and general usage, it is a measure of the degree to which a force or force element has demonstrated its intended military capability. A force is considered effective if it has achieved or has somehow demonstrated the ability to achieve its objectives under the expected conditions. Similarly, an aircraft forming part of a force is considered effective if it has demonstrated that it can fulfil the missions for which it was designed. To assess the effectiveness of a force in meeting a capability, Measures Of Effectiveness (MOE) must first be defined. The current practice in the USA and UK is to define both threshold and objective MOE where appropriate, and to use the difference between the two as trade-off space during equipment acquisition. When a solution to a particular capability has been developed, the MOE might include measures of performance, such as aircraft performance parameters, availability, and interoperability.

"Readiness" is a measure of the degree to which the intended capability has been acquired or generated. The readiness of a force or force element is usually expressed either as an estimate of the degree to which it can deliver its intended capability or an estimate of the time it will take for it to acquire or develop its intended capability [3].

2.2.3 Aircraft Availability – A Key Measure of Force Effectiveness and Readiness

Only available aircraft can deliver capability. If insufficient aircraft are available to deliver a given capability, the force will be only partially ready or effective. Therefore, aircraft availability is an important measure of both effectiveness and readiness in relation to a capability that requires aircraft to help achieve the desired effect.

"Aircraft availability" is defined differently in detail by different organisations, but the term generally refers to the availability of aircraft for operational use in the immediate or near future. It can be expressed simply as a number of aircraft. However, when "availability" is used as a forward looking performance parameter, most definitions imply that it is the probability that an aircraft in a defined group will be fit for operational use immediately or within a defined recovery period whenever tasked, in defined operational conditions, over a defined operational period. The probability may be replaced by an equivalent metric, such as "the percentage of aircraft in a defined group that will be fit …". Differences in the usage and definition of the term availability as a performance parameter mostly arise from differences in the group of aircraft under consideration, the minimum acceptable standard of fitness for operational use, the allowable recovery period, the operational conditions, and the operational period. For example:

- Some definitions exclude aircraft undergoing depot/depth maintenance from the group;
- A distinction may drawn between aircraft that are fit for some assigned missions and those that are fit for all missions;
- An "available" status may include aircraft that will not be recovered for several hours; and
- There may be different availability targets for home base and deployed aircraft.

Predictions or contract specifications of availability may be derived from the past performance of a sample of aircraft operating under specific conditions, such as an exercise or expedition, or they may be based on the past annual performance of a whole fleet without close regard to individual variations in operating conditions.

2.2.4 Relationship of Capability, Effectiveness and Availability in Systems Modelling

In the contexts of systems analysis and operations analysis, the terms "capability" and "effectiveness" may be defined differently than in the more general usage described above. For example, Mil-Hdbk-338 [7] describes several models of effectiveness that have been used in systems analysis in the past by ARINC, the USAF, and the USN. These are outlined in Figure 2-1. In these models, capability is viewed as contributing to effectiveness rather than the reverse. Nevertheless, availability remains a major parameter in all three models.

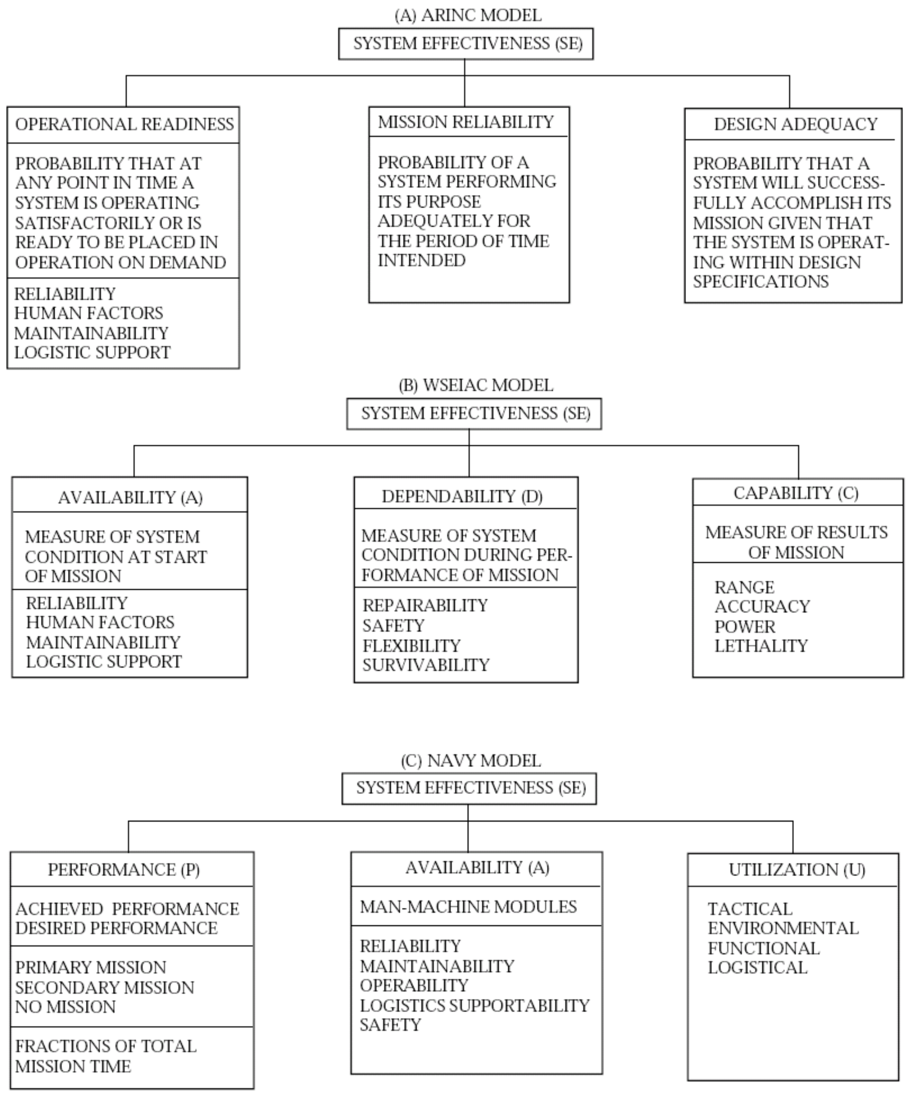


Figure 2-1: System Effectiveness Models Described in Mil-Hdbk-338B that have been Used in the Past by: (a) ARINC Inc.; (b) The USAF Weapon Systems Effectiveness Industry Advisory Committee (WSEIAC); and (c) The US Navy.

2.2.5 Availability and Mission Reliability

Once an aircraft has been launched on a mission, its continued availability depends on its "mission reliability". Most definitions of mission reliability imply the probability that an aircraft or equipment that is initially fit for operational use will not fail to complete a given mission profile due to equipment failure, taking into account redundancy. A "mission profile" is a time-phased description of the tasks, events, durations, operating conditions, and environments for each phase of a mission.

The concept of mission reliability is consistent with the general concept of “reliability”, which is the probability that an item can perform its intended function for a *specified interval* under stated conditions. However, mission reliability is assessed against very short intervals of time or usage, while aircraft reliability is assessed over long intervals of time or usage. Also, the definition of failure is not the same in each case. Mission reliability is governed only by the probability of a single mission-critical failure, while (general) reliability is governed by all failures and potential failures that occur over a long interval, regardless of their criticality. In an aircraft specification, a distinction is drawn between reliability and mission reliability. Also, other specific reliability characteristics may be included, each of which may include its own definition of failure.

The maintenance/support system and aircraft design features that facilitate maintenance/support can influence both the availability of aircraft on the flight line, i.e. the average availability, and the continued availability of the aircraft during the mission, i.e. the mission reliability. Therefore, this report is concerned both with average availability and with mission reliability.

Mission reliability is closely allied with flight safety, and both are governed by the design of the aircraft and its preventive maintenance program. The flight safety requirements in the aircraft specification might create a need for preventive maintenance over and above that required for mission reliability. However, the marginal increase is likely to be small. Thus, the specified level of mission reliability is the main driver of preventive maintenance.

The term “dependability” is sometimes used in the context of mission reliability to express the conditional probability that an aircraft or equipment is available/operational at any moment during a mission [7]. “Dependability” may also be used as a general term to describe the availability and its influencing factors: reliability, maintainability and maintenance supportability [8]. The term is not used in this report, except in Figure 2-1.

2.2.6 Maintenance-Free Operating Period (MFOP)

With the trend to more expeditionary operations by NATO forces, it is important to have the ability for limited periods to enhance the availability of deployed aircraft while simultaneously minimising their logistics footprint. The term “Maintenance-Free Operating Period (MFOP)” is sometimes used to describe this maintenance concept [9].

A MFOP, or at least a period of substantially reduced maintenance and higher availability, can be achieved to some extent by the appropriate management of maintenance/support. The necessary measures include focussing resources on the deployed aircraft, and so the availability of non-deployed aircraft may be reduced for a period during the deployment. However, there need not be any adverse effects on the long-term average availability of the whole group, unless an unusually high operating tempo has to be maintained for an extended period.

To achieve a good MFOP capability, it is necessary to design an aircraft and its maintenance/support system specifically for the purpose. In general, this means giving special attention to the maintainability of the aircraft when operating with a reduced range of specialist personnel, spares, facilities and other maintenance/support resources. The necessary design measures may include increasing the degree of automation in inspection and diagnostics, lengthening the intervals between some servicing, providing internal auxiliary power and oxygen generation, substantially increasing the general reliability and mission reliability of the least reliable components, and modularising the aircraft in a way that permits major airframe and engine repairs to be performed without special facilities. However, the targeted reliability improvements may be difficult to achieve without special measures to increase fault tolerance.

Some of these measures are needed to exploit fully the Reliability Centred Maintenance (RCM) concept of on-condition maintenance. As explained later in this chapter, on-condition inspections allow a potential failure to be detected before functional failure occurs. If the aircraft is designed to be damage or fault tolerant and optimum inspection methods are used, the interval between detection of potential failure and functional failure can be made large enough to allow corrective maintenance to be planned so that it does not interfere with operations. The use of fully automated, on-board inspection systems can help. A reduction in safety margins can also help, provided this is warranted by the operational situation.

There is more discussion of the MFOP maintenance concept in Chapter 6.

2.2.7 Availability Targets

Targets for the average availability of assigned aircraft are essential for the planning and provision of equipment and in-service support resources. While it is difficult to predict future operational demands with precision, it is important that availability targets are derived with due care, and that they are met.

The optimum fleet sizes and availability targets for different operational scenarios are ideally derived with the help of operations analysis and the modelling of in-service support and life-cycle cost. This approach can also help in setting targets for many other operational and support parameters. Comprehensive modelling is an emerging technology, and so experience and judgement, exercised within a robust systems engineering approach, are also important in determining and updating aircraft and support system requirements through life. The metrics and modelling of aircraft platform availability are addressed in Chapter 4.

The tasking and required readiness levels of aircraft are determined by operations staff. The associated targets for average availability are passed down by the commander to the maintenance/support organisation. In some cases, there may be some negotiation of targets. Some NATO Air Forces may set lower availability targets for aircraft not assigned to active duty. The lower targets are designed to reduce operating costs and preserve resources while maintaining the desired states of readiness for all required combat capabilities. Higher targets for availability may be needed during periods of active combat operations, even if the whole fleet is not committed, to deal with higher average demand, higher peak demand, a reduction in the total force due to attrition, and a general need for higher readiness. In the absence of combat operations, the readiness and effectiveness of an Air Force is tested periodically by exercises that include a surge requirement, high operational demand, and a simulated threat. In the USA, it is DoD policy that all mission essential systems and equipment be maintained to the optimum mission capable status [10]. However, it is recognised that “flexible goals” for materiel condition (availability) that take into account a unit’s task or deployment status may be appropriate. For example, higher goals may be appropriate for deployed units compared to non-deployed units.

The US Navy is reportedly dissatisfied with the use of average availability for setting targets for the maintenance/ support organisation, and will move to alternative targets for newer aircraft, such as the F-35 Joint Strike Fighter (JSF) [11]. The US Navy considers that the average availability metrics currently used in targets and status reports provide only a limited historical perspective and do not address issues that are important to war-fighting commanders such as how often an aircraft can fly missions over the course of a day and the probability that the aircraft will complete its mission. The F-35 JSF, for example, will use “mission reliability” targets instead of or as well as the traditional “Mission Capable (MC)” and Full Mission Capable (FMC)” targets. According to Navy officials, the predictive value and information on flight frequency and reliability provided by this new measure is very valuable to war-fighting commanders and is better for mission-planning purposes than the traditional measures. It is possible that mission reliability targets could be used throughout DoD's inventory of aircraft.

Full details on availability targets and statistics may not be published openly by some Air Forces for security reasons. Some of the open data on availability targets and performance in the USA, UK, and France are reproduced later in this chapter.

2.2.8 Efficiency and Availability

Improvements designed for efficiency in the use of existing resources tend concurrently to improve availability, or can be traded for improvements in availability. The reverse is also true. Therefore, it should be a goal to improve both continuously. Improvements in efficiency and availability are particularly important in the context of expeditionary operations. Such operations have become a larger component of the defence strategies of several NATO countries since the end of the Cold War. Expeditions tend to have long, costly, and vulnerable supply lines, and so it is important to reduce the logistic support required to sustain adequate in-theatre capability – i.e. to reduce the "logistics footprint" in deployments. In this regard, changes that improve the availability and reduce the maintenance/support of deployed aircraft are likely to have a high return on investment, even if they fall short of achieving a true MFOP capability.

On a larger scale, some NATO countries have found that substantial reduction in maintenance/support costs have been possible without reductions in fleet size, by a series of measures, including:

- The reorganisation of maintenance/support to take advantage of economies possible as a result of strategic changes following the end of the Cold War;
- Greater emphasis on joint forces capability management and the economies this can provide;
- Increased doctrinal focus on aircraft availability and its key role in joint forces capability, as discussed earlier in this chapter;
- The empowerment of integrated project teams with responsibility and authority for availability and life-cycle cost seamlessly throughout the life of the aircraft;
- Greater integration of design and maintenance/support through renewed emphasis on system engineering management, clearer objectives and processes, improved communications, improved training, and, in some cases, through delegating the design and management of the maintenance/ support system to the aircraft manufacturer for the first twenty years;
- The use of availability-based contracting (performance-based logistics) with industry and organic depots for maintenance/support work, with incentives and penalties directly linked to availability and cost;
- Greater emphasis on efficiency in aircraft maintenance/support, including the use of lean methodologies and inventory management and procurement concepts that have proven successful in industry; and
- Continued development of global and local communications and information systems to streamline all aspects of aircraft design and maintenance/support.

2.3 AIRCRAFT AVAILABILITY IN SOME NATO AIR FORCES

Availability targets and statistics in the open literature for some important NATO aircraft are presented in this section, together with relevant comments by government agencies. The data are for illustrative purposes.

2.3.1 Aircraft Availability in France

The French government has been concerned for several years with the inadequate availability of its military equipment and the escalation of maintenance/support costs. France's National Assembly has given high priority to budgetary and managerial changes to improve the availability of its military equipment – « Disponibilité Technique Opérationnelle (DTO) ». In the French Air Force a special organisation was established in 1999 to improve aircraft availability while controlling maintenance/support costs. This organisation is known as « Structure Intégrée de Maintien en condition opérationnelle des Matériels Aéronautiques du ministère de la Défense (SIMMAD) » (Integrated Organisation for Maintaining Ministry of Defence Materiel in Operational Condition).

In a statement to the Defence Commission of the French National Assembly in 2005 [12], General Richard Wolsztynski, Chief of Staff of the French Air Force, reported that considerable effort had been made since 2000 to overcome critically low aircraft availability, that two out of three aircraft were now available, and that Air Force personnel were motivated to make further improvements[1]. General Wolsztynski pointed out that, despite the general difficulties, very high aircraft availability, approaching 100%, was being achieved during deployments[2].

The availability of French "military" aircraft was reported to the French Senate in November 2006 in the form of Table 2-1 and Table 2-2 [13].

Table 2-1: Average Availability of French Military Aircraft Compared to Availability Targets. The minimum availability target is needed to meet current commitments. The optimal availability target is needed to meet future commitments to be met. (Source [13])

Aircraft Fleet	Minimum Target Number Available	Optimum Target Number Available	Average Number Available Over 7 days	Average Age in 2006
Combat	173	216	167	16.5
Tactical Transport	50	61	46	25.4
Strategic Transport	2	3	3	18.6
Helicopters	42	53	44	21
Support	10	13	11	35
Training	131	150	137	20.5

[1] « Un effort significatif a été consenti en matière de maintien en condition opérationnelle afin de sortir d'une situation critique: il y a cinq ans, certaines flottes ne comptaient plus qu'un avion disponible sur trois. La SIMMAD, nouvelle structure intégrée, n'a pas encore atteint son régime de croisière, alors que le passif à résorber représente un véritable défi, mais elle a permis d'importants progrès : le taux de disponibilité est, d'ores et déjà, de deux avions sur trois. Le personnel est particulièrement sensible au niveau de disponibilité opérationnelle et ne comprend pas toujours les raisons qui ne permettent pas de progresser dans ce domaine. »

[2] « En revanche, pour les opérations extérieures, telles que celles menées à partir de Douchanbe, il faut souligner l'excellente disponibilité des équipements, une disponibilité voisine de 100% qui s'impose d'elle-même lors d'engagements opérationnels. »

Table 2-2: Average Availability of French Military Aircraft from 1998 to 2006.

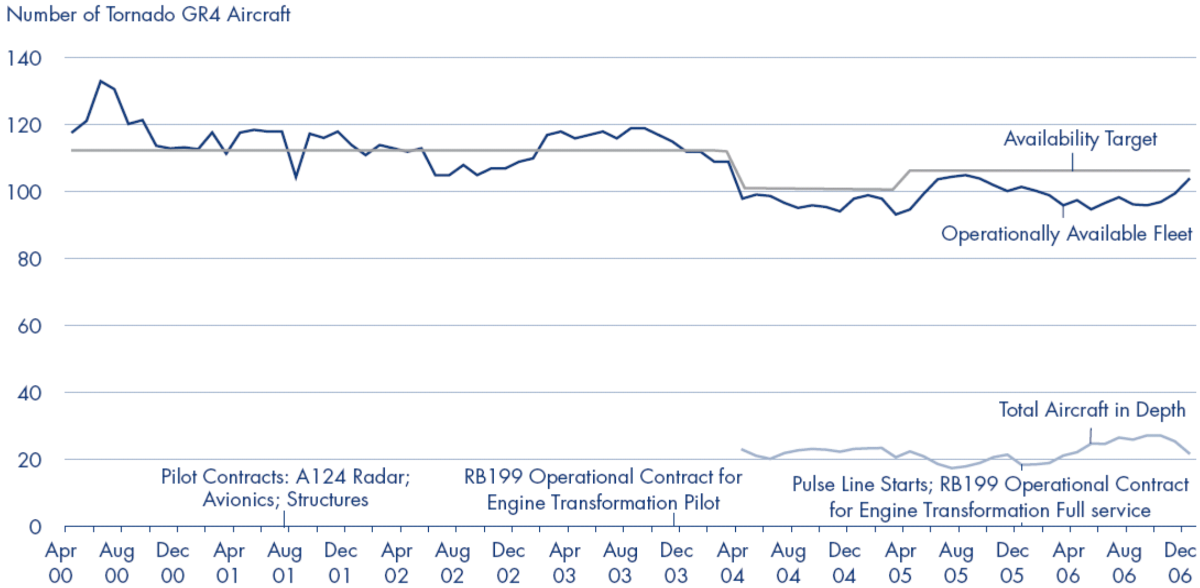
		Fleet Size 2006	No. of Aircraft 3rd and 4th Line	Average Duration 3rd/4th Line (Months)	1999 %	2000 %	2001 %	2002 %	2003 %	2004 %	2005 %	2006 %
Combat	Mirage 2000 B/C	94	2	5	68	66	68	66	70	66	59	51
	Mirage 2000 5F	33	0	5	64	66	68	58	65	59	53	56
	Mirage 2000 D	80	5	5	72	67	63	55	55	57	54	51
	Mirage 2000 N	67	3	5	61	58	63	57	68	69	70	66
	Mirage F1B	14	2	6.6	63	58	58	38	60	72	62	71
	Mirage F1CR	47	3	5	61	63	60	68	63	69	56	56
	Mirage F1CT	30	1	3	60	59	51	61	62	70	65	63
Transport	C 160	58	9	7.2		52	56	57	57	55	53	63
	C130	14	(1)			64	65	48	49	64	74	68
	CASA	19	(1)			67	72	66	61	62	68	75

2.3.2 Aircraft Availability in the UK

The United Kingdom Ministry of Defence (MOD UK) is transforming the provision of maintenance, repair and overhaul activity for Harrier and Tornado aircraft. The key driver for the change was a strategic goal of reducing operating costs by 20% (around £1.862 billion) by 2006. In the three years since its 2003 End-to-End Review of logistics [14], MOD UK has significantly changed the arrangements for maintenance/support of fast jets. The MOD and industry previously performed maintenance on fast jets at four different levels at multiple locations. Since 2003, it has rationalised maintenance into two organisational structures: "forward" maintenance is performed by the operational squadrons, while "depth" maintenance has been centralized at a single "depth hub" at a main operating base. These changes were strategically possible, because the change in the threat since the end of the Cold War removed the need to disperse the maintenance/support organization across multiple airfield sites in case of an attack on a Royal Air Force (RAF) main operating base.

While the UK's Defence Logistics Transformation has been motivated primarily by cost and enabled by a change in broad defence strategy, the MOD has required that aircraft availability targets be maintained or exceeded. The target and actual numbers of aircraft available for operational use during 2000 – 2006 for the Tornado and Harrier, expressed as monthly averages, are shown in Figure 2-2 and Figure 2-3, respectively, which are taken from a UK National Audit Office Report published in 2007 [15]. The number of available Tornado aircraft was on or slightly below target during this period. The number of available Harrier aircraft was significantly below target for many years, but recovered in 2006 as a result of the reorganization of maintenance/support under the Defence Logistics Transformation program.

The number of Tornado GR4 aircraft available has in recent years failed to achieve the required target, but the fall in availability pre-dated transformation.



Source: National Audit Office analysis of Ministry of Defence data

NOTES

1 The change in the Customer Supplier Agreement Availability Target in March 2004 reflects the change in the Department's definition of operational availability (Forward Available Fleet) to exclude all aircraft in depth maintenance. The subsequent change, in March 2005, reflects a release of aircraft to the front line from a planned upgrade programme.

2 The Tornado Integrated Project Team was only able to provide a consistent picture of the number of Tornado GR4 aircraft in depth repair from March 2004 onward.

Figure 2-2: Operational Availability of UK Tornado GR4 Aircraft 2000 – 2006.
(Source: UK National Audit Office (NAO) [15])

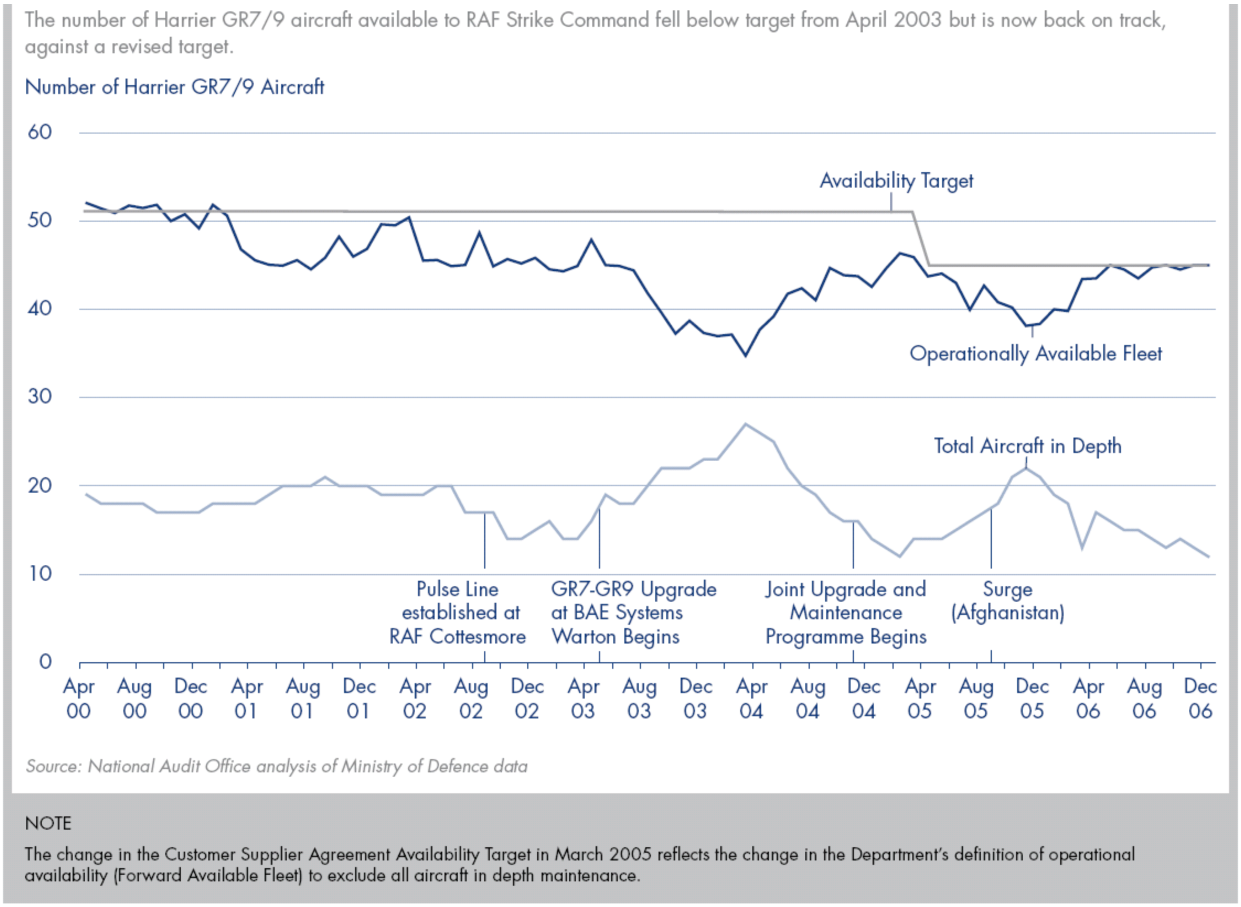


Figure 2-3: Operational Availability of UK Harrier Aircraft 2000 – 2006.
(Source: UK National Audit Office (NAO) [15])

The situation with the UK's fleets of battlefield helicopters is more problematic. As shown in Figure 2-4, there will be a major shortfall in operational lift capability until about 2016 [16]. Careful management of helicopter fleet capabilities is needed, and availability must be kept as high as possible. Management of the helicopters of all three services has been centralized in the Joint Helicopter Command, which was mandated a total of over 100,000 flying hours in 2003 – 2004 by the Defence Logistics Organisation for its Lynx, Gazelle, Chinook, Puma, and Sea King fleets. With the exception of Lynx, each individual aircraft is resourced to fly approximately 400 hours per year. The Lynx fleet is resourced for 23,900 hours, which averages 206 hours per aircraft.

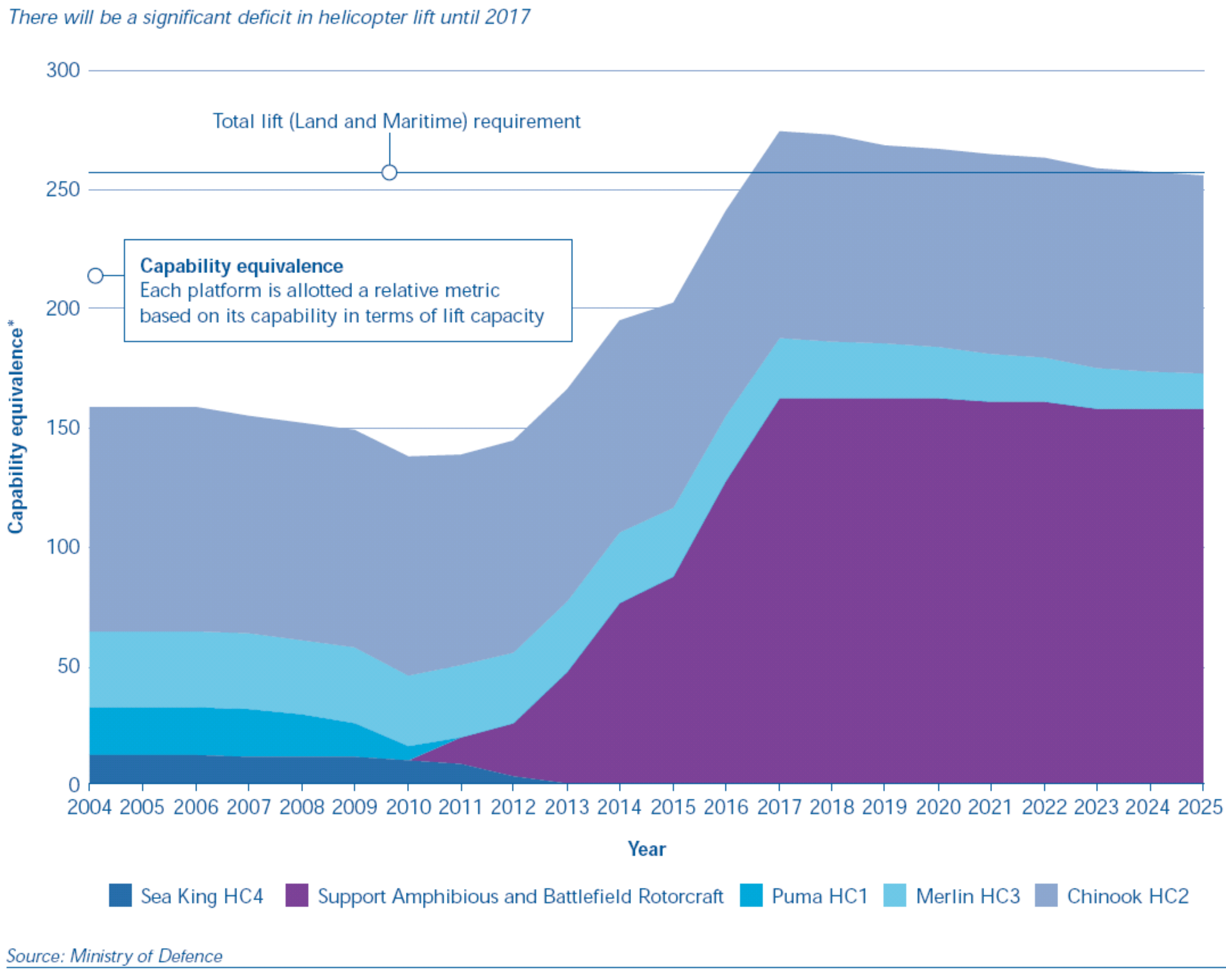


Figure 2-4: UK Joint Battlefield Support Helicopter Requirements. (Source: UK National Audit Office (NAO) [16])

The UK deployed approximately 100 helicopters to Iraq during the Spring 2003 offensive. The availability of helicopters during the war-fighting phase of the operation was as shown in Figure 2-5 [17]. Average helicopter availability was 66%. This was a marked improvement on an exercise in Oman in 2001, when the average was 55%. The Lynx anti-tank helicopter's availability peaked at approximately 80% during the war-fighting phase, but averaged 53% overall, largely due to the harsh, dusty environment in which it was continuously operating, and also due to a lack of spare parts.

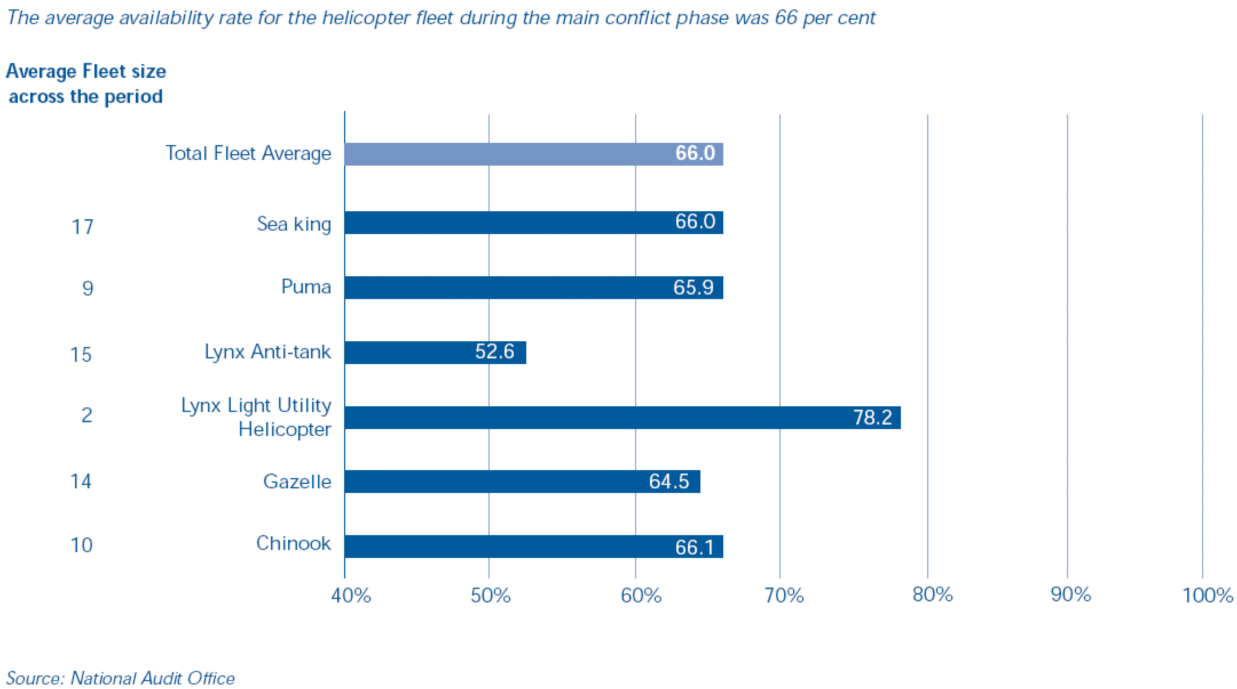


Figure 2-5: Average Availability of UK Helicopters Committed to Iraq Operations. (Source: UK National Audit Office (NAO) [17])

2.3.3 Aircraft Availability in the USA

In the United States Armed Forces, the Office of the Deputy Under Secretary of Defense (DUSD) for Logistics and Material Readiness (L&MR) provides a strong focus on readiness through its Material Readiness and Maintenance Policy and associated education and publicity. An overview of US Department of Defense (DoD) managerial and technological initiatives in the areas of material readiness and maintenance can be obtained from the L&MR Internet site, www.acq.osd.mil/log. There are also high-level departments in the various services dealing specifically with readiness and related issues such as corrosion and aging equipment.

The key measures of aircraft availability in the US DoD currently include the “Mission Capable (MC)” rate and the “Full Mission Capable (FMC)” rate. These rates are usually expressed as percentages of the total number of aircraft assigned to a given formation or operating base. An aircraft that is FMC is fit for all assigned missions. An aircraft that is MC may be fit for one or all of its assigned missions. Consequently, FMC is a sub-set of MC. In USAF and USN statistics, the base quantity used in calculating MC and FMC percentages excludes aircraft that are undergoing depot maintenance.

In a report on military readiness published in 2003 [18], the US General Accounting Office (GAO) observed that the DoD was shifting to a new defence strategy that included the capability for quick reaction in a wide range of situations as a way of dealing with uncertainty, and that a key ingredient of the new strategy was the availability of aircraft to meet the various contingencies. The GAO was concerned to find that less than one-half of the 49 aircraft types that it reviewed had met their MC or FMC targets during fiscal years 1998 – 2002. The GAO also discovered that there was a need to define more clearly the process by which the availability targets were determined and updated. DoD has since clarified its readiness policy in an update of DoD Instruction 3110.05 [10].

The GAO reported that over the 5 years 1998 – 2002, the Army and Air Force had the highest average MC rates, at 77 – 83% (Figure 2-6). They were followed by the Marines, at 71 – 75% and the Navy, at 61 – 67%. Figure 2-7 compares the average MC rates by aircraft type. Helicopters had the highest at 76 – 80%, followed by cargo aircraft and tankers at 75 – 79%, fighter/attack aircraft at 75 – 77%, bombers at 64 – 69%, and electronic command/control aircraft at 60 – 67%. Average FMC rates followed similar rank order patterns (Figure 2-8). The MC/FMC goals for the main DoD aircraft are listed in Table 2-3. The MC rates achieved in 2002 by many of these aircraft are in Table 2-4. This table also shows the calendar ages of the aircraft.

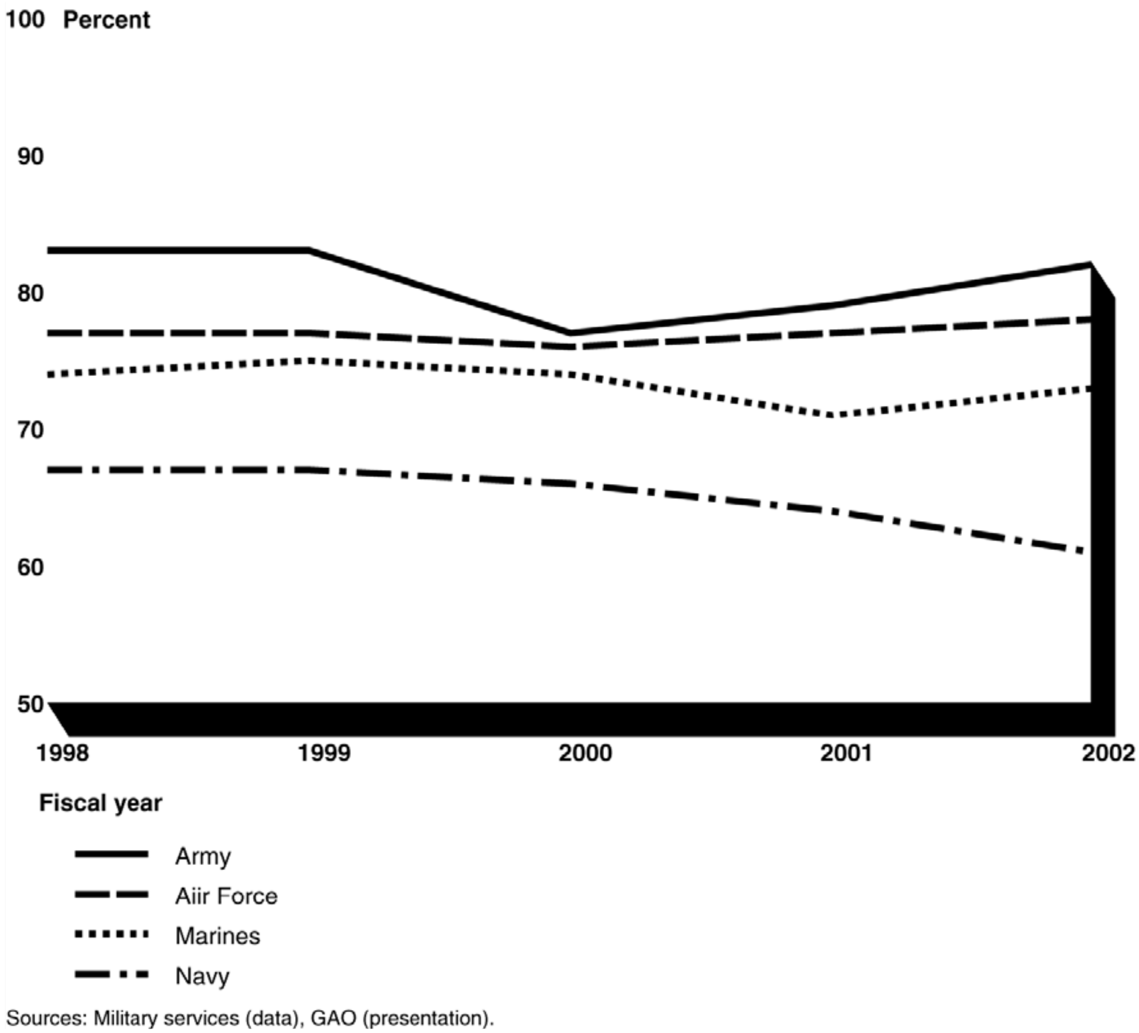


Figure 2-6: US DoD Average Annual Mission Capable (MC) Rates of US Military Aircraft by Service in Fiscal Years 1998 – 2002. (Source US GAO [18])

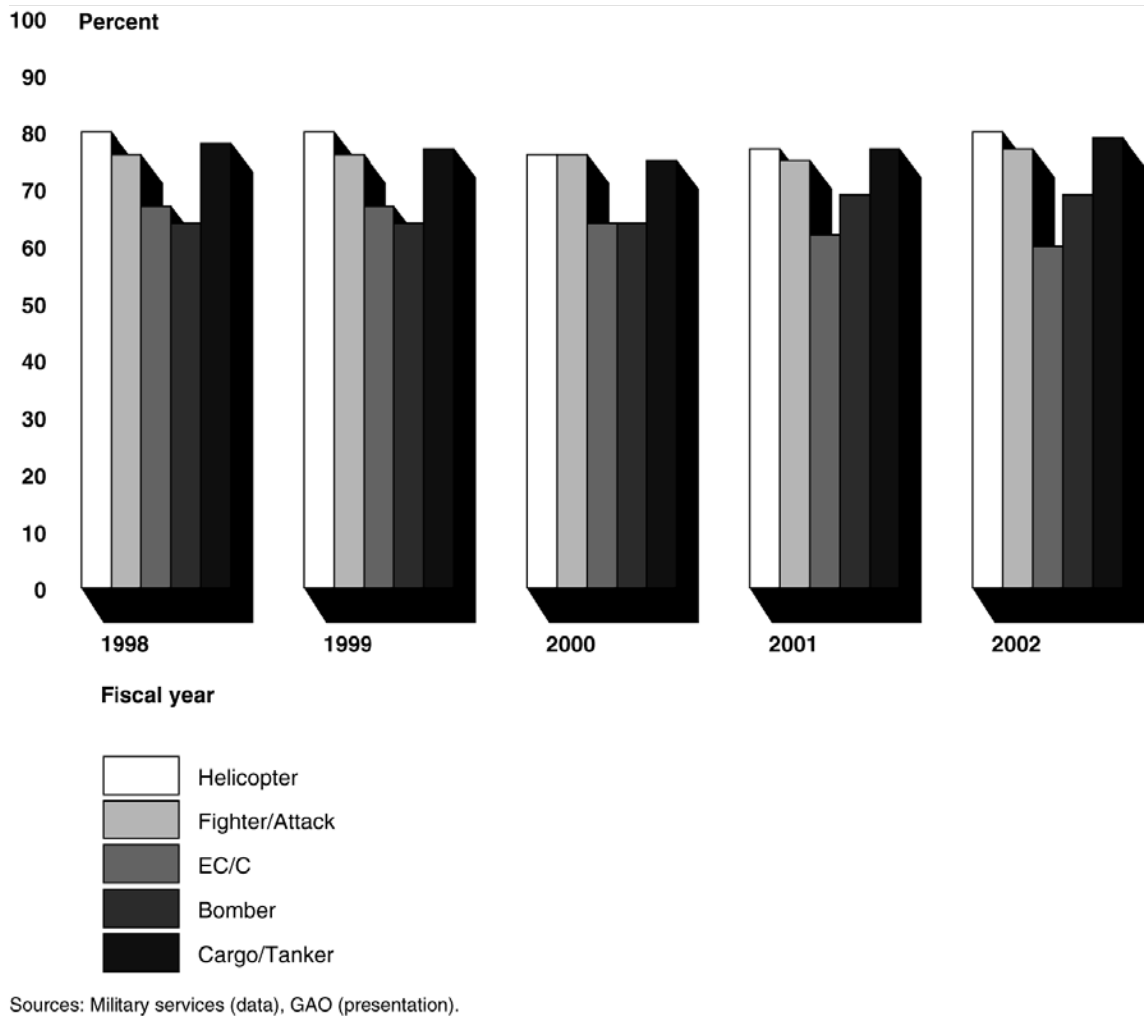
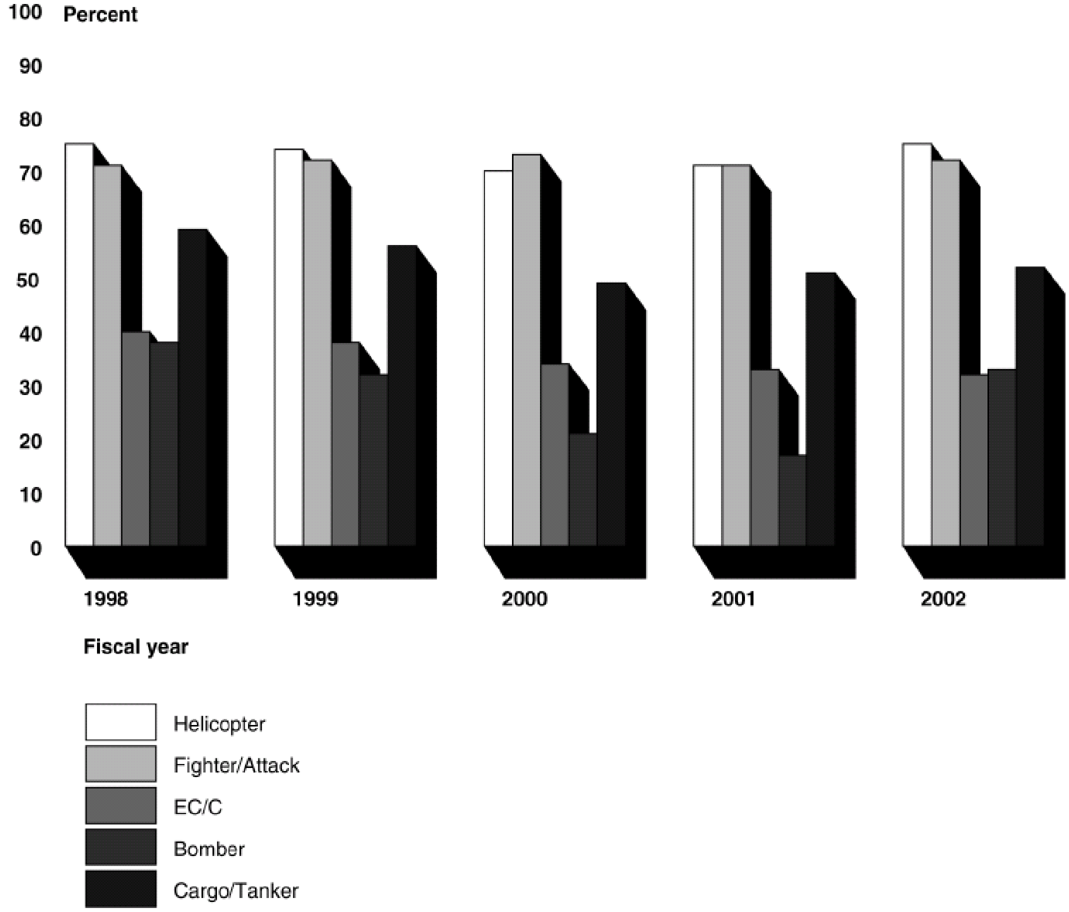


Figure 2-7: US DoD Average Annual MC Rates by Aircraft Type in Fiscal Years 1998 – 2002. Note: EC/C refers to electronic command and control aircraft. (Source US GAO [18])



Sources: Military services (data), GAO (presentation).

Note: EC/C refers to electronic command and control aircraft.

Figure 2-8: US DoD Average Annual Full Mission Capable (FMC) Rates by Aircraft Type in Fiscal Years 1998 – 2002. (Source US GAO [18])

Table 2-3: Key DoD Aircraft Models and 2002 MC (Suffix ^{a}) and FMC (Suffix ^{b}) Goals in Percent. (Source US GAO [18])

2002 mission capable/full mission capable goals in percents

Category	Fighter/Attack aircraft	Bombers	Electronic command/control	Tankers/Cargo aircraft	Helicopters
Aircraft	A-10 Thunderbolt	B-1 Lancer	E-3 Sentry	C-5 Galaxy	AH-64A Apache
Service	Air Force	Air Force	Air Force	Air Force	Army
Goal	82^a/NA^b	67^a/NA^b	85^a/NA^b	75^a/45^b	75^a/70^b
Aircraft	F-15 Eagle	B-2 Spirit	E-8 Joint Stars	C-17 Globemaster	AH-64D Apache
Service	Air Force	Air Force	Air Force	Air Force	Army
Goal	83^a/NA^b	50^a/NA^b	75^a/NA^b	88^a/78^b	75^a/70^b
Aircraft	F-15E Eagle	B-52 Stratofortress	RC-135 Rivet Joint	C-130 Hercules	UH-60A Black Hawk
Service	Air Force	Air Force	Air Force	Air Force	Army
Goal	81^a/NA^b	80^a/NA^b	75^a/NA^b	75^a/48^b	80^a/75^b
Aircraft	F-16 Fighting Falcon		U-2	C-141 Starlifter	UH-60L Black Hawk
Service	Air Force		Air Force	Air Force	Army
Goal	83^a/NA^b		85^a/NA^b	80^a/59^b	80^a/75^b
Aircraft	F-117 Nighthawk		S-3B Viking	KC-135 Stratotanker	CH-47D Chinook
Service	Air Force		Navy	Air Force	Army
Goal	80^a/NA^b		70^a/54^b	85^a/77^b	75^a/70^b
Aircraft	F-14A Tomcat		E-2C Hawkeye	KC-10 Extender	OH-58D Kiowa
Service	Navy		Navy	Air Force	Army
Goal	65^a/50^b		70^a/54^b	85^a/77^b	75^a/70^b
Aircraft	F-14B Tomcat		P-3C Orion	KC-130F Hercules	SH-60B Seahawk
Service	Navy		Navy	Marines	Navy
Goal	65^a/50^b		85^a/61^b	72^a/53^b	77^a/58^b
Aircraft	F-14 D Tomcat		EA-6B Prowler	KC-130R Hercules	SH-60F Seahawk
Service	Navy		Navy / Marines	Marines	Navy
Goal	71^a/61^b		73^a/54^b	75^a/58^b	75^a/60^b
Aircraft	F/A-18A Hornet				MH-53E Sea Dragon
Service	Navy /Marines				Navy
Goal	75^a/58^b				70^a/60^b
Aircraft	F/A-18C Hornet				CH-46E Sea Knight
Service	Navy / Marines				Marines
Goal	75^a/58^b				80^a/77^b
Aircraft	F/A-18D Hornet				CH-53D Sea Stallion
Service	Marines				Marines
Goal	75^a/58^b				73^a/65^b
Aircraft	F/A-18E Super Hornet				CH-53E Super Stallion
Service	Navy				Marines
Goal	75^a/58^b				70^a/60^b
Aircraft	AV-8B Harrier				AH-1W Super Cobra
Service	Marines				Marines
Goal	76^a/70^b				85^a/75^b
Aircraft					UH-1N Huey
Service					Marines
Goal					85^a/75^b

Source: Military services' records.

Table 2-4: Comparison of the MC Rates and MC Goals of DoD Aircraft in 2002. (Source US GAO [18])

Aircraft model	Average age (years)	2002 MC rate/goal (percent)	Aircraft model	Average age (years)	2002 MC rate/goal (percent)
KC-130F	40.1	64/72	F-14D	15.3	67/71
B-52	40.0	81/80	B-1	14.6	61/67
KC-135	39.6	82/85	CH-47D	14.4	75/75
RC-135	38.3	76/75	AH-64A	14.2	83/75
C-141	35.0	74/80	SH-60B	13.7	63/77
CH-46E	33.6	76/80	CH-53E	13.7	70/70
CH-53D	31.9	78/73	AH-1W	12.3	73/85
C-130	29.2	81/75	MH-53E	11.5	48/70
UH-1N	27.6	69/85	F-16	11.1	80/83
S-3B	26.2	43/70	F-117	10.7	83/80
KC-130R	25.4	65/75	SH-60F	10.6	54/75
P-3C	24.5	61/85	F-15E	10.2	76/81
E-3	22.0	74/85	F/A-18C-Navy	10.2	66/75
F-14A	21.0	69/65	F/A-18C-Marine	10.2	82/75
A-10	20.1	76/82	E-2C	10.2	51/70
C-5	20.0	66/75	F/A-18D	9.6	78/75
EA-6B-Navy	19.8	58/73	OH-58D	8.5	88/75
EA-6B-Marine	19.8	68/73	UH-60L	7.6	84/80
F-15C/D	18.7	79/83	B-2	7.4	44/50
UH-60A	18.4	76/80	AV-8B	7.0	71/76
U-2	18.3	76/85	C-17	4.1	83/88
KC-10	16.9	83/85	AH-64D	3.3	83/75
F-14B	16.0	73/65	E-8	3.0	84/75
F/A-18A-Navy	16.0	62/75	F/A-18E	1.8	71/75
F/A-18A-Marine	16.0	80/75			

Source: Military services' data.

The GAO found that difficulties in meeting MC and FMC goals were caused by a complex combination of interrelated logistical and operational factors, with no dominating single problem. The complexity of aircraft design, the lack of availability and experience of maintenance personnel, aircraft age and usage patterns, shortages of spare parts, depot maintenance systems and other operational factors, and perceived funding shortages were all identified by service personnel as causes of difficulties in meeting the goals. Action is being taken by the DoD in all these areas to improve aircraft availability.

Some interesting comments on these factors were provided by the GAO, and are summarised here. Design is a key factor, and complexity has tended to reduce MC rates. Personnel problems have included low retention rates and low manpower utilisation on maintenance activities due to various distractions. There is no obvious general correlation between aircraft age and lower availability. Spare parts inventory is a critical issue. Shortages of spare parts have been due to several factors, including inaccurate forecasting, obsolescence, and contracting problems related to low incentives. Cannibalisation rates have been excessive. The three services continue to experiment with different organisations of maintenance levels, and depot maintenance capacity has been progressively reduced by 50 – 60%. The reductions were partly due to restructuring and contraction after the end of the Cold War and partly due to the transfer of more maintenance/support work to industry. The debate continues on how best to organise in-service support. However, management integration between "the operations and logistics sides" of the organization is clearly viewed as key to aircraft availability. Good coordination between these two groups is essential because of the complex and multi-faceted causes of MC problems. For instance, underfunding of spare parts inventories, maintenance depots, and other aspects of the maintenance and supply systems has been a key problem. The GAO points out that this problem may worsen, since spending for operations and maintenance for aircraft increases by 1 to 3% for every additional year of age.

In [19], Hart included a graph of the average downtime of all USAF aircraft over the period 1991 – 2004 (Figure 2-9, blue upper curve). The graph shows that the average downtime (period of unavailability) per flying hour doubled over the ten years 1991 – 2001. Average downtime reduced sharply by 20% during 2001 – 2002, and then resumed its upward trend. This improvement in aircraft availability during 2001 – 2002 was due to the deferral of some scheduled maintenance during the First Gulf War. The second and third (pink and yellow) curves in the graph are the downtime per flying hour attributed to maintenance tasks and supply, respectively. They indicate that maintenance tasks and supply delays both contributed to the overall adverse trend in aircraft availability. The curves for maintenance and supply each include the downtime attributed jointly to maintenance and supply, and so their sum is greater than the total curve.

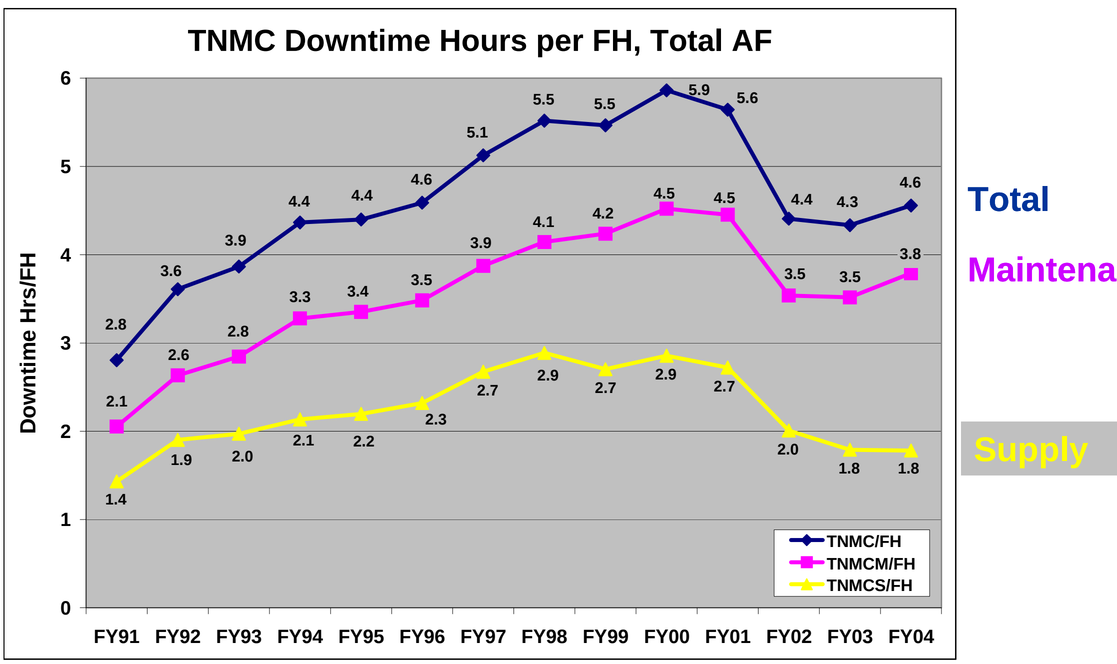


Figure 2-9: Average Downtime per Flight Hour During the Period 1991 to 2004 of All USAF Aircraft Assigned to Operational Units. (Source USAF Hart [19])

Due mainly to the importance attached to aircraft availability, there has been a recent trend in some NATO Nations towards Performance-Based Logistics (PBL). PBL is the use of performance-based criteria in acquisition and support contracts. The US DoD has defined the following five top level metrics that all PBL strategies should strive to maximize [20]: operational availability, mission reliability, cost per unit of usage, logistics footprint, and logistics response time. Contracts in the USA and other countries may also include subsidiary performance metrics, but the key performance parameters in recent acquisition and in-service support contracts include availability and mission reliability.

2.4 GOALS AND STRATEGIES FOR IMPROVING AIRCRAFT PLATFORM AVAILABILITY INCLUDING MISSION RELIABILITY

2.4.1 Availability Depends on the Need for Maintenance and the Associated Downtime

Average aircraft availability is governed by the *need for maintenance* and the time taken by the maintenance/ support system to perform this maintenance – known as *downtime*. To improve average availability, both the need for maintenance and the associated downtime must be reduced.

As mentioned earlier, the continued availability of an aircraft during a mission – mission reliability – is governed only by the conditional probability of a mission-critical failure. It was pointed out that the specified level of mission reliability is the main driver of preventive maintenance. As such it is a constraint on average availability. Consequently, measures to improve mission reliability will usually also improve average availability. The reverse is sometimes true, but not always.

The flight safety requirements in the aircraft specification might create a need for even more preventive maintenance. However, the marginal increase over the preventive maintenance required for mission reliability is likely to be small.

To develop goals and strategies for improving availability and mission reliability, it is necessary to understand all the drivers of aircraft maintenance. Aircraft maintenance is needed to:

a) Replenish fuel, weapons, lubricants, and other consumables;

b) Maximise mission reliability and flight safety to the extent feasible with the existing design;

c) Repair failures and potential (incipient) failures that occur during the routine operation of the aircraft; and

d) Repair failures and potential failures caused by non-routine events, such as accidents, hostile action, and operation outside the specification (e.g. damage due to collisions, missiles, and extreme manoeuvres).

The frequencies of replenishments (Item a) depend on the design of the aircraft and on operational factors. The downtime for replenishments is mainly controlled by the design, but speed and efficiency in execution are also important.

As already discussed, the need for preventive maintenance to maximise the mission reliability and flight safety (Item b) depends mainly on the design of the aircraft. The downtime for the preventive maintenance depends on the design and management of the maintenance/support system. It also depends on the ability of the design and maintenance/support organisations jointly to devise fast and efficient preventive maintenance strategies for reducing the probability of a mission-critical failure.

The arising rate of repairs (Item c) depends on the general reliability of the aircraft. The downtime for repairs depends on both the design of the aircraft and the design and management of the maintenance/support system.

The arising rate of repairs for non-routine events (Item d) and the scope of each repair depend primarily on factors other than design and maintenance/support. However, the design of the aircraft and the maintenance/ support system can significantly influence the downtime and cost associated with each task. In particular, if adequate availability is to be sustained in the face of damage from hostile action, the aircraft and the maintenance/support system must be designed accordingly.

The remainder of the current section develops goals and strategies for minimising the need for the maintenance listed above and for minimising the associated downtime.

2.4.2 Through Life Goals for Optimizing Aircraft Availability

Aircraft are part of an integrated system of equipment, infrastructure, and trained personnel that provides an enduring and adaptable military capability. It is generally recognized that the optimisation of an aircraft and its maintenance/support system with respect to availability and other elements of capability is most efficiently and effectively accomplished during the design phase. However, joint force capabilities may have to change very rapidly to address a new threat, and transformational changes may be needed quickly in current Air Force capabilities. It is quicker, and often more cost-effective, to improve an existing capability by making incremental changes to an existing aircraft and its maintenance/support system rather than acquiring a new aircraft.

In recognition of the need to improve the capabilities of existing aircraft at short notice, there is a trend in aircraft platform acquisition doctrine, particularly in Europe, to plan for a long service life with the intention of making several upgrades in capability through technology insertion (design modifications). Mid-life upgrades are not a new concept. Historically, aircraft have undergone several major upgrades in avionics, weapon systems and engines during their life cycle. While it is less practical and cost-effective to make major design changes to an existing airframe, substantial airframe modifications and requalification programs have also been undertaken to address specific reliability/durability problems or to extend the life of the airframe beyond the original design goal. The new doctrine is important because it recognises the need to design aircraft specifically to accept technology insertion later in life quickly at minimum cost.

Consistent with this doctrine, the goals developed in this report for improving aircraft platform availability and mission reliability are through-life goals. Since design and maintenance/support have generally been performed by separate organisations with different cultures, some high level goals for these two organisations are presented in the next two sub-sections. It will be seen that these overlap, and that the design and management of the aircraft and its maintenance/support system need to be integrated throughout the life cycle. Therefore, these goals are subsequently reformulated in Sections 2.4.3 and 2.4.4 as integrated (joint) goals – firstly for minimising the need for maintenance, and secondly for minimising the associated downtime.

2.4.2.1 Goals for Aircraft Design and Development

The relevant goals for aircraft design and development, including in-service modifications, are to:

a) Reduce the need for maintenance by optimising inherent reliability and mission reliability; and

b) Facilitate the reduction of maintenance downtime by optimising maintainability.

Any progress towards these goals will enable the maintenance/support organisation to reduce the number of maintenance tasks and/or the associated downtime.

An improvement in inherent reliability will reduce the need for both preventive and corrective maintenance. Additional measures targeted specifically at improving inherent mission reliability, will further reduce the need for preventive maintenance.

Since, as indicated above, reliability and maintainability jointly control the average availability of an aircraft, one can be traded against the other at the design level in achieving the specified availability. For example, poor reliability can be offset by good maintainability, provided mission reliability is adequate. Ideally, both reliability and maintainability should be optimised in balance with other program requirements.

2.4.2.2 Goals for the Maintenance/Support System

The relevant goals for the design and management of the maintenance/support system are to:

a) Design and perform preventive maintenance to maximise mission reliability to the extent feasible and cost-effective with the existing design;

b) Minimise downtime by performing only essential maintenance as quickly and efficiently as possible;

c) Reduce the downtime for specific preventive and corrective maintenance tasks by developing joint design and maintenance/support solutions;

d) Reduce the need for preventive and corrective maintenance by identifying potentially cost-effective improvements in inherent reliability and mission reliability for design action; and

e) Reduce the need for corrective maintenance by minimising failures due to maintenance errors and any other shortcomings in maintenance/support.

While these are goals for the maintenance/support organisation, they apply throughout the life of the aircraft from concept design onwards.

With respect to the first item on the list above, preventive maintenance can enhance mission reliability and flight safety by reducing the “conditional probability of failure”. This is the probability that a failure will occur during a specific period, provided that the item concerned has survived to the beginning of that period. The conditional probability of failure of a component can be reduced either by replacing/restoring the component before it is likely to fail, or by including inspections to detect potential failures before functional failure occurs. Such preventive maintenance only affects mission reliability. It does not alter the reliability of the aircraft in the more general, long-term sense.

Action in support of the listed goals must be tailored according to the military capabilities to which the aircraft is required to contribute, current operational priorities, and available resources. This is a difficult balancing act, since defence budgets are under constant pressure and defence policy must continuously evolve.

A great deal of effort has been devoted by national governments and Armed Forces in NATO to finding the best managerial approaches for maintenance/support. In the 1960s the managerial concept known as Integrated Logistics Support (ILS) emerged. The ILS process is a major element of the systems engineering approach that is employed by most NATO countries for the acquisition and life-cycle management of aircraft. It is a disciplined approach to the design and management of the aircraft and its maintenance/support system that is specifically aimed at optimising aircraft availability while minimising life-cycle maintenance/support costs.

Originally, ILS was a collaborative process between the aircraft manufacturer and the client Air Force, and was built into the acquisition contract. This is still the case in many NATO countries, such as the UK, Germany, and Canada. In the USA, the term ILS is no longer used, and Military Specifications relating to ILS, such as Mil-Std-1388 “Logistic Support Analysis” [21], have been discontinued as contractual documents. Detailed but non-compulsory manuals for training and guidance exist on systems engineering and the design of weapon systems and maintenance/support systems for maximum availability and minimum life-cycle cost. However, the government project team is now given the freedom to manage the acquisition program with minimal constraints from military standards. Similarly, the aircraft manufacturer is given the freedom to decide how best to achieve the aircraft capability and maintenance/support requirements defined by the project team. These freedoms are not absolute, but there is now much more emphasis on properly defining program performance and output requirements rather than defining the processes that a prime contractor must use in achieving them. The Aircraft Structural Integrity Program (ASIP), currently defined in Mil-Std-1530C, is one example of a process that DoD has recently restored to mandatory status for all new programs.

In 2007, the US DoD introduced a new all-embracing maintenance policy called Condition-Based Maintenance Plus (CBM+) [22]. It is defined by DoD as follows:

> "CBM+ is the application and integration of appropriate processes, technologies, and knowledge-based capabilities to improve the reliability and maintenance effectiveness of DoD systems and components. At its core, CBM+ is maintenance performed on evidence of need provided by Reliability Centered Maintenance (RCM) analysis and other enabling processes and technologies characterized in Enclosure 2. CBM+ uses a systems engineering approach to collect data, enable analysis, and support the decision-making processes for system acquisition, sustainment, and operations."

It appears from the new policy that CBM+ consists of RCM, other elements of the previous ILS process, and R&M management.

In several NATO countries, there has been a trend to delegate more responsibility and accountability to the aircraft manufacturer for achieving the required aircraft availability. Acquisition and maintenance/support contracts of this type are called "performance-based contracts" or "availability-based contracts". Except in the case of the USA, the ILS process in its traditional form is usually retained as a mandatory element of such contracts. More information on the ILS concept is provided in Chapter 5.

2.4.3 Joint Goals and Strategies for Minimising the Need for Maintenance

It can be seen in the previous section that the separate goals for the design and maintenance/support organisations overlap. This overlap highlights the need to integrate the design and management of the aircraft and its maintenance/support system throughout the life cycle. Accordingly, the goals presented in Section 2.4.2 have been reformulated in Sections 2.4.3 and 2.4.4 as integrated (joint) goals – firstly for minimising the need for maintenance, and secondly for minimising the associated downtime. The goals are represented by the sub-headings. The text under each sub-heading contains strategies for making progress towards the goal in question. Chapters 5 and 6 provide more information on management and equipment concepts and technologies that could help to implement the strategies.

The current section presents the joint design and maintenance/support goals and strategies for *minimising the need for maintenance*.

2.4.3.1 Maximise the Inherent (Design) Reliability and Mission Reliability

Reliability is generally expressed either as the duration of failure-free performance under stated conditions or as the probability that an aircraft (or component) can perform its intended function for a specified interval under stated conditions. NATO ARMP-7 [2] adds a useful sub-category known as "basic reliability", which is the reliability estimated for a full life profile.

The inherent reliability of an aircraft is determined by its design. Standard definitions of "inherent reliability" vary slightly. It is generally viewed as the highest level of reliability that the aircraft can achieve with the approved design. An approved design is one in which the production drawings, and associated manufacturing processes have been qualified – i.e. validated by flight and ground testing or other means. Reliability parameters are measured during the qualification test program, and the validated estimates of reliability can be used as a baseline measure of inherent reliability for future reliability management. Changes in the design or a manufacturing process may change the inherent reliability.

Human and other factors inevitably result in shortcomings that will lower the reliability of the aircraft from its inherent value. The manufacture of aircraft is subject to strict, independently supervised quality control measures to keep the risk of premature failures within design specifications. Design also plays an important role in reducing the probability of manufacturing errors. For example, designers should use robust design concepts and proven standard parts where possible, and should avoid unnecessary complexity, the need for unfamiliar or difficult manufacturing processes, etc. It is important that the design and the manufacturing processes are developed concurrently, and that both the design and the manufacturing processes are clear, unambiguous, and subject to strict configuration management down to the lowest component level.

It is standard practice in NATO to establish a formal Reliability And Maintainability (R&M or RAM) management program at the concept design stage. This is intended to ensure good communication between the client and manufacturer, and to obtain assurance through reviews, reliability growth testing, and other measures that the reliability and maintainability specifications will be met before the aircraft enters service. As a result of R&M management during design and manufacture, the aircraft should achieve the specified level of reliability and mission reliability at the time it enters service. To allow some margin, the design should have an inherent reliability that is higher than the specified reliability at this point.

The R&M management program is continued during series production and the life of the aircraft, to ensure that the actual reliability and mission reliability do not fall significantly below the inherent values, or at least the specified values, during the design service life of the aircraft. While the R&M management program initially focuses on design and manufacture, it provides essential information for the design of the maintenance/ support system and for dealing with any later shortfall in reliability. Consequently, when the aircraft enters service, the R&M management program typically evolves to become an integral part of the maintenance/ support program.

In some countries, such as the UK, the R&M management program is viewed as a separate but parallel program to ILS that provides essential input to the ILS program. Regardless of whether the R&M management program is viewed as integral or parallel to ILS, R&M should be managed actively from the earliest stages of design throughout the life of an aircraft.

Some major reliability and safety problems have occurred in the past with aircraft structure. These have given rise to a program dedicated to achieving and sustaining a high degree of structural integrity (high reliability and a low conditional probability of failure). In several NATO Air Forces this is known as the “Aircraft Structural Integrity Program (ASIP)”. This program has evolved over the past 40 years. In the US DoD it was recently restored to mandatory status as Mil-Std-1530 [23]. It defines the requirements necessary to achieve structural integrity in USAF aircraft while managing cost and schedule risks through a series of disciplined, time-phased tasks. It provides direction to government personnel and contractors engaged in the development, production, modification, acquisition, and/or sustainment of USAF aircraft. In this sense, ASIP makes a major contribution to the design and management of the aircraft and the maintenance/support system.

Engine R&M is usually managed as part of another parallel program known as the Engine Structural Integrity Program (ENSIP). This program is an organized and disciplined approach to the structural design, analysis, qualification, production, and life management of gas turbine engines. In the US DoD it is currently defined in

Mil-Hdbk-1783B [24]. Unlike ASIP, it is currently not a mandatory program in the US DoD. The goal of ENSIP is to ensure engine structural safety, durability, reduced life-cycle costs, and increased service readiness. In this sense, ENSIP or the contractor's equivalent program also makes a major contribution to the design and management of the aircraft and the maintenance/support system. ENSIP, or its equivalent, is applied by many NATO Air Forces.

More detail on advanced R&M management concepts is given in Chapter 5. Since this report deals primarily with maintenance concepts and technologies, it does not discuss reliability engineering methods for modeling and optimising reliability in any detail. Reliability engineering is a well-established discipline with many dedicated university departments. Readers may wish to refer to text books such as [25] and military manuals such as [7] and [26] for more detail on reliability engineering methods.

2.4.3.2 Achieve the Inherent (Design) Reliability and Mission Reliability in Service

The reliability and mission reliability that an aircraft achieves in service may be lower than their inherent values for many reasons, which can be grouped into the following categories:

a) Design estimates and qualification testing related to reliability are based on simplifying assumptions and may result in an optimistic assessment of inherent reliability metrics or their variability;

b) Production quality control cannot be perfect, and so shortcomings in manufacture may result in excessive early failures or potential failures in service;

c) The usage, including the environment, may deviate from the aircraft specification, resulting in excessive early failures due to faster wearout and/or higher stress;

d) Corrective maintenance may not be successful in all cases, particularly if it is not feasible to fully verify on the ground that all faults have been repaired;

e) It may not be feasible or cost-effective to restore the inherent reliability of some components during repair or restoration; and

f) Premature or unforeseen failure modes may be inadvertently induced by prior preventive or corrective maintenance.

The descriptions given above of these categories serve also to indicate the strategies needed to deal with them. However, there are a wide variety of potential underlying causes associated with each of these categories, and the development and execution of the strategies may not be simple or quick.

One of the important roles of the maintenance/support system is to achieve the required levels of mission reliability and flight safety through preventive maintenance. Even if the specified levels have been achieved in service, there is usually a desire to maximise them to the extent feasible and cost-effective. To improve mission reliability, effort must be focussed on those mission-critical components with the lowest reliability.

The R&M management program described earlier helps to identify and define reliability problems and to promote their successful resolution. It also usually aims to achieve continuous reliability growth, even if the original specified and inherent reliability levels have been achieved in service. Some of the maintenance/support concepts and technologies described in Chapters 5 and 6 can help both to maintain reliability growth and to maximise mission reliability and flight safety.

Design strategies to improve reliability and mission reliability usually overlap to a considerable extent, but may conflict in some aircraft components. For example, it may sometimes be necessary to employ redundancy to achieve the required mission reliability. However, redundancy may increase the need for maintenance and may reduce the general reliability [7], [26]. The benefits of redundancy may also have to be traded against the negative effects of increased cost and weight.

2.4.3.3 Limit Maintenance to Essential Tasks

The design of an aircraft and its in-service support system is an iterative process. A process known as "Reliability Centred Maintenance (RCM)" is widely used in NATO and civil aviation in designing preventive maintenance programs. The RCM process provides a means of determining in progressively greater detail during successive design iterations what preventive maintenance tasks are necessary and how best to perform them. During the remaining life of the aircraft, it provides an objective basis and process for reviewing the maintenance program. The data generated during the RCM process, in particular the results of the Failure Modes and Effects Criticality Analysis (FMECA), also facilitate the planning of corrective maintenance, although this is not the primary aim of RCM. The application of the RCM process together with the R&M management program from an early stage helps to highlight the areas where improvements to inherent R&M and the maintenance/support system would provide a good return on investment.

Maintenance tasks designed according to RCM principles fall into one of the following categories:

a) Preventive maintenance:

   1) Servicing: the replenishment of consumable materials and weapons that are depleted during normal use, including corrosion preventive/inhibitive compounds; and routine washing/cleaning to remove damaging atmospheric contaminants.

   2) Hard time tasks to replace or restore components that have reached their safe life or economic life.

   3) On-condition tasks to detect potential, i.e. incipient, failures.

   4) Failure-finding tasks to detect hidden failures, i.e. failures not obvious to the aircrew or ground-crew unless a demand is placed on the component in question.

   5) The monitoring of parameters that might provide insight into environment, condition, performance, failure modes, rate of degradation, etc., with the aim of improving the effectiveness and efficiency of the maintenance program. This is known in RCM terminology as "age exploration".

   Note: On-condition and failure finding tasks are frequently referred to as "inspections".

b) Corrective Maintenance:

   1) Diagnosis.

   2) Repair, including testing.

Rigorous application of the RCM process ensures that only essential preventive maintenance is performed, and that it is performed in a cost-effective manner. Where possible, preventive maintenance should be limited to tasks that:

- Replenish fuel, weapons, lubricants, and other consumables; and
- Maximise mission reliability to the extent feasible with the existing design.

The conditional probability of failure may be expressed quantitatively or qualitatively in the specification in a number of different ways, or it may have to be inferred from other requirements. Whichever method is used, clear notions of the required availability and mission reliability are needed to enable the design of a cost-effective preventive maintenance program.

The core principles and minimum process requirements of RCM are defined in international standards and military handbooks, and are discussed in more detail in Chapter 5. However, each organisation defines its own RCM process and may expand the definitions of essential preventive maintenance given in these standards and handbooks. For example, military and civil regulatory agencies require the combined use of hard time and on-condition tasks for safety reasons for some components, and commercial airlines add criteria related to customer satisfaction. Since the RCM standards are not necessarily mandatory in NATO Air Forces and are costly to apply, it is important to understand RCM and appreciate its value as an advanced management concept that provides a sound basis for maximising aircraft availability.

The next section illustrates how improvements in design and maintenance/support might reduce downtime for each of the maintenance categories listed above. More detail is provided in Chapters 5 and 6.

2.4.4 Joint Goals and Strategies for Minimising Downtime for Required Maintenance

As mentioned earlier, the goals presented in Section 2.4.2 have been reformulated in Sections 2.4.3 and 2.4.4 as integrated (joint) goals – on the one hand for minimising the need for maintenance, and on the other hand for minimising the associated downtime. The goals are represented by the sub-headings. The text under each sub-heading contains strategies for making progress towards these goals. Chapters 5 and 6 provide more information on management and equipment concepts and technologies that could help to implement the strategies.

The current section presents the joint design and maintenance/support goals and strategies for *minimising the downtime for required maintenance*.

2.4.4.1 Design the Aircraft for Maintainability (Ease of Maintenance)

Maintainability is the relative ease and economy of time and resources with which an aircraft (or component) can be maintained. Like reliability, it is an “interval” concept. As a performance parameter, maintainability is generally expressed either as a measure of the time required to repair a percentage of all aircraft failures – such as the “mean time to repair 95% of all failures” – or as a probability of restoring the aircraft to operational status within a period of time following a failure. In this sense, maintainability is a design parameter that is based on the existence of a specific maintenance/support system and assumes that the necessary resources are immediately available to the aircraft in question. If the maintenance/support system differs significantly from the assumed one, the base for measuring maintainability and, therefore, the values of maintainability metrics will also differ. Clearly, it is advantageous to integrate the design of the aircraft and the maintenance/support system so as to obtain maximum synergy.

Since reliability and maintainability jointly control availability, one can be traded against the other at the design level in achieving the specified aircraft availability. For example, poor reliability can be offset by good maintainability, provided mission reliability is not compromised. Ideally, both reliability and maintainability should be optimised in balance with other program requirements.

Because of this interrelationship, maintainability is closely managed as part of the R&M management program mentioned earlier. This program is a major element of the umbrella Integrated Logistics Support (ILS) program or equivalent systems engineering management approach that is employed by most NATO countries. In some cases, such as in the UK, the R&M management program is viewed as a separate but parallel program that provides essential input to the ILS program. Regardless of whether the R&M management program is viewed as integral or parallel to ILS, R&M should be managed actively from the earliest stages of design throughout the life of an aircraft.

Any shortcomings in the maintainability of the aircraft platform are likely to have a direct impact on aircraft availability. Shortcomings in the maintainability of repairable components in the supply chain have a less direct effect. The following list illustrates the kind of design measures that can improve the maintainability of the aircraft platform:

a) Improve the accessibility for preventive and corrective maintenance by appropriate arrangement of aircraft components, the provision of access panels, the provision of interfaces for the remote testing of avionics and electrical systems, etc., with due consideration of human factors.

b) Ensure that, to the extent required by the specification, all maintenance tasks can be performed easily, reliably, and quickly by personnel in adverse environments wearing protective clothing.

c) Use simple design concepts with a minimum of parts and fasteners.

d) Use common or standard design features and parts with proven maintainability characteristics.

e) Minimise the need for special tools and maintenance facilities.

f) Minimise the need for maintenance processes that would be difficult to apply during expeditions (deployments).

g) Design components at all levels for ease of inspection and fault diagnosis (inspectability and testability).

h) Design components for ease of removal, handling, and installation, including methods of locking for retention.

i) Design for a high degree of damage tolerance in the airframe structure, engines, and other mechanical components, to allow the use of proven and relatively inexpensive Non-Destructive Inspection (NDI) techniques to detect potential failures.

j) Facilitate or fully automate inspection and diagnostics, at least to the level of Line-Replaceable Units (LRU), by providing sensors, Built-In Test (BIT), self diagnostics, maintenance data recorders, and interfaces for ground-based inspection and diagnostic equipment.

k) Use appropriate modularity in the design the airframe structure and electrical, optical, and hydraulic transmission systems for ease of repair in the event of fatigue failure and environmental damage, and damage due to accidents and hostile action.

l) Design the aircraft for interoperability with NATO Allies, by using common or interchangeable fuel, weapons, lubricants, other consumables, and by using existing standard NATO parts, processes, and ground equipment as far as possible – as promoted by various NATO Standardisation Agreements (STANAGs).

m) Identify opportunities to improve maintainability through joint improvements to the design of the aircraft and the maintenance/support system.

Advanced technologies can be used to assist with many of these measures. The following are illustrative examples:

- The software currently used by aircraft manufacturers for design integration and visualisation in 3-D, such as CATIA, provides an excellent tool for optimising the accessibility of internal equipment and structure for maintenance (Item a).

- More recently, software has also become available for the simulation and visualisation of human movements during maintenance tasks (Items a and b).
- Several self-locking fastener systems are available on the market, and some are designed for use by personnel wearing protective clothing (Items b and g).
- The Non-Destructive Inspection (NDI) industry and government research laboratories continue to provide more efficient and effective inspection methods requiring less disturbance to the aircraft (Items a, h, and i).
- There is a strong drive in NATO Air Forces to develop sensors and on-board signal and data processing systems to perform automated inspections, diagnostics, and reassessment of remaining useful life during flight, where this would be cost-effective (Items h and i).
- There are major ongoing R&D programs to improve ground-based Automatic Test Systems/ Equipment (ATS/ATE), including ATS for use at 1st Line (Items i and j).
- Advances have been made in the modular design of airframes and engines in aircraft, e.g. the Rafale fighter, to facilitate major repairs and component changes at forward bases (Item k).
- Continued development of the systems engineering management concept and the use of through-life Integrated Project Teams (IPT) will promote the integration of design and maintenance/support in achieving joint improvements in aircraft maintainability (Item m).

Additional strategies for reducing the downtime for each category of maintenance listed in Section 2.4.3.3 are outlined in the remainder of Section 2.4.4.

2.4.4.2 Reduce Downtime for Servicing

The general maintainability strategies already discussed apply to servicing. In particular, the downtime for servicing (Item 2.4.3.3a)1) above) can be reduced by designing the aircraft to operate for longer periods without replenishments and other servicing, and by providing automatic indication of the need for replenishments. The following additional strategies may also be useful.

Routine washing/cleaning to remove damaging atmospheric contaminants can be very beneficial over the long term in reducing the need for corrective maintenance to the structure of airframes and engines. The routine application/restoration of Corrosion Preventive/Inhibitive Compounds (CPC/CIC), independently or in conjunction with washing, can be beneficial for the same reasons. For optimum effect, both procedures and their frequency of application must be carefully designed. Over-application will increase downtime without any benefit.

On occasions when fuel is the only consumable that needs replenishment, in-flight refuelling is a maintenance concept that can significantly reduce the downtime for servicing. In-flight refuelling also reduces transit time to and from the target zone, and can thereby further increase aircraft availability in the target zone. It also effectively extends the combat radius and ferry range. The cost of a tanker fleet is high, but may be justified by the overall increase in capability provided by in-flight refuelling.

A more modest improvement in aircraft platform availability during a period of high operational tempo can be obtained by keeping the engines running during crew changes and/or refuelling on the ground. This approach is known as a “hot turnaround” or “hot refuelling”.

2.4.4.3 Reduce Downtime for Replacement/Restoration of Lifed Components

2.4.4.3.1 Focussed Design for Maintainability

The downtime for planned component replacement or rework (Item 2.4.3.3a)2) above) can be reduced by applying many of the aircraft maintainability strategies already discussed with particular attention to the components in question.

2.4.4.3.2 Extend Remaining Useful Life

The accumulation of downtime for the replacement of lifed components can be stopped or reduced by extending the lives of the components. This might be achievable in several ways, for example:

- Extra investment in design and development without a change in technology;
- Redesign of the component or system to take advantage of more advanced technology; and
- An improvement in usage monitoring and failure modelling to reduce uncertainty, and hence reduce the safety factors used in life estimation.

2.4.4.3.3 Improve the Scope and Accuracy of Usage Monitoring

With regard to the last option, the useful life can be maximised for a given probability of failure by updating the usage input to the estimate of Remaining Useful Life (RUL) as frequently and accurately as possible, and by adjusting the maintenance schedule accordingly. Increasing the accuracy of usage monitoring reduces the uncertainty in the estimate of remaining life.

Usage monitoring is essential for determining when to perform preventive maintenance, and improvements in monitoring can reduce downtime and life-cycle costs. In its simplest form, usage monitoring consists of keeping written records of flying hours and elapsed time for the aircraft and its lifed components. For some high value components with limited lives, it is cost-effective to monitor usage more accurately using dedicated monitoring systems. For example, accelerometers and strain gauges have been used for many years to record the fatigue usage of some structural components.

With advances in monitoring technologies, including data handling and processing, it has become feasible to monitor the usage of ever more components while improving accuracy and reducing costs. Also, it has in some cases become worthwhile to calculate the remaining useful life and reschedule component replacement using an on-board system rather than a ground-based system. In such cases usage information is fed directly to the on-board system in flight. Such a system is sometimes referred to as a prognostic system.

The monitoring and processing of usage data and other parameters in flight require additional components, which add weight, complexity, and their own requirements for maintenance. To be useful, such on-board maintenance systems must provide a net benefit in aircraft availability and/or life-cycle cost.

2.4.4.3.4 Use On-Condition Inspections Instead of Component Replacement/Restoration (Condition-Based Maintenance – CBM)

A net reduction in downtime might be achieved by substituting the mandatory replacement of a component with a series of on-condition inspections to detect incipient failure. Improvements in failure modelling, usage monitoring, and inspection technology might be needed to make an on-condition approach technically feasible, to make it cost-effective, and to achieve a significant reduction in net downtime. This investment has been found worthwhile for certain categories of components, even on legacy aircraft. For example whole fleets have been retired early or have required major restoration programs, such as new wings, because of unforeseen factors in the estimation of the safe lives of some structural components. Since there will always be unforeseen factors, a move to on-condition maintenance could be viewed as insurance against such catastrophic losses in fleet availability.

Of course, such a change in maintenance concept also benefits safety and life-cycle cost. The benefit to safety in an on-condition approach is that the conditional probability of predicted failure modes can be reduced while also providing some opportunity to detect accelerated degradation and unforeseen failure modes before functional failure. The benefits to life-cycle cost arise mainly from the ability to extract more useful life out of high value components.

An example of safety enhancement is the use of automated on-condition inspections and enhanced usage monitoring on the drive trains of helicopters operating over the North Sea. In this case, the mandatory replacement lives have been retained. The systems have proven so effective in improving safety that they are now mandated for this region by the civil regulatory authorities.

An example of benefits to both cost and availability is the US Army's use of automated usage monitoring and automated on-condition inspection of drive train components in attack helicopters in Iraq and Afghanistan. Through the close management of individual components, aircraft availability has been improved significantly and the maximum useful life has been extracted from high value components.

The strategy described in this section is sometimes referred to as Condition-Based Maintenance (CBM). CBM is not yet well defined in military and international standards. There are no international standards describing CBM in any detail, but the following are two short international standard definitions of the term CBM:

- Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. The performance and parameter monitoring may be scheduled, on request, or continuous. European Standard NF EN 13306 [8].
- Maintenance performed as governed by condition monitoring programs. ISO 13372 [27].

According to the above definitions, automation and embedded inspection systems are not prerequisites of CBM. Nevertheless, the term has become associated with such systems. For example, a standard Open System Architecture (OSA) for implementing condition-based maintenance systems, named OSA-CBM, was developed in 2001 by an industry led team partially funded by the US Navy. There is more on this in Chapter 5.

As mentioned earlier, the US DoD has recently introduced the term CBM+ as the name of a new all-embracing policy for the maintenance/support of military equipment of all types. Clearly, CBM should not be confused with CBM+. However, CBM is an important strategy within CBM+. The new DoD policy defines CBM as follows:

> "A maintenance strategy based on equipment operational experience derived from analysis. CBM includes maintenance processes and capabilities derived from real time or approximate real-time assessments obtained from embedded sensors and/or external tests and measurements using either portable equipment or actual inspection. The objective of CBM is to perform maintenance based on the evidence of need while ensuring safety, reliability, availability, and reduced total ownership cost."

This DoD definition includes traditional, ground-based inspection methods as well as embedded sensor systems. The policy refers the reader to a new "DoD Guide for Achieving Reliability, Availability and Maintainability (RAM)" [28] for more information. This guide confirms that DoD regards CBM as embracing all forms of inspection, including ground-based NDE. It clouds the issue by stating elsewhere: "Continuous monitoring or continuous inspection is the basis of CBM". However, this statement may refer primarily to land and sea vehicles, where sensor systems would present lesser problems of weight, integration, and cost.

The definitions and perceptions of CBM illustrated above differ mainly in where and how CBM tasks should be performed. The common factor in most usage of the term is that CBM is consistent with the RCM concept of "on-condition" maintenance. RCM lays down no preconditions on where or how an inspection should be performed. Instead, it seeks the most cost-effective approach.

2.4.4.4 Reduce Downtime for Inspections (On-Condition and Failure Finding Tasks)

To determine how inspection downtime might be reduced, it is important to understand the purposes of inspection. An inspection is defined in NATO ARMP-7 [2] as the process of systematically examining, checking, and testing aircraft structural members, components and systems, to detect actual or potential unserviceable conditions. On-condition and failure finding tasks (Items 2.4.3.3a)3) and 2.4.3.3a)4) above) consist of inspections. In the context of a maintenance program, such inspections are mandatory activities that can only be cancelled or deferred with the approval of the relevant regulatory authority. The inspections monitor aircraft components for evidence of potential or actual failure at intervals based on usage or elapsed time. If inspections are performed continuously in flight by an on-board system, the inspection interval is effectively zero.

The scope and process of inspection is typically specified in each maintenance task. To help in training and communication, it is useful to use standard processes and terminology to the extent feasible. For example, maintenance programs based on the Air Transport Association of America standard MSG3 [29] use standard inspection terminology such as "Detailed Inspection (DET)", "General Visual Inspection (GVI)", "Special Detailed Inspection (SDI)", and "Functional Check".

The terms "monitoring" and "condition monitoring" may or may not signify an inspection as defined above. These terms are not defined clearly in many relevant standards, while the term "inspection" is defined with reasonable consistency in several relevant standards.

The downtime for on-aircraft inspections can be improved by many of the maintainability design measures outlined earlier. Other complementary strategies are outlined below.

The packaging of maintenance tasks for performance at different levels of the maintenance organisation can significantly influence the average downtime of the fleet and the downtime of aircraft at the front-line squadrons (1^{st} Line). It is important to be capable of a fast Turnaround Time (TAT) at 1^{st} Line, to cope with high operational tempo. Therefore, servicing and inspections must be minimized and streamlined to the maximum extent possible. Equipment technologies, such as maintenance panels and maintenance data systems, can be used to facilitate and automate some 1^{st} Line inspections as well as the diagnostics following failures. Air to ground data links and networks can be used to relay the results of automated inspections to home base and the supply chain for anticipatory action.

Where possible, the aircraft should be designed so that inspections can be performed at 3^{rd} or 4^{th} Line. Here, they can be organised efficiently in parallel with other inspections, any associated corrective action, other preventive maintenance, and any design modifications.

Inspection technology can strongly influence the downtime and cost associated with inspections. Consequently, there is considerable ongoing R&D effort in both ground-based Non-Destructive Inspection (NDI) and on-board inspection systems. Advances in ground-based NDI systems have reduced the need for extensive dismantling of engines and airframes to inspect internal structural components and hidden surfaces in joints with adequate probability of detection. When access for inspection remains a problem, an alternative strategy is to embed sensors in the aircraft. They can be interrogated either on the ground or by an on-board inspection system.

On-board inspection systems are likely to incur cost and weight penalties and may result in additional preventive and corrective maintenance tasks. Nevertheless, they can sometimes be cost-effective in reducing the net downtime for preventive and corrective maintenance, by one or more of the following means:

a) Reducing or eliminating the downtime for the originally required inspection;

b) Providing earlier detection of potential failures and hidden failures than ground-based inspections, such that the corrective action can be planned in advance; and

c) Facilitating the detection and diagnosis of those potential failures and hidden failures that are difficult to detect and assess on the ground.

Interest in these three strategies has prompted the development of several novel sensor technologies. A review of sensor technologies is presented in Chapter 6.

Strategy b) requires the deferment of corrective action for potential failures. This may require regulatory approval, since there is a general policy in NATO Air Forces and civilian regulatory authorities of “find it fix it”.

2.4.4.5 Reduce Downtime for Age Exploration

Age exploration consists of the collection and analysis of aircraft data in service with the aim of improving the efficiency and effectiveness of the maintenance program. It might result in the addition of new maintenance tasks and the validation or improvement of existing ones. For example, age exploration is often undertaken to provide a basis for extending usage limits. The data may be obtained while the aircraft is on the ground, or it might be obtained through automatic monitoring of parameters using an on-board system. The downtime for age exploration tasks can be reduced by means similar to those for inspection tasks.

2.4.4.6 Reduce Downtime for Diagnostics

If potential or actual failure is detected, corrective maintenance is required. Usually, this starts with the process known as “diagnosis” or “fault diagnosis” or “diagnostics”. The latter term is frequently used in the industry, and has several consistent international standard definitions. NATO ARMP-7 [2] defines diagnostics as the detection, isolation and analysis of faults and failures. In this report, all three terms are regarded as equivalent.

In the case of on-condition and failure-finding inspections, the expected failure modes will normally have been studied carefully during the Failure Modes and Effects Criticality Analysis (FMECA) that is part of the RCM process. If so, full diagnostics of a failure or potential failure will either not be needed or will be relatively straightforward. Moreover, most inspections of this nature are performed during 2nd, 3rd, or 4th Line maintenance of the aircraft or Line-Replaceable Unit (LRU), where a reasonable delay for diagnostics may not increase net aircraft downtime.

On the other hand, unexpected failures and failure modes are much more likely to occur at 1st Line (during aircraft operations), where they will normally require diagnostics to at least LRU level. Here diagnostics could result in considerable downtime that directly affects operations. Therefore, technologies to improve diagnostics at 1st Line have a direct impact on aircraft availability.

The level of diagnostics required depends on the organisational maintenance level. At 1st Line, repairs are normally limited to the replacement of faulty LRUs and to minor structural repairs, for which standard repair schemes are usually included in the structural repair manual. Therefore, diagnostics at 1st Line can be limited to the level of systems and LRUs, together with the interconnecting wiring and databus. At other organisational maintenance levels, faults need to be isolated to specific modules and piece-parts. In a two-line maintenance system (base and depot only), or during deployed operations, this may require that the LRU be sent to a central depot away from the operating base.

The rapid, efficient, and effective diagnosis of faults to any depth – system, LRU, wiring, databus, module, or piece-part – requires advanced technologies. These include technologies to support NDI, wiring diagnostics, Built-In Test (BIT), other on-board diagnostic systems, ground-based Automatic Test Systems (ATS), and Interactive Electronic Technical Publications (IETP). Artificial intelligence technologies, such as neural networks, Bayesian causal (belief) networks, case-based reasoning, and information/data fusion, can play important roles in the automation, enhancement, and integration of these other technologies. Technicians should be given access to all the information and decision support they need through portable computers with wireless links to local and global networks.

2.4.4.7 Reduce Downtime for Failures that Cannot be Duplicated (CND)

Despite considerable advances in diagnostic systems a significant percentage of reported failures cannot be confirmed or duplicated on the ground. Such occurrences may be termed “Cannot Duplicate (CND)”, “No-Fault-Found (NFF)”, or “Re-Test OK (RTOK)”. This is primarily a problem with electrical and electronic systems. If the CND is due to an intermittent fault that only occurs under the stress of flight conditions, it may only be possible to diagnose it in flight or with the help of flight data. If the CND is an intermittent fault whose probability of occurrence is equal on the ground or in flight, it is still necessary for efficient diagnostics to have access to relevant flight data. If the CND is due to an inability of the diagnostic systems to recognize the fault, the only solution is to improve the diagnostic systems.

It is possible for diagnostic systems to give false alarms and incorrect diagnoses. Some BIT systems in electronic LRUs have gained a reputation for this form of unreliability. A false alarm in flight may impact the mission, even though there is no system failure. False alarms, whether they occur in flight or on the ground, can result in the same downtime for diagnostics as real failures, and can exacerbate a problem with CND. Consequently, the reliability as well as the efficiency of diagnostic systems is an important issue for aircraft availability.

Excessive CND and false alarms can also affect the supply chain to 1st Line in two ways. Firstly, they have the obvious effect of reducing the buffer stock of serviceable spares until the supply chain can recover. The associated risk to aircraft availability can be amplified by a temporary increase in LRU failures due to unforeseen environmental factors or a high operational tempo. Secondly, an intermittent fault that only occurs under flight conditions and remains unidentified will continue to occur in susceptible LRU. These susceptible LRU will tend to accumulate in the spares pipeline, and will magnify the adverse effect of the intermittent fault on availability at 1st Line.

There appears to be no single solution to the problem of high CND false alarm rates. Only a rigorous systems engineering approach during the definition of requirements, design, and development of aircraft components and their diagnostic systems will guard against the hardware, software, and environmental issues that cause diagnostic unreliability. To address the possibility of unforeseen intermittent failures that only occur in flight, it would help to expand the monitoring of parameters during flight that might contribute to later diagnostics. Where appropriate, this approach can be taken one stage further by incorporating more diagnostic systems on the aircraft. For components that are already in service, it would help to be able to perform ground inspections that simulate the flight environment. This capability is currently not a normal part of 2nd, 3rd, or 4th Line maintenance.

2.4.4.8 Reducing Downtime for Repair

At 1st Line, most repairs are required as the result of failures in flight. Any single repair may directly affect aircraft availability, and the aircraft must be returned to service within a matter of hours, regardless of the failure. A quick turnaround capability is also important at other organizational maintenance levels, but, unlike 1st Line, a single repair will not be on the critical path for an aircraft unless there is no buffer stock of serviceable LRU in the supply chain or unless there is an excessive delay for the design of a non-standard structural repair scheme. Therefore, a capability for rapid repair as well as diagnostics at 1st Line is particularly important. This requirement must be taken into account during the concept design of the aircraft and its support system, and throughout the entire life cycle of the aircraft. The need exists in all operational scenarios.

To minimise the downtime for repair at 1st Line, it is important that the LRU partitioning of systems during the early stages of the program is carefully considered from the perspective of aircraft maintainability, and that the aircraft and maintenance/support system are designed to ensure that:

- LRU can be replaced quickly and with a minimal requirement for external testing after installation; and
- Spare LRU are available when required.

Traditionally, corrective maintenance at 1st Line has been performed before the next flight. Any deferral of corrective maintenance has usually involved special approval procedures and sometimes special additional maintenance tasks pending full repair. In some cases, it is possible to improve aircraft availability at 1st Line by streamlining the approval process. One way of doing this is to create a pre-authorised GO/NOGO list of equipment or functions for each type of mission. Such lists are sometimes called Minimum Equipment Lists (MEL).

It was mentioned earlier that as a matter of general policy NATO Air Forces do not routinely defer the repair of failures and potential failures. This is primarily a 1st Line issue, but could also arise during aircraft 3rd and 4th Line maintenance. There is increasing interest in deferring the repair of potential failures when feasible, so that corrective action can be planned for greater efficiency and less net downtime. There is also interest in using this approach to help manage a limited stock of high value spares so as to optimise fleet availability. This interest has grown in parallel with the ongoing automation of on-condition inspection, because the required technologies are similar.

The downtime for 3rd and 4th Line (depot) maintenance of aircraft is heavily influenced by the management of the work. This is also true of engines and some other LRU. However, the concepts and technologies used in repair also play an important role. For example, the modular design and manufacture of some engines and airframes facilitates the interchange of modules to minimize aircraft and LRU downtime. The use of cold working of holes and surfaces, bonded patches, laser beam welding, friction stir processing, thermal spray of surface protection, and other repair technologies can minimize the duration of repair work to airframes, engines and transmissions in the event of unexpected corrosion and fatigue cracking. Finally, the use of robotics can help in reducing the time to repair both large and small and large components.

In the case of structure and other mechanical components, it is sometimes possible to specify in advance the limits of acceptability for certain types of degradation and to provide standard procedures for damage mitigation, such as the blending of mechanical damage, the removal of corroded material, and the restoration of protective treatments. This information is typically included in the aircraft maintenance manuals. These manuals also contain standard repair schemes for damage and degradation likely to be encountered in service. In general, it would be beneficial for aircraft availability to include as much information as possible in repair manuals. This is particularly important at 1st Line. It is also important at other organisational maintenance levels, because there can be a long lead time to obtain a new repair scheme from the manufacturer or other design authority.

There are other solutions to this problem. For example, Boeing has placed experienced engineers alongside USAF maintenance staff at Tinker Air Force Base, to minimise the lead time for repair schemes and other design input for KC-135 tanker aircraft. These engineers played an important role in the recent remarkable transformation of KC-135 depot maintenance. A similar initiative has been undertaken in the UK by BAE Systems with Tornado depth maintenance at Royal Air Force Marham.

In combat situations, aircraft availability can be severely reduced by attrition. To minimise attrition, there must be provision for rapid salvage and repair of aircraft damaged during extended combat operations. In this context salvage means the recovery of crashed aircraft from the field. Rapid salvage and repair may involve the use of centralised resources in some cases, but should ideally be designed for performance in theatre at forward bases or, in the case of helicopters, in the field.

To be effective, plans for rapid salvage and repair must be made well in advance, and the necessary resources must be available when required. In particular, the aircraft should be designed for rapid salvage and repair, and acceptable repair schemes/procedures for both minor and major repairs should be pre-authorised. In some cases, it may be appropriate to include procedures for “expedient” repairs that have full strength but reduced durability. The policy on this topic varies by Air Force and aircraft type. The Dassault Aviation Rafale fighter is an example of an aircraft that has been designed to facilitate field repairs of major damage due to accidents or hostile action. There is further discussion of this case in Chapter 6.

2.4.5 Health Monitoring and Management (HUMS/SHM/PHM/DPHM/IVHM)

Terms and abbreviations like the following are used increasingly in the aircraft industry, but are not yet defined in international standards:

- Health and Usage Monitoring System (HUMS);
- Structural Health Monitoring (SHM);
- Prognostics and Health Management (PHM);
- Diagnostics, Prognostics, and Health Management (DPHM); and
- Integrated Vehicle Health Management (IVHM).

The terms HUMS, SHM, PHM, DPHM, and IVHM are used throughout this report in quotations from Workshop and other papers. Some definitions from a variety of sources are given in Annex C, but the reader should interpret the terms in the context in which they are used.

They have become useful collective terms, because they generally imply the use of certain groups of advanced technologies to reduce maintenance downtime and life-cycle cost. Some aircraft may include the technologies in a larger system by a different name. For example, the Eurofighter Typhoon aircraft incorporates one of the most advanced maintenance decision support systems currently available. It is known as the Integrated Monitoring and Recording System (IMRS). Its functions in support of maintenance management and execution are described in Chapter 5.

Although it is used widely, the term “prognostics” only has one international standard definition. ISO 13372 [30] defines prognostics as analysis of the symptoms of faults to predict future condition and remaining useful life. The definitions by specialists in aircraft maintenance vary, mainly in the scope of the definition. The central feature of prognostics in most definitions is an estimate of the Remaining Useful Life (RUL) of a component from available information on the design, past usage, and estimated future usage. The purpose of the estimate is either to schedule the repair of “on-condition components” in which potential failure has been detected, or to plan the replacement/restoration of “lifed components”. The term “prognostics” is a useful descriptor of systems that fulfil these purposes, whether they are on-board systems, ground-based systems, an engineer with a calculator, or a combination of these.

In most cases, HUMS/SHM/PHM/DPHM/IVHM systems allow necessary maintenance/support tasks to be performed more efficiently and effectively. They do not represent any departure from RCM, and generally implement RCM-based strategies to reduce net maintenance downtime and life-cycle cost, including strategies already mentioned in the current chapter. At the upper level of sophistication, they provide advice (decision support) to the aircrew on reconfiguring systems to optimise capability in the event of failures during a mission. Sophisticated systems may also include automatic prognostics to provide information to the aircrew on unexpected reductions in the remaining useful life of safety-critical components, such as helicopter transmissions and rotors. However, most current systems emphasize decision support to the ground-crew and strictly limit aircrew advisories.

As discussed earlier, CBM is not well defined in military and international standards, but in essence is a failure management strategy consistent with the RCM concept of “on-condition” maintenance. Embedded sensors and integrated avionics with open architectures facilitate the application of the on-condition failure management strategy to a wider range of components, and thereby extend the potential scope of CBM.

Some users of the term CBM seem to equate it with on-board health monitoring or management systems [31], [32]. However, recently released US DoD maintenance policy documents [22], [28] also include traditional ground-based inspection in CBM.

The increased use of information analysis and distribution technologies in HUMS/PHM/DPHM/IVHM leads naturally into the integration of aircraft health information with other maintenance/support and operations information systems. For example, the Autonomic Logistics Information System (ALIS) offers an integrated solution for the management and logistics programs for the F-35 JSF. In [33], Major Hawkins, USAF, explains that as a comprehensive network, ALIS is enabled by two technological constructs: a constellation of diagnostic sensors to detect impending faults via reasoning algorithms; and a supporting information architecture to quickly process information for responsive action throughout the Performance-Based Logistics (PBL) infrastructure. The development of ALIS was prompted by the increasing technological complexity of US DoD weapon systems and the corresponding activities required to maintain them. As such, ALIS is designed specifically to reduce aircraft downtime and maintenance costs and eliminate fault-detection inaccuracies. Major Hawkins points out that the ALIS concept is central to JSF life-cycle sustainability and the successful implementation of the PBL philosophy.

Up-to-date perspectives and relevant theory on integrated diagnostic and prognostic systems by a group of authors who have been closely associated with recent US DoD programs, including the F-35 JSF, can be found in [34].

Health management systems have undergone considerable development over the past fifty years. Further development seems likely to increase the complexity of aircraft, but this will to some extent be mitigated by technologies that are enabling greater integration of health management functions with other aircraft systems. These include the concept of the "virtual sensor", which involves the processing of data already available on the aircraft databus to provide useful information on usage, potential failure, and failure. More information on health management systems and associated maintenance/support strategies is provided in Chapters 5 and 6.

Chapter 3 – SOME NATIONAL PERSPECTIVES ON AIRCRAFT MAINTENANCE/SUPPORT

3.1 POLAND

This section is based on Paper 1.1 by Szczepanik and Leski.

3.1.1 Effect of Political Change on Aircraft Maintenance

Polish military aviation comprises the Air Force, the Navy aviation and that of the Army. At present, there are 20 types of aircraft operated thereby. The operated fleet comprises, with only few exceptions, aircraft and other systems manufactured in the 20th century in the ex-Soviet Union and Poland. The accession of Poland to NATO has considerably affected Polish military aviation. Changes of standards in force at that time as well as a demand for compatibility with the Armed Forces of other NATO member states have forced a number of changes in all areas of activity. The Polish Air Force Institute of Technology (ITWL) activity provides R&DE and other support to military aviation in the context of aircraft maintenance/support.

When the most current aircraft were being introduced into service, Poland was a member of the Warsaw Pact. Hence, the Soviet maintenance system was adopted. Scheduled maintenance tasks and intervals were determined by the manufacturer. The 'safe-life' philosophy was predominant.

After Poland joined NATO, relations with the Soviet Union and later with Russia weakened. Aircraft in service could no longer rely on support from the manufacturer. It became difficult to deal with in-service problems, develop aircraft improvement programmes, and even to obtain spare parts for normal maintenance.

When the Cold War ended, ITWL initiated a number of projects with the objective of improving self-reliance and effectiveness. The goals were as follows:

- To provide for the operation and maintenance of aircraft with the minimum of help from the manufacturer;
- To use to best advantage the manufacturer-determined service lives of systems in service;
- To extend the lives of existing aircraft; and
- To improve the availability of aircraft in service.

Some of the projects that have served these objectives are highlighted below.

3.1.2 Reverse Engineering

To compensate for the difficulty of obtaining design data and other support from Soviet/Russian manufacturers, reverse engineering methods were developed.

3.1.3 Collection and Analysis of Maintenance and Operational Data

To provide the data needed to improve the management and capability of existing equipment, the Polish Air Force, Army, and Navy use a unified system to collect, process, and analyse operation- and maintenance-related information on military aircraft. This is known as the SAN system [36]. It consists of:

- Main system modules including sub-systems to record and process data on aircraft operation;
- Cumulative operational-data bank with processing sub-systems;
- Central operational and reliability data bank with processing sub-systems; and
- Module to analyse military aircraft operation and reliability rates.

The system allows the Polish Air Force to:

- Collect, process, and transmit data on the operational use and maintenance of military aircraft; and
- Control the processes of military aircraft maintenance/support, and to examine the availability and reliability of the fleet.

For example the SAN system was used to prepare the distribution of failures of the Mi-14 helicopter shown in Figure 3-1.

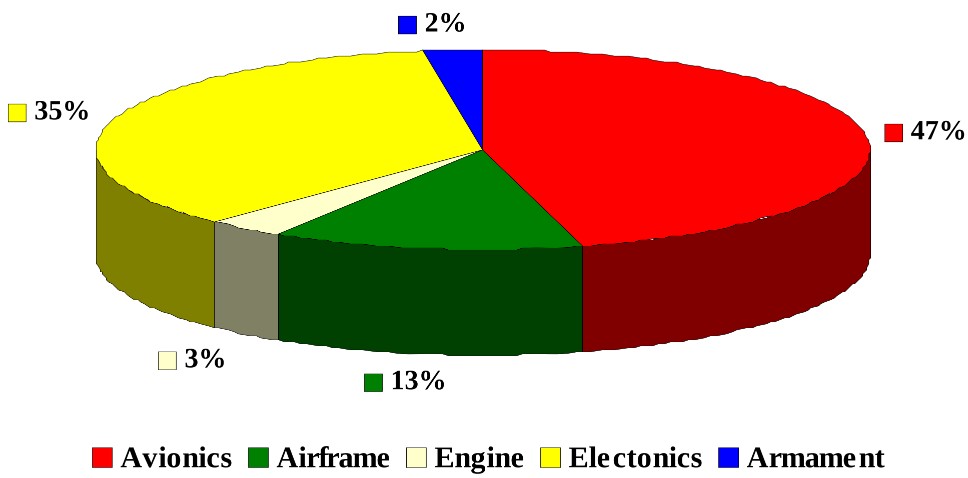


Figure 3-1: Distribution of Failures Among Sub-Systems in the Mi-14 Helicopter.

3.1.4 Monitoring of Aircraft Loads and Usage

A key element in meeting the goals was an improvement in the assessment of aircraft loads and the monitoring of aircraft structural usage. The importance of this increased later as the damage tolerance maintenance concept was introduced. Figure 3-2 illustrates the importance by comparing the actual usage of two different groups of MiG-29s, one with mild usage and the other with more intensive usage. The previously estimated usage is also shown. Other projects such as the flight parameter decoding system, THETYS, the flight data recorders of the IP- and S-series, have complemented the loads and usage monitoring project.

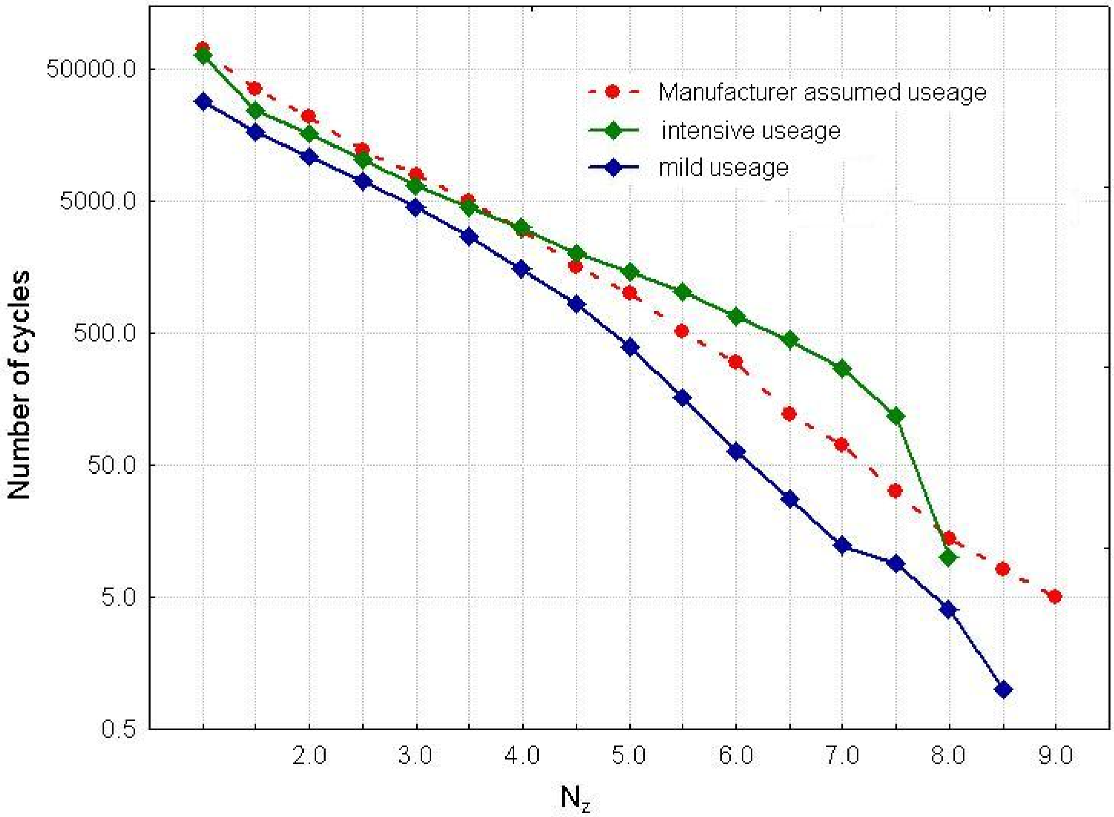


Figure 3-2: Service Profiles of the Two Groups of MiG-29 Aircraft.

3.1.5 Diagnostic and Non-Destructive Inspection Systems

ITWL's specialists have invented and manufactured numerous diagnostic instruments and systems to support ground staff responsible for aircraft maintenance. The SD-KSA field system to monitor health/maintenance status of the clutches in the MiG-29's electrical generator is an example. This diagnostic system detects wear of the clutches by detecting disturbances in the angular velocity of the alternator's rotor.

Figure 3-3: The SD-KSA Diagnostic System in Operation.

With all tests successfully completed, the system has been introduced into service. The system is easy to use. Taking measurements consists of connecting the sensor to the power supply system of the aircraft. Checks of this type are easily performed in the course of maintenance and ground running of an aircraft engine.

Another diagnostic system is one to monitor health/maintenance status of blades of a turbojet. The tip-timing technique has been applied to measure vibrations of the compressor and turbine blades. A microwave probe enables examination of blades in the hot section of an engine.

Figure 3-4: A Microwave Probe.

The large-scale introduction of such solutions results in considerable increase in safety of aircraft operation on the one hand, and on the other hand, in reduction of downtime/time of remaining grounded, because severe failures could be avoided and time for repairs – shortened.

The Polish Air Force has introduced automatic NDI systems such as the MAUS (USA) and DAIS (Canada) to inspect aircraft structure for damage and corrosion. The MAUS is an automatic scanner that enables various measuring probes/sensors to be mounted. The DAIS (D-Sight Aircraft Inspection System) is an optical system that quickly assesses corrosion in riveted skin joints, dents and cracks in metallic components, and barely visible surface damage in composite materials. These systems provide considerable savings in aircraft downtime, together with improved safety.

Figure 3-5: The DAIS System in Operation.

3.1.6 Changes in Maintenance Systems

Following the purchase of several MiG-29 aircraft from Germany, a decision was made to emulate the German Air Force by using a predominantly damage tolerant approach to the maintenance of these particular aircraft, instead of the predominantly safe-life approach in use on MiG-29 aircraft already in the Polish Air Force inventory. Germany provided the expertise and training necessary to do this.

Considerable non-recurring costs were incurred in making this change to Polish maintenance practice, but several significant improvements were realised in relation to the other MiG-29 aircraft:

- 30% reduction in cost of overhauls (major repairs);
- 50% extension in the intervals between intermediate inspections;
- Only 26 life-limited parts;
- Improved spare parts management, e.g. an extension of shelf lives;
- Improved safety through a service loads monitoring program;
- An expected 35 – 40% reduction in total maintenance cost; and
- Expected improvements in aircraft availability through the reduction in downtime for maintenance.

The other MiG-29 aircraft and all other Soviet-made and Polish-made aircraft will be converted to the new maintenance concept to the extent feasible.

The introduction of the F-16 into the Polish Air Force has proven to be another catalyst for change in the Polish military-aircraft maintenance system, in that it will enable Poland to overcome problems of hardware and organisational incompatibility with other NATO members.

3.2 FRANCE

3.2.1 Change Motivated by Poor Availability and High Costs

In 2002 France's National Assembly expressed concern with the unsatisfactory state of the maintenance and availability – Disponibilité Technique Opérationnelle (DTO) – of its military equipment. Under the leadership of the prime minister, budgetary and managerial changes were given high priority. This action followed years of relative neglect of the maintenance chain of existing equipment in favour of new procurement. The situation had been exacerbated by delays to new equipment. While the French Armed Forces had been responding adequately to operational requirements, new pressures from overseas deployments had accelerated the ageing of material and highlighted budget shortfalls. As mentioned in Chapter 2, some changes had already been initiated by the French Air Force with the creation in 1999 of an organisation known as "Structure Intégrée de Maintien en condition opérationnelle des Matériels Aéronautiques du ministère de la Défense (SIMMAD)" – "Integrated Organisation for the Maintenance in Operational Condition of Ministry of Defence Aircraft Materiel". This important and innovative organisation is described in more detail below. There have also been efforts to improve efficiency through the outsourcing of some maintenance to industry, including foreign industry. Not all have been successful, and so there is debate on the best approach to adopt. In general, the availability of aircraft fleets has stabilised. However, despite focused effort and investment, the availability of the C-160 Transall fleet has continued to decrease. Perhaps a law of diminishing returns is applicable on older fleets. The Rafale multi-role fighter is expected to provide improved levels of availability and lower maintenance costs compared with earlier fleets. One innovation is the division of the aircraft into Shop Replaceable Units (SRU), such that the complete aircraft and complete engine are not subject to depot maintenance. Built-in deployability and supportability will help maintain availability during distant deployments.

France's perspective on the evolution of aircraft maintenance/support is exemplified by the approach used in the design of the Rafale fighter and its in-service support system and by the creation of SIMMAD. Overviews of both topics are given in this section, based on part of Paper 4.9 by Absi and Lemaignen and Paper 1.2 by Joubert. More detailed information on the Rafale is included in Chapter 6 in the contexts of diagnostics and rapid repair strategies.

3.2.2 Evolution in Design and In-Service Support to Achieve Deployability and Repairability

3.2.2.1 French Air Force and Navy Experience with Deployed Operations

In Paper 4.9, Absi and Lemaignen highlight the conclusions of AGARD-AR-327 in 1994 [35] concerning the high mobility and deployability of the French Air Force. It recognized that the "French Armed Forces have been involved overseas almost without pause" and that their "long-standing requirements of operations in Africa had led to a greater emphasis on the mobility and deployability issues". "Routinely, French Forces have operated from isolated and extremely austere airfields lacking adequate runways … maintenance facilities, and other basic support services". From this experience, many lessons have been learnt and implemented in the requirements and design of "compact, robust, and easily deployable support assets and combat aircraft".

The French Navy, for similar reasons, and by tradition, has always been very proud of its autonomy and has put robustness and repairability at the top of its mandatory requirements for carrier-based aircraft. As the single supplier of the French fighter A/C, Dassault Aviation has used its best engineering efforts to design this mobility and deployability into its aircraft. Their experience in this regard has been reinforced by the operational feedback from about 40 different foreign countries all over the world which operate or have operated their military aircraft. Recent operations in coalition or in training deployments (such as Red Flag or Maple Flag) have demonstrated the successful operation of French Air Force aircraft with very limited personnel and very few means, i.e. a very small logistic footprint, compared to other participants.

3.2.2.2 The Use of Integrated Logistics Support (ILS) to Achieve Deployability and Repairability

To achieve such results, the French Air Force and Dassault Aviation follow a structured approach to Integrated Logistic Support (ILS) during the design of an aircraft that is illustrated in Figure 3-6 and [36]. The main objectives of this approach are important to the achievement of a small logistics footprint and the ability to perform rapid repairs in deployed operations. The objectives are as follows:

- Reliability (simplicity, robustness).
- Maintainability (size and replaceability of components, modularity, repairability).
- Testability (self-contained diagnostics, very few GSE).
- Usability, which means ease of use, repair, training, etc.

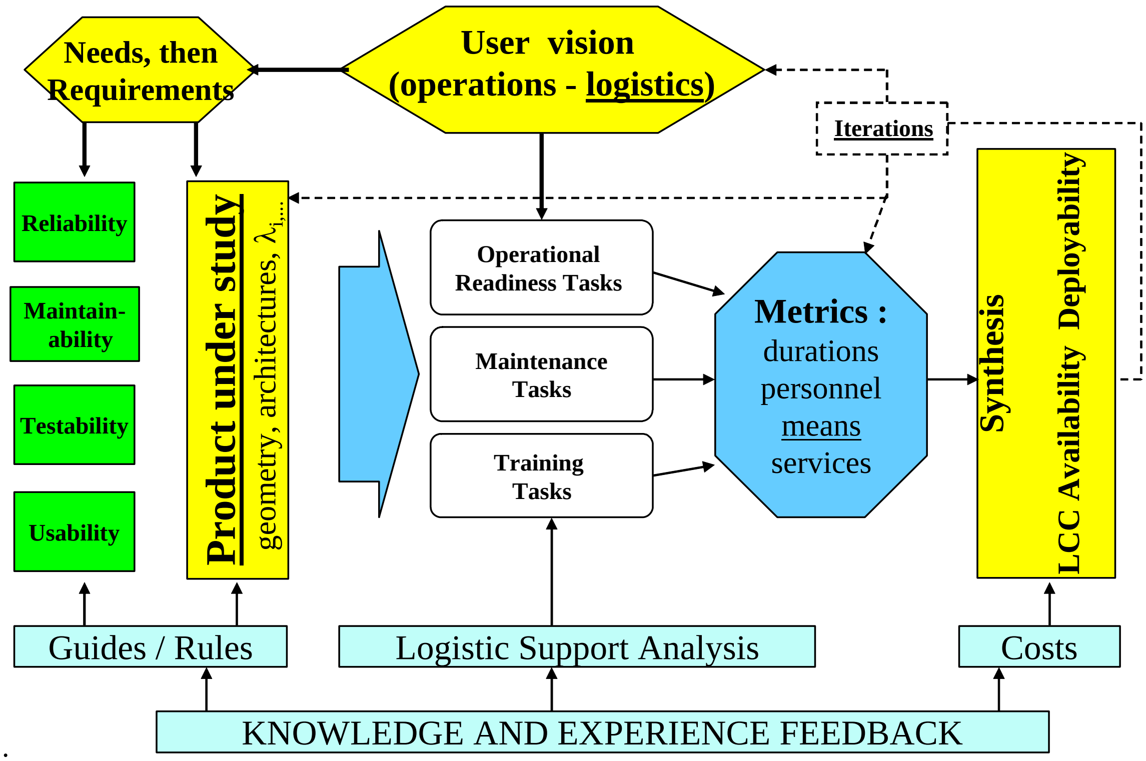


Figure 3-6: The Integrated Logistic Support Approach of the French Air Force and Dassault Aviation.

3.2.3 Structure Intégrée de Maintien en condition opérationnelle des Matériels Aéronautiques du ministère de la Défense (SIMMAD)

SIMMAD is a unique, innovative, and effective concept for managing aircraft maintenance/support so as to guarantee improved availability. It is described in some detail in this section using information provided by Joubert in Paper 1.2.

3.2.3.1 SIMMAD's Genesis

At the end of 1990s, the French Armed Services faced a superposition of negative effects that were reducing equipment availability and increasing costs:

- Contextual factors that affected the whole military aeronautical market. These included a loss of economies of scale, a monopolistic situation marked by wide ranging industrial restructuring, and a strategic orientation towards more lucrative civilian market segments.
- Structural factors, like the ageing of military aircraft fleets, as well as budget cuts and low support spending.
- Last but not least, domestic factors of organisational nature hampered the in-service support for air systems which was shared among many agencies within the French MoD.

To solve those latest, the decision was taken to merge all In-Service Support (ISS) managing agencies into a new joint one that gathers in all the previous functions that were scattered around the defence establishment.

Thus, Structure Intégrée de Maintien en condition opérationnelle des Matériels Aéronautiques du ministère de la Défense (SIMMAD) was brought into being in December 2000.

SIMMAD is responsible for directing the In-Service Support for all air systems in the French inventory, as well as for such things as Ground Support Equipment (GSE), radars, and air-delivered munitions. Overall, this implies being responsible for the support and maintenance of some 1,900 aircraft in the four Services (Air Force, Navy, Army and Gendarmerie) with a budget of €1.6-billion, excluding fuel, infrastructure, and manpower. SIMMAD's mission includes advising the French Ministry of Defence on how to ensure consistency and optimum performance in In-Service Support.

3.2.3.2 SIMMAD's Position in its Institutional Environment

SIMMAD's mission implies a close coordination between development and support, i.e. between the French procurement agency, Délégation Générale pour l'Armement (DGA), and SIMMAD (Figure 3-7).

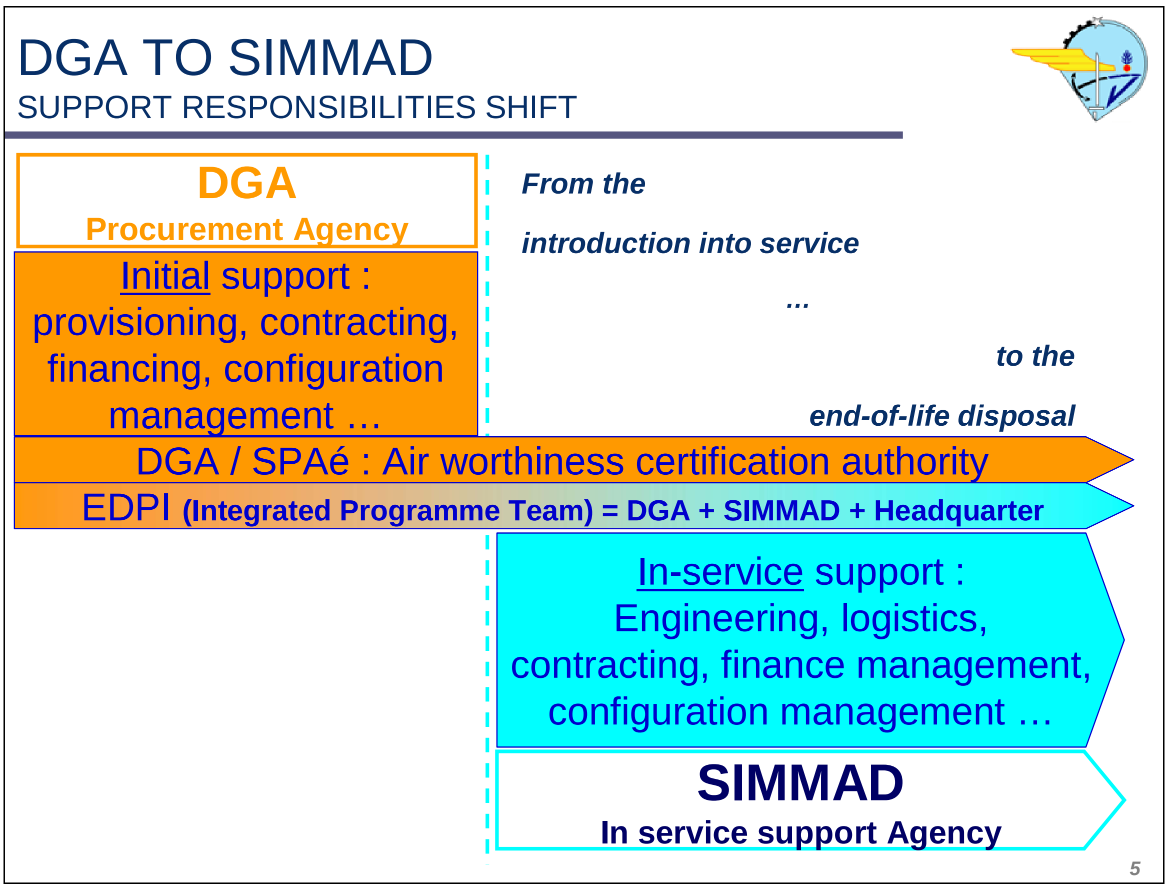


Figure 3-7: DGA to SIMMAD – Support Responsibilities Shift.

In this perspective, the air support responsibilities can be split in two successive time periods:

- The DGA bears the responsibility for the early stages of any procurement programme. It therefore fulfils all support functions until the aircraft is turned into service. However, since initial options taken during the very first development steps deeply influence the future in-service-support architecture, a SIMMAD representative is involved in this process to have future ISS aspects taken into account.

- With the introduction into active service, a shift of support responsibilities occurs and the SIMMAD assumes the day to day management of ISS. Nevertheless, the DGA remains the airworthiness certification authority for all flying equipments of the Ministry of Defence before and after the introduction into operational service.

During operational service, SIMMAD continues the day to day management of ISS for aircraft. However, significant changes in policy must be approved by the single Services and the joint staff. The chain of command for joint aircraft maintenance/support is shown in Figure 3-8. SIMMAD has delegated contractual and financial responsibilities from the Ministry of Defence (MoD), and is also the delegated directing body for aeronautical systems maintenance and logistics.

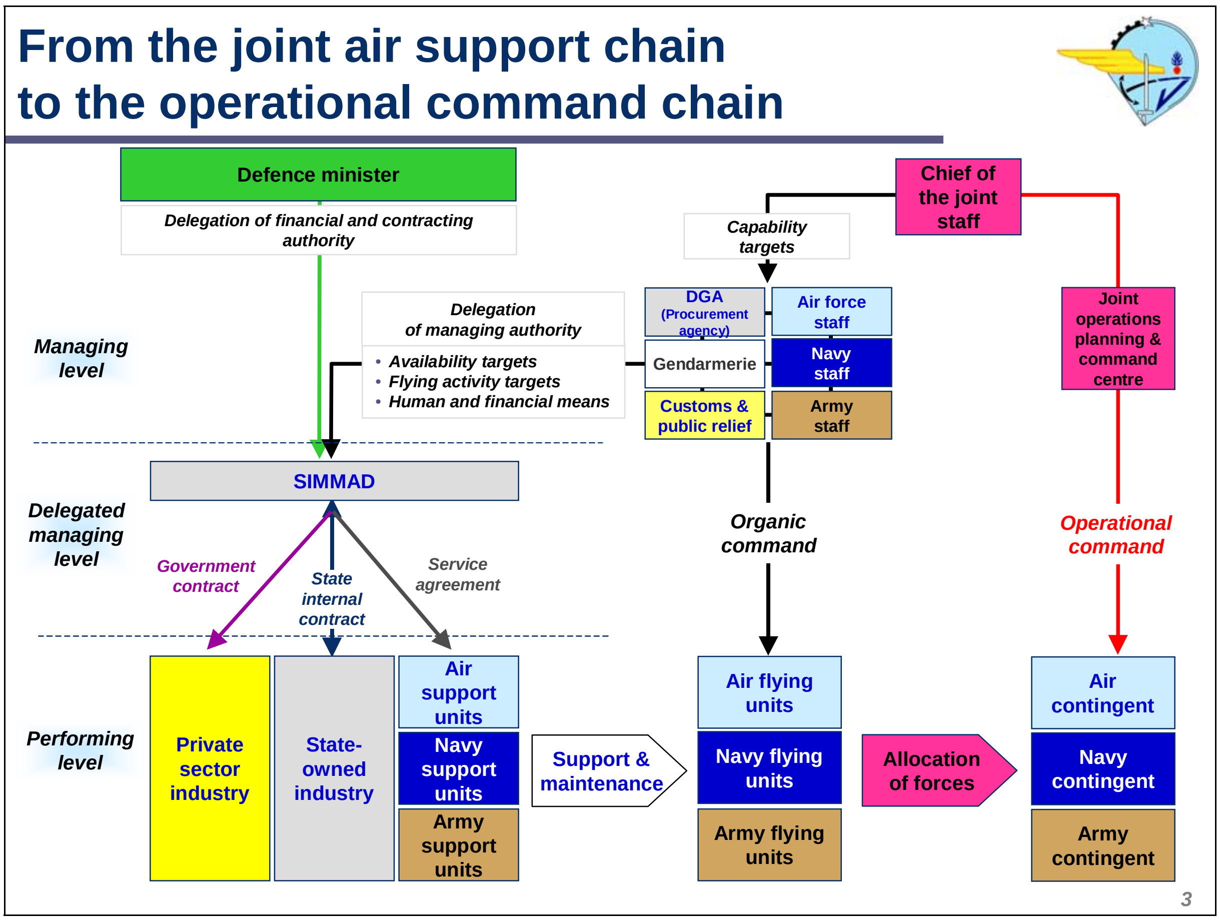


Figure 3-8: The Chain of Command for Joint Aircraft Maintenance/Support – From the Joint Air Support Chain to the Operational Chain.

SIMMAD's steering committee gathers at least once a year under the presidency of the Chief of the Joint Staff and defines the availability and flying activity targets to be pursued, as well as allocated human and financial resources. SIMMAD in turn establishes contractual relationships with the different In-Service Support agencies in private industry and the public sector. Private and public contractors then deliver maintenance/ support services to the flying units.

3.2.4 Innovative Maintenance Concepts

As the single, unified aeronautical ISS organisation, SIMMAD is responsible for researching and implementing improvements in maintenance and logistics. In his Paper 1.2, Colonel Joubert includes some examples of how this has been done.

3.2.4.1 The Case for Outsourcing

While many Armed Forces seek to out-source their support and maintenance quite rapidly, the French MoD takes a more graduated approach since the advantage of out-sourcing depends notably upon the type of aircraft. Taking into account both German and British experiences, work is in hand to assess the feasibility and potential benefits of focused outsourcing moves. The French MoD is focussing particularly on identifying which sovereign capabilities are to be maintained in public hands and assessing economic and operational impacts of transferring air support functions to an outside supplier.

Such a decision must remain coherent with the need for military maintenance teams that must be able to deploy out of area and perform maintenance tasks wherever it is needed. In this regard, the French MoD is presently exploring ways to swap personnel between private and public sectors in a pretty comparable way to the German “cooperative model”.

Outsourcing to industry has already been applied in initial pilot training. Four companies decided to tender for a contract that encompasses both flying and flight simulator assets. EADS won this competition and was awarded a 10-year contract to operate a mixed aircraft fleet composed of state-owned Epsilon as well as privately acquired Grob aircraft and new flight simulators. All in all, the French Air Force expects a 35% cost decrease. Moreover, EADS is expected annually to propose improvements in the training syllabus and the associated technical, logistical, and maintenance processes. The achieved benefits will be shared on an equal basis between the Air Force and Industry.

The supply of consumable aircraft parts has also been outsourced. Specific incentives have been included in this contract to make the achievement of the desired availability and training targets into shared objectives for the Air Force and the contractor. To this end, a long-duration contract of 10 years has been authorised.

3.2.4.2 Maintaining the Rafale

SIMMAD of course benefits from the new technologies and maintenance concepts brought by the latest generation of aircraft.

With the Rafale now in service with both the French Air Force and Naval Aviation, the maintainers are experiencing the advantages for the first time of an analytical isolation of all low MTBF (Mean Time Between Failure) equipments. This new iterative method is based on real-time fault analysis by the aircraft integrated testing systems and usually leads to on-condition maintenance. The approach is also used to focus technological development by industry so as to meet aircraft reliability requirements.

Another improvement is the segmenting of Organisational Level (O Level) maintenance tasks into elementary sub-tasks for independent assessment. This facilitates the organisation of tasks for maximum speed and efficiency, and has significantly reduced downtime.

During its development phase, the Rafale had to pass several tests to be carrier-operated, which meant adequately responding to severe constraints of weight and dimensions of its maintenance equipment. As a consequence, a single test bench is used to monitor the whole aircraft and the dimensions of GSE have been drastically reduced.

In an operational scenario, the foregoing technical characteristics, which are summarised in Figure 3-9, contribute to reducing the deployed technical and human footprint, which in turn requires a slimmer and less vulnerable supply chain.

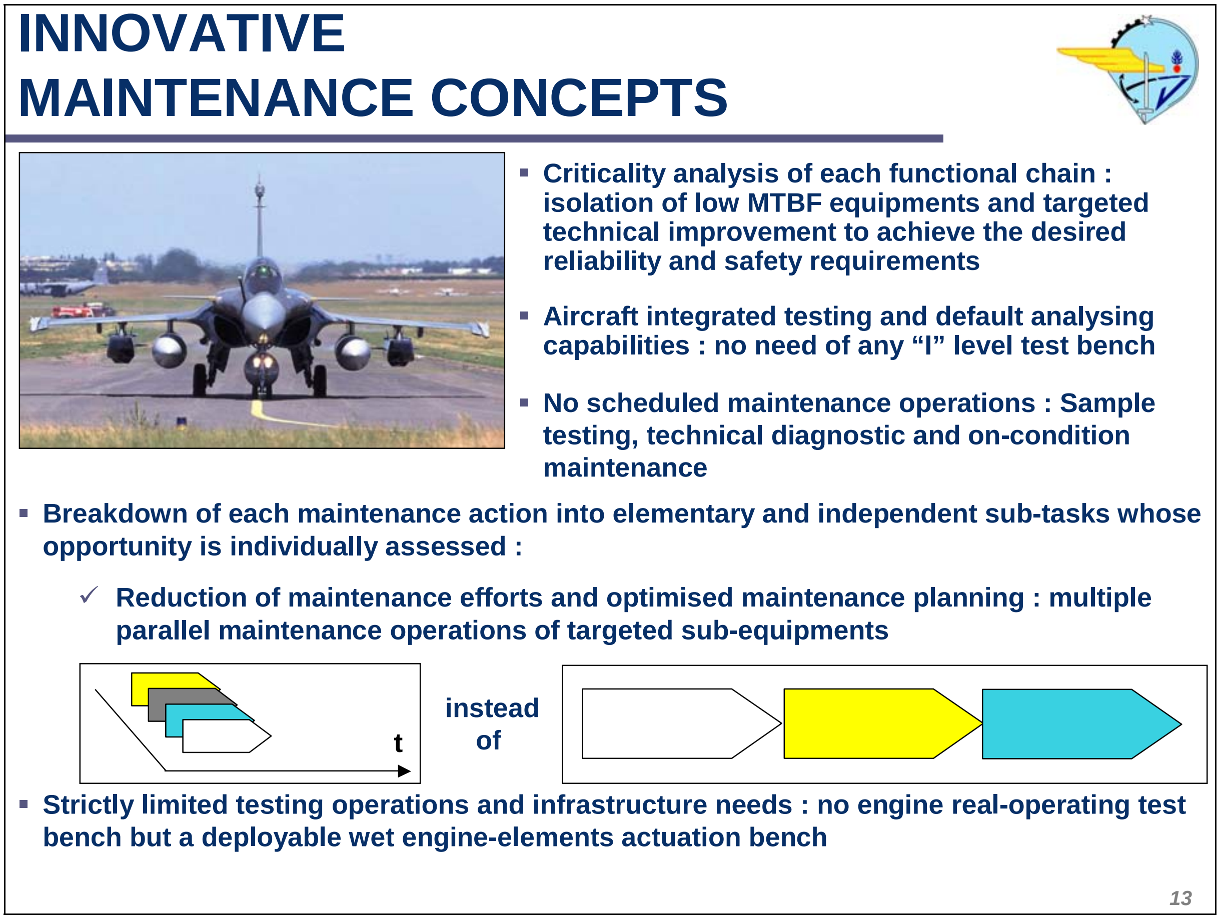


Figure 3-9: Innovative Maintenance Concepts.

Moreover, the improved analysis and repair capabilities enable a minimization of the out of theatre flow of the Shop-Repairable Equipment (SRE) that previously had to be transferred back to France for inspection and fixing. This means reduced costs, enhanced effectiveness, and shorter periods of unavailability.

The Rafale's design for autonomy, mobility, and intensive use are evident in its maintainability at first line. In his presentation, Copéret explained that the preparation for flight takes one person 30 minutes and requires no equipment. Turn-around servicing and rearming take less than 15 minutes. If a reconfiguration of weapons is required for the next mission, this takes only 40 minutes. Some design features of particular value at first line are the on-board auxiliary power supply (which enables autonomous air-conditioning, electrical supply, and engine starting), the on-board oxygen generation system, the centralised weapons safety system, the pneumatic weapons release system, and the long interval of 10 hours between fluid replenishments.

3.3 CZECH REPUBLIC

This section is based on Paper 1.3 by Bulanek, Kvetina, and Tesar.

3.3.1 Historical Events

The evolution of aircraft maintenance/support in the Czech Republic is described by Bulanek in Paper 1.3. With the retirement of the last MiG-21 aircraft units in the year 2005 the decades-long period of utilizing Soviet jet technology in the Czech Air Forces (CzAF) came to an end. The CzAF operated the following aircraft types during the 1980s and 1990s: Su-7, Su-22, Su-25, MiG-21, MiG-23, and MiG-29. These aircraft came to the CzAF inventory as established and operated types including full logistic support. They were purchased from the USSR, where these aircraft were developed, qualified and already in service for several years prior to delivery to the CzAF.

While Czechoslovakia produced jet trainer aircraft in the 1960s and 1970s, these were designed according to NP CAGI standards (design standards for military aircraft of USSR).

The situation changed after 2005. Today, the CzAF operates two types of tactical aircraft the JAS-39 Gripen (12 a/c of C-version and 2 a/c of D-version) and L-159 (24 a/c). The JAS-39 Gripen aircraft are operated using a lease agreement between Sweden and Czech Republic signed in 2005. The L-159 (Figure 3-10) was designed in the Czech Republic as a major international joint venture with North American and European sub-contractors, and has been in operation since 2000. It is a modern fighter aircraft with a small logistics footprint in deployed operations. It includes the following advanced systems:

- Multi-mode pulse Doppler radar.
- Advanced human/machine interface with Head-Up Display (HUD), Multi-Function Colour Display (MFCD) and Hands-On-Throttle-And-Stick (HOTAS) controls.
- Avionics Integration based on Mil-Std-1553 databus.
- Accurate and autonomous navigation system with laser gyro based Inertial Navigation System (INS) and Global Positioning System (GPS).
- Extensive in-flight recording and debriefing capability for video, audio, self-protection system, engine and aircraft parameters (AMOS).
- On-condition maintenance and fatigue monitoring system for low operational cost and optimum use of aircraft service life (FRAME159).
- On-Board Oxygen Generating System (OBOGS), On-Board Inert Gas Generating System (OBIGGS) and Auxiliary Power Unit (APU) for self-contained operation with minimum support.
- Seven pylons for various stores.
- Ability to operate from semi-prepared airfields.
- Two-shaft, non-afterburning turbofan engine, controlled by dual FADEC with Engine Monitoring System (EMS).

- Self-protection system installation and use of redundant systems for high level of survivability and flight safety.
- Zero height and zero speed ejection seat.

Figure 3-10: Aero Vochody L-159 Light Combat Aircraft (Czech Republic).

3.3.2 The Development of the Maintenance Concept for the L-159 Light Combat Aircraft

With the introduction of the Gripen and L-159 aircraft, the maintenance/support system has changed from one based on predominantly hard time tasks, as defined in RCM terminology, to one based on much greater use of on-condition maintenance and automated condition monitoring.

Bulanek's paper focuses on the L-159 aircraft as a representative of the current state of the evolution of Czech maintenance/support concepts and technologies. This aircraft is also one in which NATO compatibility requirements, standards, and specifications (US Mil Specs and STANAGS) were implemented for the first time in the Czech Republic. It was necessary to adopt these standards and determine the appropriate ways to work according to them. In addition, a systems engineering approach, including integrated logistic support and its related elements, was applied for the first time on an Aerospace project of this size in the Czech Republic.

Early on, it was agreed that some Czech standards (CSN, CSVN and CSN ISO) and some USSR standards (ENLGS, NP CAGI) would be applied together with US Mil Specs and RTCA standards to the process of development, design and testing of the L-159. Important standards with respect to logistic support are listed below:

- Airframe structure according to NP CAGI (USSR standard).
- Aircraft structural integrity program according to Mil-Std-1530A.
- Reliability program according to Mil-Std-785B.
- Reliability predictions of electronic equipment according to Mil-Std-217E.

- Reliability design qualification and production acceptance tests according to Mil-Hdbk-781A.
- Safety program according to Mil-Std-882B.
- FMEA/FMECA analysis performed according to Mil-Std-1629A.
- LSA according to Mil-Std-1388-1A.
- LSAR according to Mil-Std-1388-2B.
- Technical manuals according to Mil-M-38784B.

Consistent with the systems engineering approach, the CzAF and MOD prepared the “Use Study” to identify and define the intended use, supportability factors, operational assumptions, and CzAF operating environment and mission. The Use Study was developed according to Mil-Std-1388-1A, Task 201.2.4. The Integrated Logistic Support Plan (ILSP) and Logistic Support Analysis Plan (LSAP) were jointly developed between Aero Vochody, Boeing (avionics) and ITEC/Honeywell (engine). These documents were maintained at Aero Vochody and were linked to the L-159 master programme schedule. This ensured that the Logistic programme was synchronized with programme requirements.

The Logistic Support Analysis (LSA) served as the fundamental source for determining the logistic support scope, location and level. The LSA objective was to create an effective aircraft maintenance concept and optimize the aircraft logistic support elements.

Life-cycle cost modelling was performed to determine the most cost effective logistic support method. It took into consideration the operational support scenario and operational environment as defined by the CzAF and looked at the available support from various sources including the military, contractors and vendors. Input data were gained from the LSA. L-159 technical manuals are provided in hard copy and will later be provided in the form of Interactive Electronic Technical Manuals (IETM).

A traditional three-level maintenance concept, consisting of Organisational Level (OLM), Intermediate level (ILM) and Depot Level (DLM) maintenance was adopted for the L-159.

Periodic and phase inspections are activities carried out on mechanical systems such as:

- Airframe systems servicing;
- Clearance check and adjustment;
- Cleaning or replacement of the filter elements; and
- Lubricating according to lubrication plan.

The other systems (engine, avionics, etc.) are maintained depending of their actual condition. The aircraft actual condition monitoring is provided by the Aircraft Monitoring System (AMOS). The AMOS identifies systems failure or condition and informs both to the Central Maintenance Panel and the Multi-Function Display in the cockpit. The technical publications then provide a guide how to deal with identified troubles. The questionnaire YES/NO trouble shooting system is provided.

The OLM and ILM are performed by the CzAF operational (OLM) and maintenance (ILM) squadrons at one AFB.

The L-159 includes some LRUs and systems from the L-39 and L-59 trainers. In these cases, the existing maintenance policies have been continued on the L-159. However, in general, the L-159 uses modern engine, avionics and weapon systems, and the maintenance/support program has been designed according to RCM on-condition maintenance principles as far as possible.

The result is summarised as follows:

- On-condition inspections and hard time component replacements, scheduled according to monitored usage – engine, avionics and airframe structure:
  - Engine: ECU (Electronic Control Unit) calculates number of cycles (TACs);
  - Avionics: BIT assists in fault detection and isolation;
  - Actual condition of a/c systems: Aircraft Monitoring System (AMOS); and
  - Airframe fatigue life: FRAME159.
- Inspections and servicing tasks scheduled according to other criteria and grouped as “Phase” or “Periodic” inspections – airframe, mostly mechanical systems:
  - Phase inspections: 125, 250, 500 flight hours; and
  - Periodic inspections: based on calendar time, cycles, starts, landings.

The L-159 fatigue design philosophy is “safe life” but important structural parts, such as the main wing spar and fuselage dorsal longerons, are evaluated as “damage tolerance” parts. The damage tolerant parts are subject to on-condition inspections.

3.3.3 Engine

The F124 is a modular engine incorporating interchangeable modules, maintenance tasks that are relatively simple and fast to perform, a reduced parts count, the elimination of safety (locking) wire on bolts, a reduced need for special support equipment, and advanced diagnostics. Maintenance tasks are scheduled as far as possible according to monitored engine and aircraft usage. The operational environment and the support concept have been adjusted to optimise savings in life-cycle cost. A significant reduction in life-cycle cost is expected with the incorporation of these features in the F124 engine.

3.3.4 Avionics

The avionics systems incorporate proven equipment military standard equipment and Commercial Off-The-Shelf (COTS) equipment. The result is highly reliable, state of the art avionic systems that are highly supportable.

3.3.5 AMOS Flight Data Recording System

The AMOS system monitors:

- Aircraft system status;
- Airframe loads and stress;
- Flight parameters;
- Pilot actions; and
- Weapon release.

The AMOS (Figure 3-11) is designed to monitor the actual condition of the aircraft systems listed in Table 3-1. The AMOS makes it possible to quickly inspect selected aircraft systems before and after a flight within the scheduled O level inspections, and to evaluate the technical status of the aircraft at I level. The Ground Support Unit (GSU) is used for data evaluation and downloads while the Portable Memory Unit (PMU) is used for data transfer into Ground Evaluating Equipment (GEE).

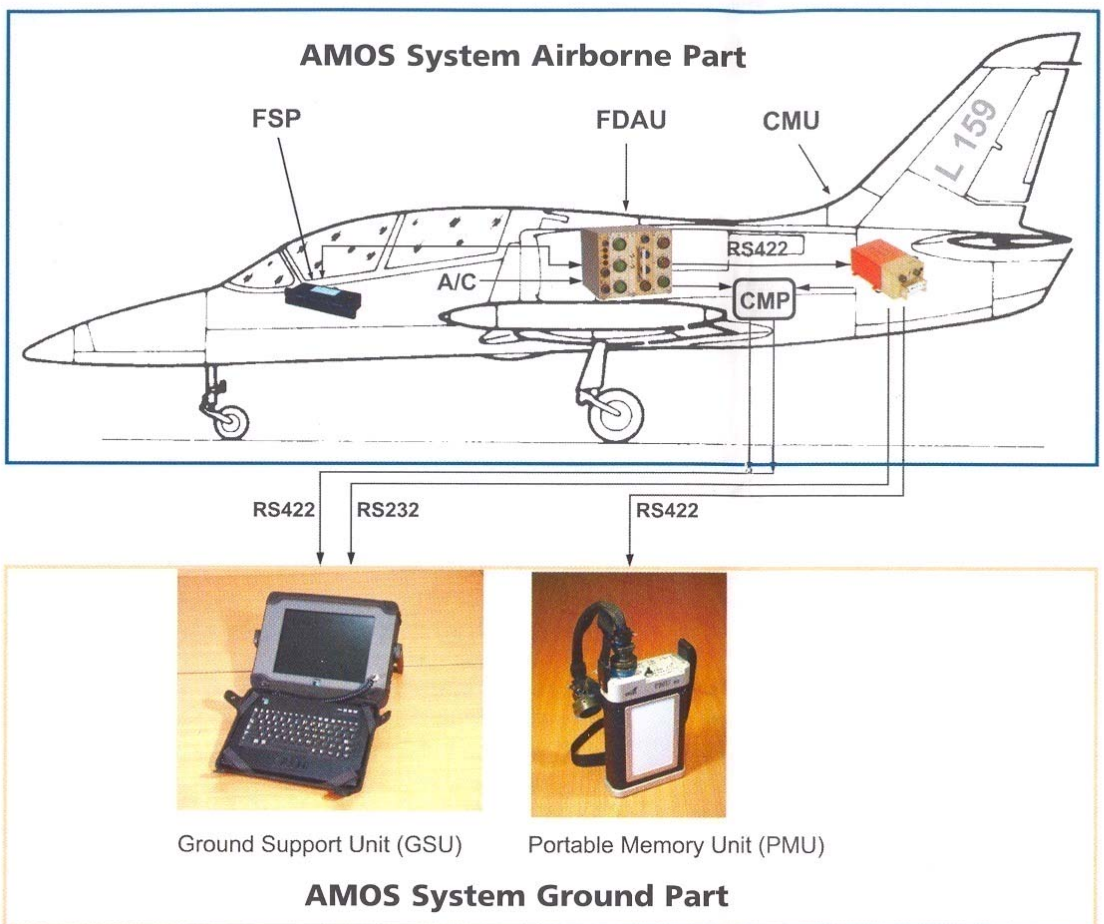


Figure 3-11: Aircraft Monitoring System (AMOS) on the Czech L-159 Aircraft.

Table 3-1: Means of Checking Individual Aircraft Systems.

System	Built-In Test Equipment (BIT/BITE)	Aircraft Monitoring System (AMOS)
Aircraft Control System	No	Yes
Nose Wheel Control System	Yes	Yes
Antiskid System	Yes	Yes
Avionics System	Yes	Yes
Autopilot	Yes	Yes
Storage Management System	Yes	Yes
Main Electrical Power Source	Yes	Yes
Emergency Electrical Power Source	Yes	Yes
Battery	Yes	Yes
Power Plant	Yes	Yes + EMS
Gearbox	No	Yes
Fuel System	No	Yes
APU	Yes	Yes
Air-conditioning System	No	Yes
De-icing System	No	Yes
Escape System	No	Yes
Fire Extinguishing System	Yes	Yes
Hydraulic System	No	Yes
Landing Gear	No	Yes
Airframe	No	Yes + FRAME159
Lighting System	Yes	Yes
OBIGGS	Yes	Yes
OBOGS	Yes	Yes

The F124 engine monitoring is performed by the engine control unit. The AMOS system receives information about engine status and values of main engine operation parameters via the RS422 serial data link.

The AMOS collects data about status of systems mentioned above and processes them in real time on-board the aircraft. The results of data processing are displayed as short text messages on the Multi-Function Displays (MFD) of the avionics system. The presence or not of faults is also indicated by coloured lamps on the Central Maintenance Panel (CMP) of the aircraft. The CMP is placed on the left side of the L159 under a quick-access cover.

Many of the parameters provided by AMOS (number of flight hours, number of engine and APU starts, engine run ratings, number of landings, etc.) are used for the purpose of maintenance scheduling and spare parts and POL consumption planning.

An Engine Monitoring System (EMS) is embedded in the FADEC providing data for engine and modules life management, hardware tracking, and performance trend monitoring. The EMS reduces support and life-cycle costs through computer-aided maintenance and fleet management. The EMS, combined with the long design life of the F124 allows all intermediate and depot maintenance to be scheduled according to usage rather than flying hours or calendar time.

The dual FADEC system of the F124 engine provides:

- Optimized performance and operability;
- Automatic relight;
- Reduced pilot workload;
- Built-In test (BIT);
- Performance trend monitoring; and
- Engine Event Recording (EER) capability for ease in maintaining and troubleshooting the engine system.

The FRAME159 system (Figure 3-12) is a part of the AMOS aircraft monitoring system. It is intended for the determination of the safe service life of the structure of each L-159 aircraft according to actual usage.

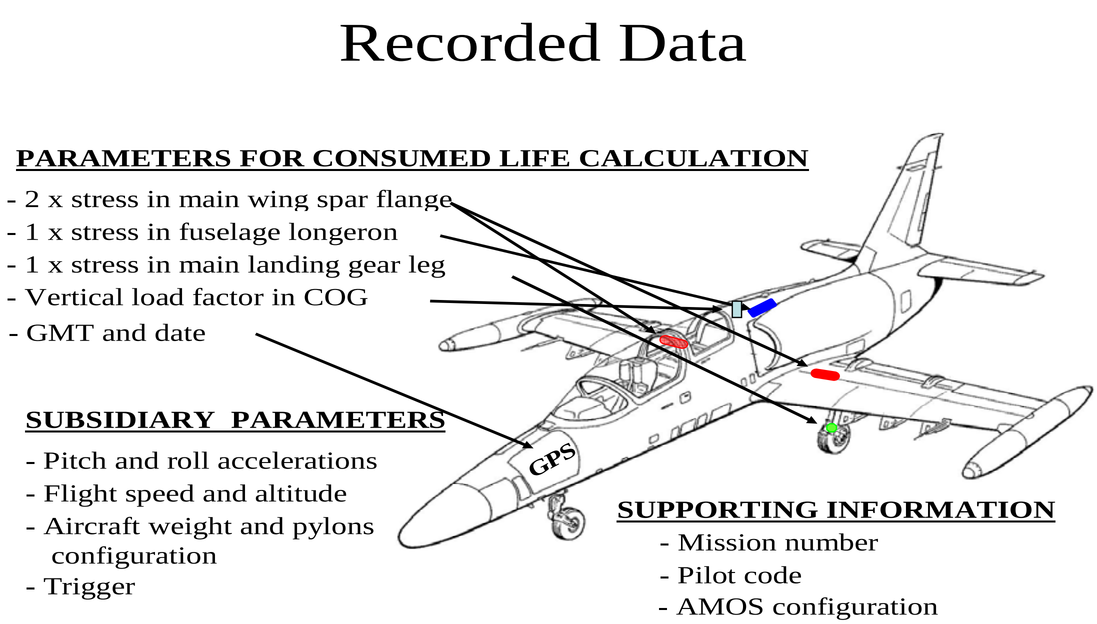


Figure 3-12: FRAME159 Structural Flight Data Recorder System.

Knowledge of the operational loading and usage allows inspection intervals to be reduced and component lives to be extended without any loss of safety.

3.3.6 Reliability and Availability

A systematic reliability improvement programme was put in place for the L-159.

This has resulted in an improvement in aircraft MTBF from 2.7 FH in 2001 to 6.6 FH in 2004. In 2005 the slight decrease of MTBF occurred due to a reduction in the size of the fleet. The aircraft MTBF is expected to improve in time to 8.0 FH.

The success of the maintenance/support programme for the L-159 light combat aircraft has been demonstrated during common exercises like the NATO Air Meet (NAM). In fact, higher reliability values were achieved there during intensive operation and concentrated support than during operations at the home air base. Examples of aircraft MTBF achieved over the years during exercises are shown in Table 3-2.

Table 3-2: Table of Reliability Parameters During Selected Exercises.

Mission	Number of A/C	Number of FH	Number of Landings	Failures		MTBF (Total)	$MTBF_F$ (Flight)
				Flight	Ground		
NAM 2003	6	31:33	26	16	7	1:22	1:58
NAM 2004	6	120:56	80	8	3	10:59	15:07
NAM 2005	6	75:17	59	18	6	3:08	4:11
Squadron Exchange 2005	6	90:53	76	7	2	10:05	12:58
Brilliant Arrow 2006	3	38:21	29	6	3	4:16	6:23

3.4 NETHERLANDS

This section is based on Paper 1.5 by Andela.

3.4.1 Availability as a Global Performance Indicator

In Paper 1.5, Andela explains that Aircraft Availability (AA) is a global performance indicator that the Royal Netherlands Air Force (RNLAF) uses to manage the aircraft fleets and the Main Operating Bases (MOB). The RNLAF has introduced a managerial control concept known as Integral Weapon System Management (IWSM). The purpose of IWSM is to guarantee the availability and effective exploitation of the aircraft throughout its life cycle. IWSM seamlessly integrates the supporting processes of the (weapon) system, by introducing standards and norms for logistics. The implementation of these logistics processes should be cost-efficient and should minimise life-cycle cost without affecting airworthiness. The life-cycle cost of RNLAF F-16 aircraft is estimated to be €23 billion, and so there is considerable incentive to improve processes and efficiency.

3.4.2 Integrated Weapon System Management

IWSM comprises the following functions:

- *Product Management* determines the operational needs of a weapon system during the whole life cycle.
- *Configuration Management* identifies and controls configurations and changes in configurations.
- *Integrated Logistics Support Management* ensures appropriate logistics support and controls costs.
- *Contract Management* sets up agreements with suppliers of products and services.
- *Financial Management* plans and organises the necessary cash flow.
- *Quality Management* ensures that products, services, and processes meet program requirements.
- *Administration* provides the managerial information for IWSM.

The responsibility for each weapon system, such as F-16, Chinook, and Apache, lies with the weapon system manager, who plans long-term enhancements and periodically evaluates of the performance indicators.

In this IWSM management concept the emphasis is on the realisation of the "employability" of the weapon system. This employability or system effectiveness is divided into:

- Operational availability;
- System reliability;
- Maintainability;
- Mission reliability; and
- Conformity of design.

These are the roots/fundamentals of aircraft availability in the RNLAF.

In the broadest sense, Aircraft Availability (AA) is defined as the portion of time the weapon system can fulfil the dedicated function. RNLAF divides AA into inherent availability, scheduled availability, and unscheduled availability. These terms are defined and discussed in Chapter 4 of this report.

3.4.3 Measures to Improve the Availability of the F-16 Fleet

The availability of the F-16 decreased at one point to 30%. While the aircraft will eventually be replaced by the F-35 Joint Strike Fighter, this level of availability is unacceptable, and several countermeasures have been taken on the F-16 and other aircraft, including:

- A life management programme and a Reliability Centred Maintenance (RCM) review for engines (discussed in more detail below).
- Increased application of on-condition maintenance using advanced technologies (see discussion of PHM below).
- Improvement in flight regime recognition for helicopters.
- The introduction of integral supply chain management, with an emphasis on organisation, competencies, Service Level Agreements (SLA) between partners in the supply chain, and effective goals and incentives.

- The introduction of Enterprise Resource Planning (ERP).
- An improvement in the training of personnel.
- The development of improved war readiness kits.
- The introduction of Public-Private Partnerships (PPP) to outsource work as far as possible.
- The introduction of availability-based contracting.
- Separation between the organisation setting the standards (norms) and those that must implement them – this is a principle known in Dutch as "*controle technische functie scheiding*".
- Careful definition of key performance indicators that encourage suppliers to deliver on time and encourage technical personnel to plan their work – the challenge is defining the right indicator, with the right standard, to be implemented by the right organisation.

The Engine Life Management Plan (ELMP) involves studies of the Scheduled Depot Visits of the F-100 engine for the remaining life of the F-16. The goal of this research was to create a model to determine a cost efficient method to phase out the F-16, while providing the required aircraft availability and avoiding a risk to airworthiness. The model is also intended to help in making decisions regarding upgrading of the engines, the purchase of new modules, and repair policy in the context of an ageing fleet of engines.

Maintenance of the engine is based on the consumption of engine cycles, i.e. usage. Module overhauls are planned for 2,000 or 4,000 cycles, depending on the module. It is necessary to manage the matching of modules to maximize engine availability. However, this is difficult to do. Swapping modules between MOBs in order to assemble engines with matching modules tends initially to result in an unacceptable loss of availability. Major modification programmes restore the life of modules and reduce the opportunities for making economies through matching.

The Reliability Centred Maintenance (RCM) review for engines was done to define some 'new' maintenance performance indicators and gain insight into the effectiveness and cost of engine maintenance. Currently, the maintenance indicators are such metrics as maintenance man-hours, shop visit rate, and LRU return rate. The RCM review was scheduled to be completed in 2006.

The study of flight regime recognition included the development of the tool "PROUD" (PROjected Usage Damage) for simple and straightforward damage prediction in the Chinook helicopter. A sort of 'damage indicator' (Chinook Damage Indicator – CDI) has been defined, which allows the severity of different mission profiles to be assessed. For example, hovering with a Chinook is less damaging to the airframe then transporting heavy loads (Figure 3-13). When implemented, the software tool will help fleet managers, maintainers, and operators in planning Chinook operations and maintenance.

Figure 3-13: RNAF Chinook Helicopter with Underslung Loads.

3.4.4 Prognostic Health Monitoring

To the RNLAF, the term Prognostic Health Management (PHM) symbolises the trend to a greater use of on-condition maintenance through the use of on-board condition monitoring and diagnostics and improved ground-based data analysis (Figure 3-14). According to Andela in Paper 1.5, The RNLAF regards PHM as consisting of the following pillars:

- *Diagnostics* – The process of determining the state of a component to perform its function(s).
- *Prognostics* – Prediction of the remaining life or time span of proper operation of a component.
- *Health Management* – The capability to make appropriate decisions about maintenance actions based on diagnostics/prognostics information, available resources, and operational demand.

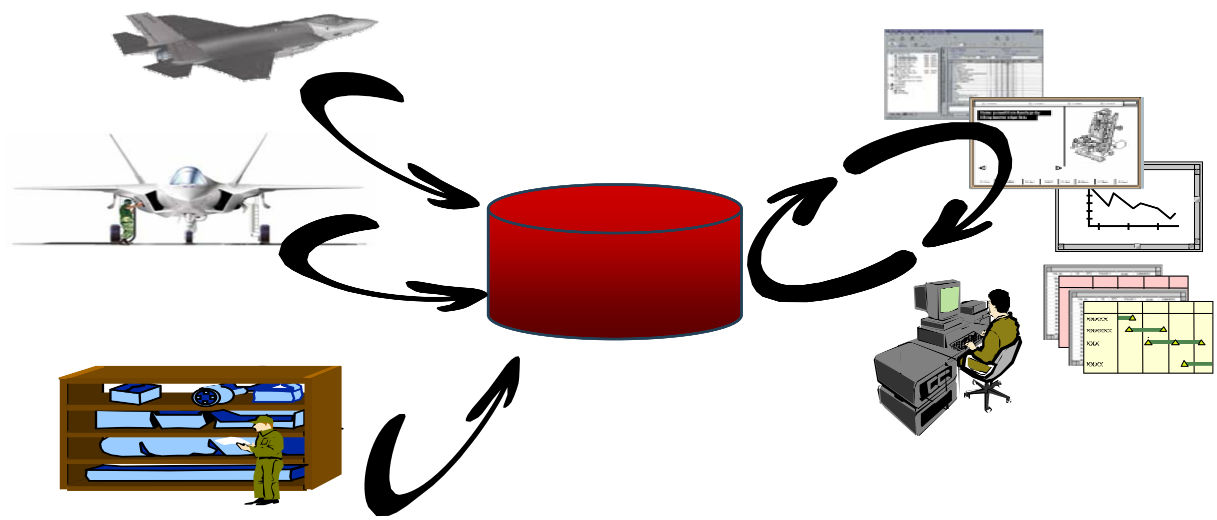


Figure 3-14: The Tools of PHM in the RNLAF.

The Netherlands involvement in the F-35 JSF programme has boosted interest in PHM, but the RNLAF also regards it as a useful concept for legacy systems.

3.5 SWEDEN

This section is based on Paper 1.6 by Barbici.

3.5.1 Introduction

This section describes the Swedish Defence Materiel Administration – Försvarets Materielverk (FMV) – and its approach to improving aircraft availability. The approach is referred to as the Availability Performance Program (APP), and is integrated with the "old", but still very efficient process of Life-Cycle Management (LCM). The Swedish Armed Forces (SwAF) has recently undergone substantial changes in organisation and operational concepts. The LCM and APP processes have been modified and improved to respond to current needs. The current LCM and APP processes are described, and two major aircraft programs are used to illustrate their application and the results achieved: the Swedish JAS 39 Gripen fighter aircraft; and the Nordic Standard Helicopter Program (NSHP).

3.5.2 Description of the Swedish Defence Materiel Administration (FMV)

FMV is an independent, civil authority. It takes care of the needs for technical solutions and material for Sweden's security by applying business skills and technology. FMV contributes to strengthening Sweden's security and defence ability through advanced, flexible, interoperable, and cost-effective materiel. It is contributing to the restructuring of the Swedish Defence Force to provide the task-force capability required by current defence policy.

The primary role of FMV is to provide the Swedish Armed Forces with effective equipment and methods to meet current and expected future needs. FMV provides the necessary technical and project management skills, and represents the government in complex international defence equipment transactions.

FMV delivers complex products for both military and civilian use, and has an extensive service portfolio:

- *Commercial Support and Procurement* – FMV is involved in procurement from the initial development of support strategy and requirements to the final delivery of equipment and support.
- *Modelling and Simulation* – FMV offers an advanced environment for the simulation of acquisition processes, including systems and enterprise analysis, business modelling, crisis management analysis, analysis of future international operations, and technology demonstration.
- *Investigations* – FMV performs research as required on acquisition issues, such as the effects of outsourcing.
- *Validation and* Verification – FMV has test ranges in several places in Sweden covering a variety of needs, and provides highly skilled and experienced personnel to support test programs. It has the larges test ranges in Europe on land, and the most modern dynamic field simulator.
- *International Materiel Cooperation and Export Support* – FMV participates in a wide range of collaborative forums in which possible collaboration is discussed. NATO activities have been expanded through the inclusion of new programmes in various fields, including security and anti-terrorism measures.
- *Certification Services* – The certification activity has been established as an independent function within FMV, known as the “Swedish Certification Body for IT Security”, which is abbreviated in Swedish to “CSEC”. CSEC was established in 2003. International recognition of the certification scheme according to the Common Criteria Recognition Arrangement is anticipated before the end of 2006.
- *Professional Commercial*, *Legal and Technical Advice* – FMV provides professional advice as required to Government clients and collaborators on commercial, legal, and technical matters.

Some of the larger projects in which FMV is extensively involved are:

- Jas 39 Gripen for SwAF – one of the world’s most modern fighter aircraft.
- Gripen for export.
- Helicopter 14 – a medium-weight helicopter for transport, search and rescue.
- CV-90 – a combat vehicle with a variety of functions.
- LedsystT – the new network-based command and control system of the SwAF.
- Project Phase-Out – the sale of large volumes of surplus materiel.
- SEP – a multi-role armoured vehicle platform.
- RAKEL – radio communication to emergency authorities.
- Corvette Visby – the world’s first stealth ship.
- Viking – a submarine.

Figure 3-15 illustrates the division of work and responsibility between FMV and industry.

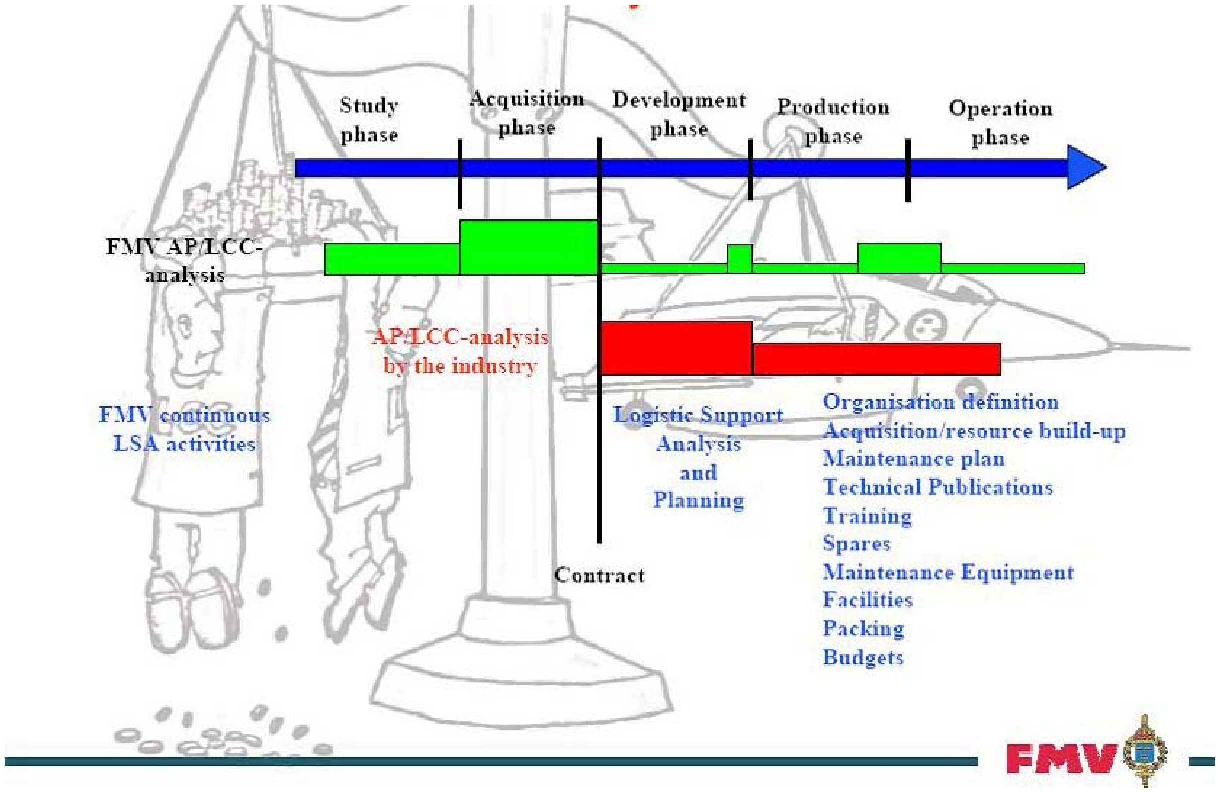


Figure 3-15: Typical Work Share Between FMV and Industry.

3.5.3 Life-Cycle Management at FMV

Life-Cycle Management (LCM) as practiced by FMV is a continuous Logistic Support Analysis (LSA) conducted in a structured and controlled way, i.e. a procedure designed to control the procurement, development and operation of a materiel system in order to achieve high reliability and low through-life costs. The LCM activity is conducted with a high degree of adaptation to the particular requirements of the project concerned, combined with clear objectives and milestones.

During the last ten years many changes have occurred that have influenced the Swedish Armed Forces (SwAF). Operational concepts have changed, as well as notions on how advances in technology might be applied to warfare. An example is network-based defence. Some other factors that are shaping the SwAF are as follows:

- Changing threat;
- Drastic reduction in the number of military units;
- Reduction in the number of command levels;
- International military efforts get the most modern equipment;
- Greater demand for integration and cooperation between land, sea and air forces;
- Smaller production runs, and more demonstrators and concept studies;
- Change from mass depot storage to small depot storage;

- Greater demand for cooperation between military and civil authorities; and
- Changed conditions for the Swedish defence industry.

The changes have resulted in a need for new equipment, processes, doctrine, force structure, training, and education. Also, the SwAF now expresses its requirements in terms of functions or capabilities rather than specific equipment.

Other issues are affecting acquisition and support. The escalating cost of defence equipment makes it necessary to design vehicle platforms to allow continuous evolution to adapt to new tasks and new technologies without extensive reconstruction. Also, technology development is no longer linear; therefore, it is becoming increasing difficult to obtain sufficient reliable data for the prediction of failure rates. These and other issues have required changes in FMV's LCM process. The need to adapt to changes in defence strategy and advances in technology are affecting FMV in several ways:

- A higher demand on systems co-ordination – capability to build system of systems;
- No longer land, sea and aerial forces – just one defence;
- A changed acquisition process;
- The necessity of an overhaul of the interface with industry;
- A higher demand on interoperability;
- New demands to change the competence profile; and
- Adjustments of the boundaries between the actors involved.

With all the above changes and challenges in mind FMV still has to provide the Swedish Armed Forces with the necessary material system for future operations, i.e. both the technical system and the integrated Operational and Support (O&S) system.

While the language of acquisition has changed and requirements are now based on a more systemic view of overall defence capabilities and functions, specific materiel must ultimately be defined, procured, and supported. The "old" LCM process as illustrated in Figure 3-16 is still the right tool for this task, and is applied throughout the whole of an aircraft's useful life, from the earliest studies until phase-out. This process entails, among other things:

- Influencing the operation and logistic support assumptions and the Availability Performance (AP) requirements for both the technical system and the logistic support system.
- Analysing the economical consequences of the AP requirements to ensure that adequate financial provision is made in the budget – for both the procurement of logistic support system resources and the subsequent operating and support costs.
- Controlling the activities of the supplier during the design, development, and production phases by including a logistic support programme in the contract statement of work, with the purpose of ensuring that the reliability, maintainability, and logistic support requirements are taken into account at the design phase.
- Iteratively developing an optimized maintenance concept.
- Realising the support concept through an optimized acquisition of logistics support resources.
- Integrating the support system of the aircraft into the existing overall support system.

- Gathering and analysing operational data, to monitor aircraft availability and life-cycle cost.
- Systematically, at an early stage, planning for the phase-out of the aircraft.

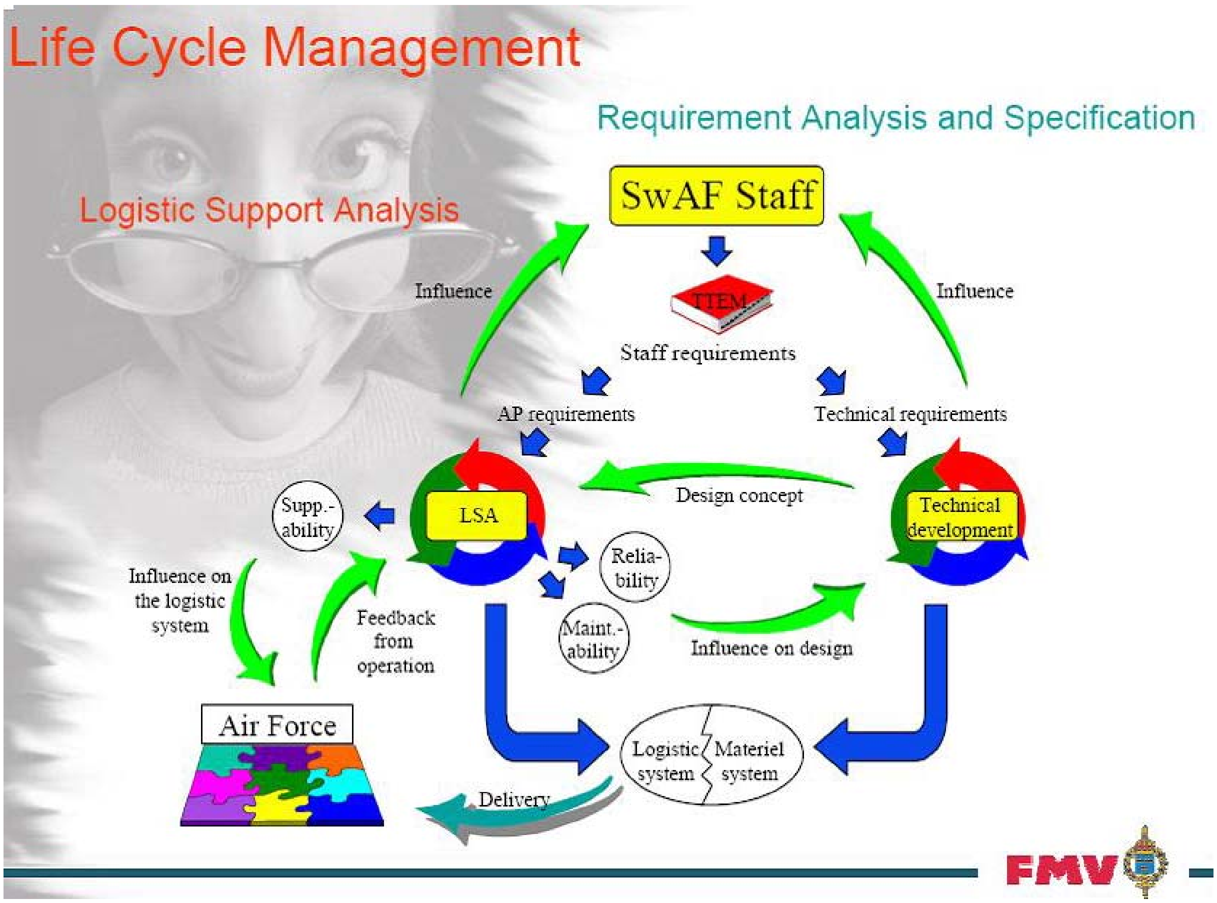


Figure 3-16: Core Life-Cycle Management (LCM) Concept in the Swedish Armed Forces.

3.5.4 Integrated Operations and Maintenance System

The framework for LCM in the SwAF is an integrated operations and maintenance system. This consists of logistic support, strategic support, and (maintenance) production support (Figure 3-17 and Figure 3-18). FMV is responsible for all three functions.

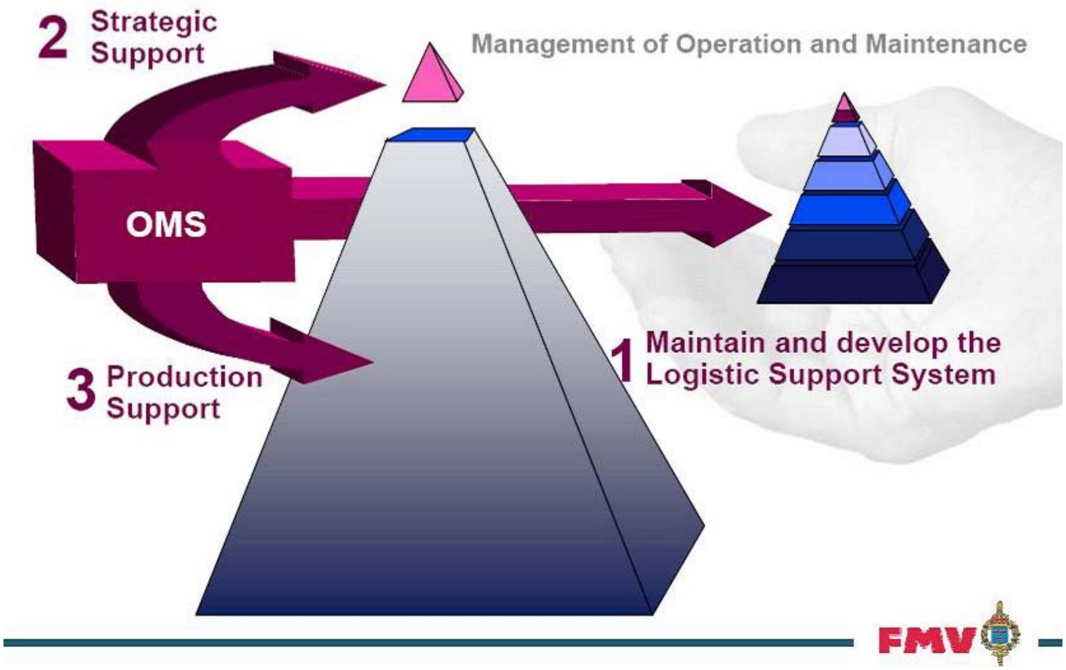


Figure 3-17: The Three Main Functions of O&M.

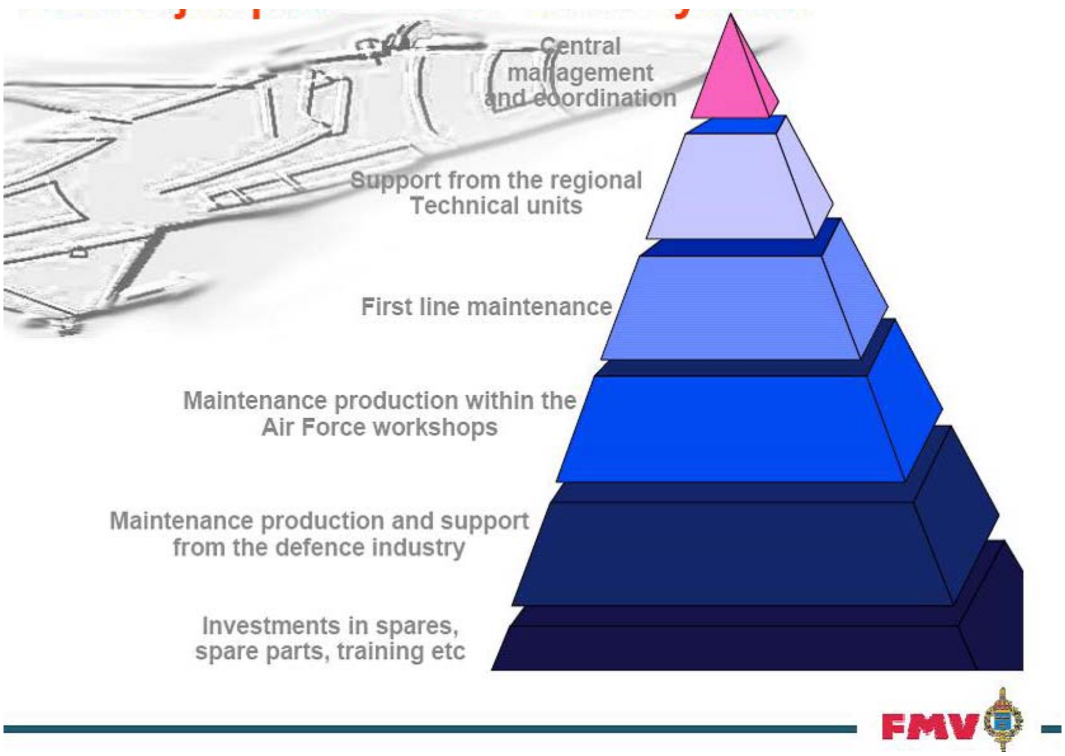


Figure 3-18: The Major Parts of the Operation and Maintenance System.

The three functions are described as follows:

a) *Maintain and* Develop *the Logistic Support System* – The purpose of this function is to provide the Swedish Armed Forces with a flexible and efficient operation and maintenance support in war, crisis, and peace. The objective is achieved by:

- Creating development strategies;
- Undertaking R&D in LCM;
- Utilizing advances in Information Technology (IT); and
- Continuously improving existing processes.

b) *Strategic Support* – This function involves continuous support to responsible persons within the SwAF related to long- and short-term planning of acquisition, operation, and maintenance. Technical, organisational, economical, and commercial advice is provided.

c) *Production Support* – This function involves direct and continuous support to personnel engaged in accomplishing operation and maintenance. It includes the supply of support systems as well as advice on economical, technical, and managerial issues. The overall aim is to improve performance and efficiency.

To enable the materiel to be utilized correctly in peacetime as well as in time of crisis or war, there is a need for properly functioning common O&M system which does not necessarily require to be changed for each new type of materiel. When future operation and support of a materiel system is being planned, it is important to find an optimum trade-off between the general elements of the O&M system and the additional elements specific to that particular materiel system. This trade-off is addressed in the LCM process.

The O&M system must function well in both peacetime and war. A common O&M system helps to ensure this. While there are over 500 different operational systems in the Swedish Air Force, the same basic O&M systems serves them all (Figure 3-19). Any specific needs are met through special adjustments to the common, integrated O&M system.

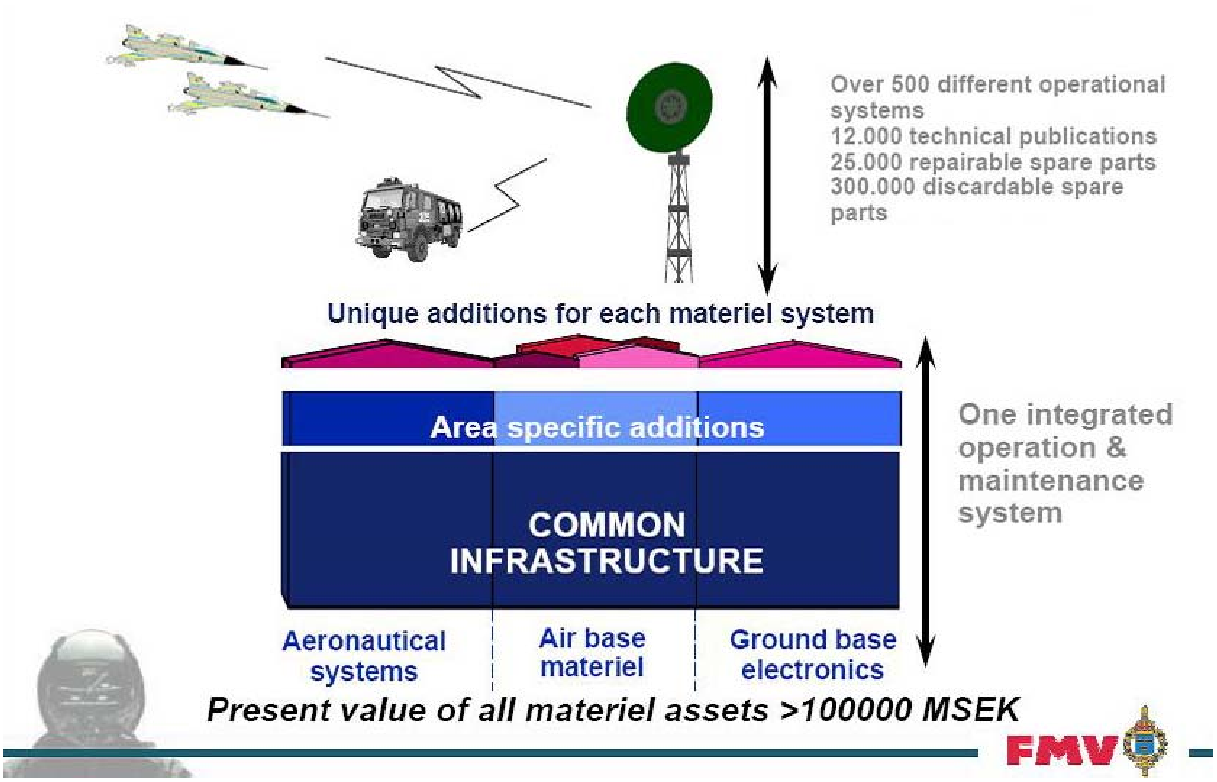


Figure 3-19: Single Integrated O&M System Covering All Swedish Air Force Materiel.

The Swedish Air Force turnover is about 3,000 million Swedish kronor (SEK) per year. The maintenance costs are approximately 3% of the materiel value, which illustrates the success of the "old" LCM process.

3.5.5 The Availability Performance Program (APP)

3.5.5.1 Purpose and Content of the APP

The APP consists of a number of engineering methods and organizational routines that control the logistic support analysis work to be performed for a specific product. Its aim is to ensure that the aircraft and support system will fulfil the contract requirements on availability and support costs. It includes a specific program of work to be performed during development and production to generate the data needed for the design, optimization, and acquisition of maintenance resources.

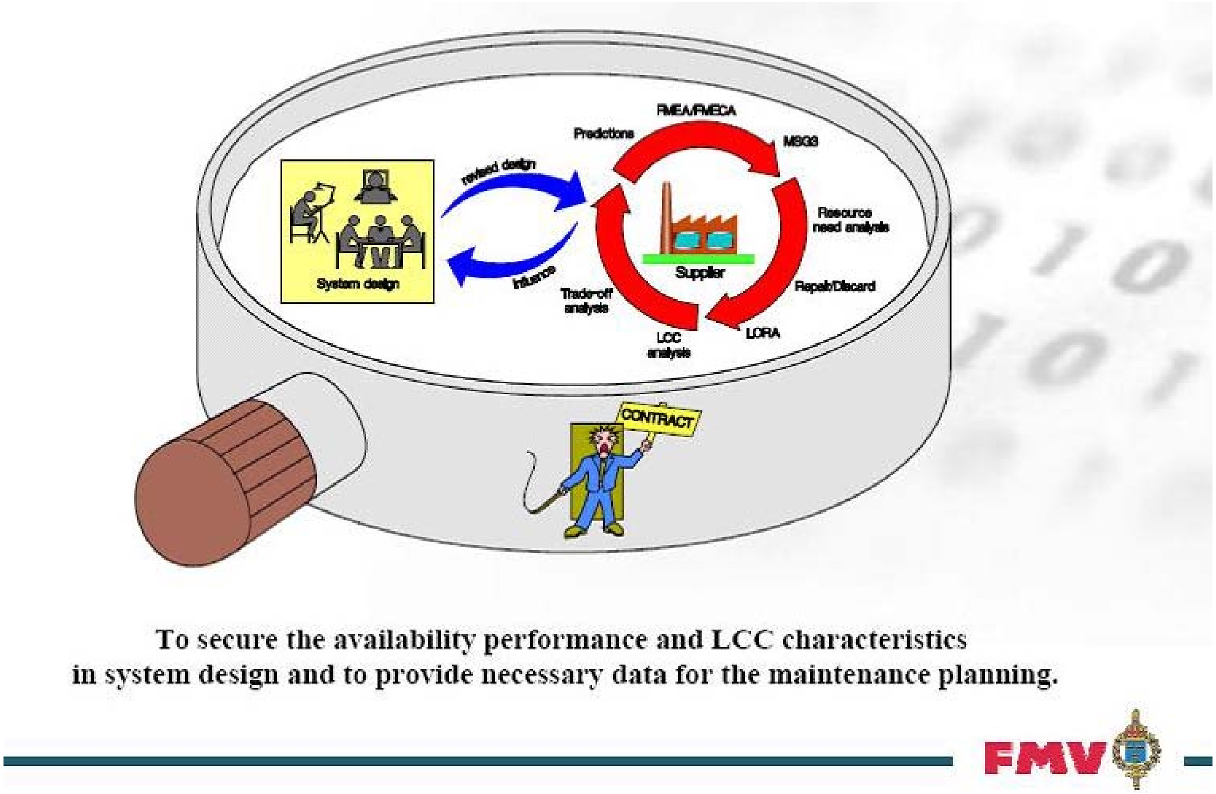


Figure 3-20: The Availability Performance Program (APP).

The availability performance program is a very important part of the LCM process. Since it is also costly, it should to be tailored to the need of the specific project. The APP requires qualified personnel at the contractor and customer and must be accepted within the contractor's organization. Some of the performed tasks and sub-tasks typically contained in an APP are as follows:

- Requirements specification and breakdown.
- Reliability analysis:
  - Reliability block diagrams.
  - Predictions.
  - FMEA/FMECA.
  - Fault Tree Analysis (FTA).
  - Software reliability.
- Maintainability analysis:
  - Test and fault localization analysis (BIT).
  - Methods for corrective maintenance.
  - Methods for preventive maintenance.

  - Design features.
  - Predictions of MTTR and the effectiveness of BIT.
- Supportability analysis:
  - Configuration analysis – define Maintenance Significant Items (MSI).
  - Modularization/standardization.
  - Maintenance needs analysis (RCM).
  - Repair/discard analysis.
  - Level Of Repair Analysis (LORA).
  - Identification of logistics resource needs.
- Life-cycle cost analysis:
  - Evaluation of proposals and design alternatives.
  - Identification of cost drivers in the aircraft and the maintenance system.
  - Control the development towards a low life-cycle cost.
- Test and evaluation.
- Feedback from tests and prototypes through the Failure Reporting Analysis and Corrective Action System (FRACAS).
- Verification.

3.5.5.2 The Importance of Understanding Operational and Support Requirements

With regard to the first item on this list, it is important that the contractor understands the customer's organisation, terminology, and requirements. It is also important for the contractor to understand how the aircraft will be used. A poor requirements analysis leads to a poor material system and an expensive logistics system. If the requirements are too high-level the aircraft will be too expensive. Studies preceding the selection of a future materiel system are largely concentrated on determining the right requirements and the right levels for these requirements.

Aircraft availability requirements are broken down to form requirements for the products to be procured. The following must be covered in a specification of availability performance:

- Evaluation principles.
- Assumptions.
- Requirements on the system – availability performance.
- Requirements on data and information to be delivered in the proposal.
- Requirements on deliveries of the support system.
- Requirements on the contractor, availability performance program.
- Requirements on verification.

3.5.5.3 Integration of the Design of the Aircraft and the Support System

The objective for all defence materiel systems is to achieve the required operational performance within the constraints of the funding available. Operational performance includes both technical and availability performance (see Figure 3-21). By technical performance we mean the technical characteristics of the system which describe how it functions. This could refer, for example, to speed or radar range.

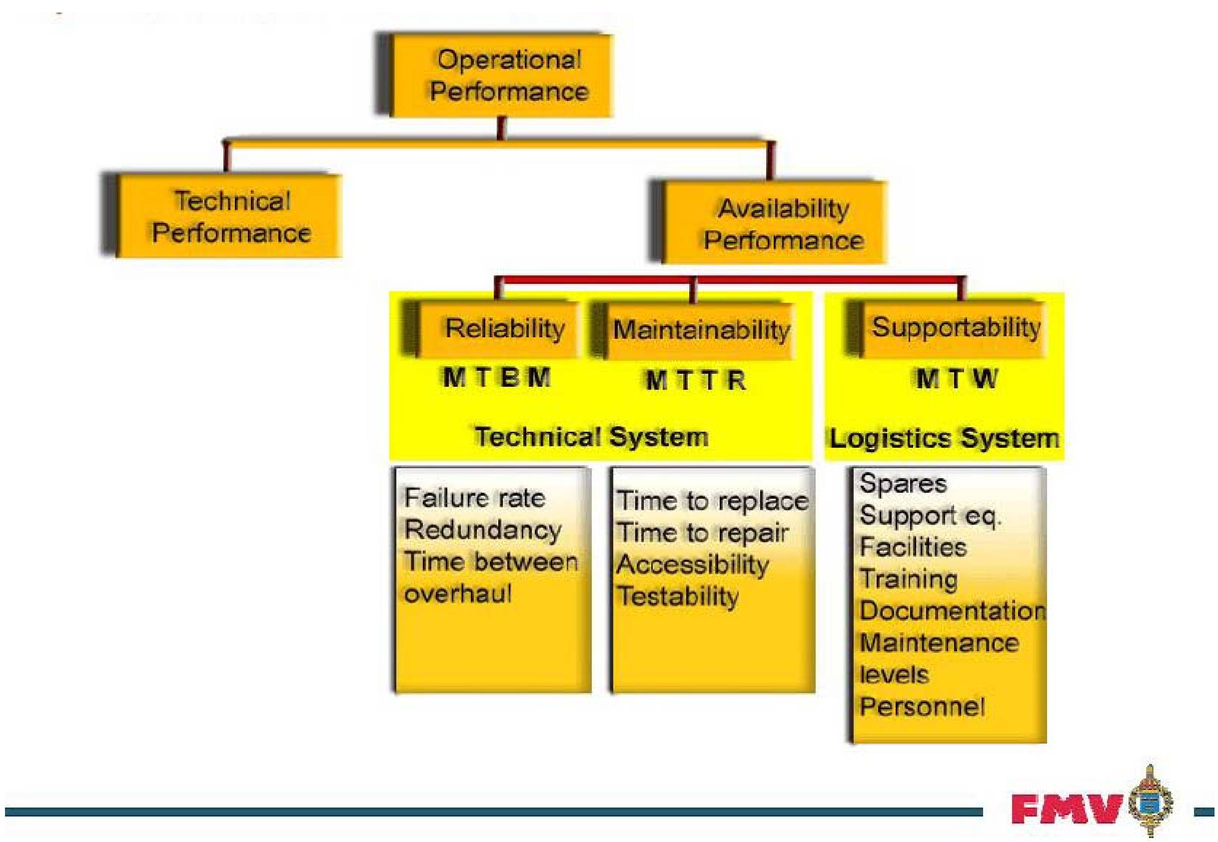


Figure 3-21: Operational Performance Breakdown with Examples of Parameters which Affect it.

The LCM process applies primarily to availability performance, i.e. those characteristics which determine when the system is functioning and how the situation is handled when it ceases to function. Availability performance thus depends both on the characteristics of the technical system and on the capacity of the maintenance system. Trade-offs can be made between these characteristics, to optimise availability with respect to life-cycle cost (Figure 3-22).

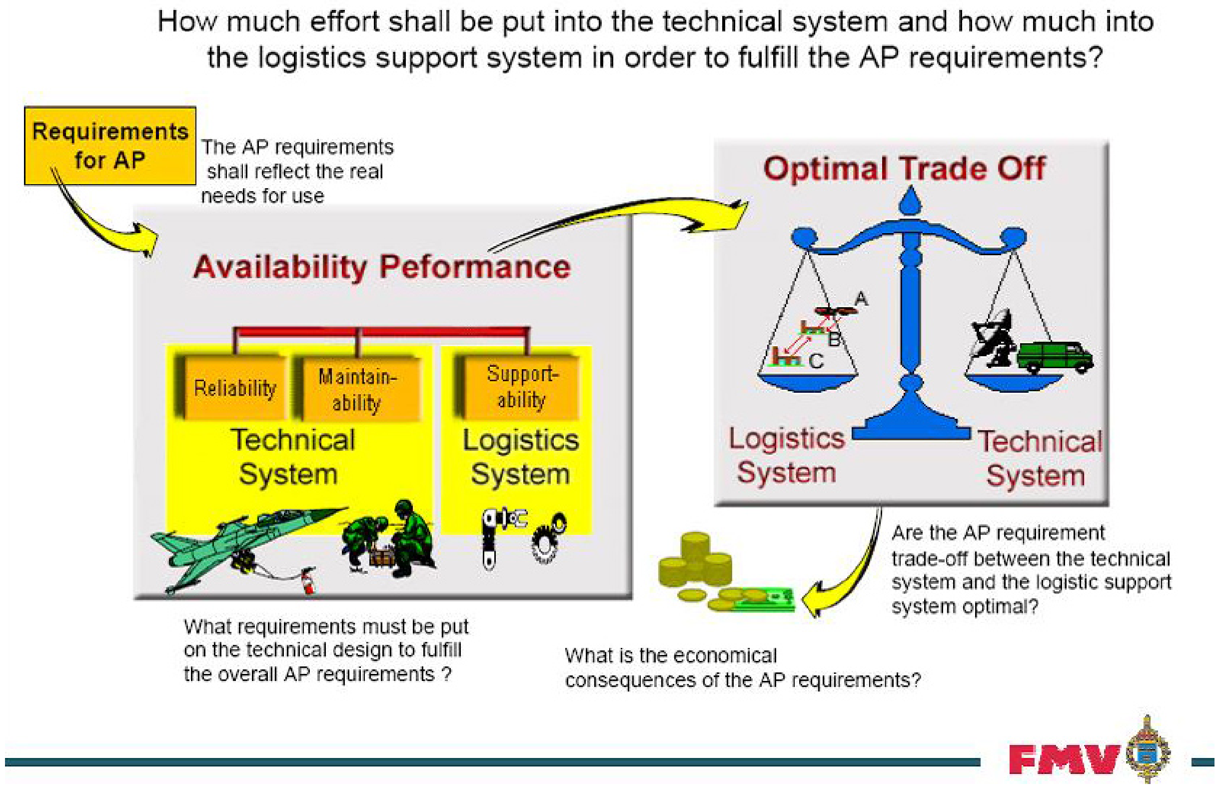


Figure 3-22: The Process of Analysing the Availability Requirements.

Life-cycle cost is central to FMV's approach to an APP. It is a measure of the overall financial consequences of a system or equipment over the whole of its useful life. These include not only all the costs associated with procurement and development of the materiel system but also the cost of procuring various support system resources and the future costs of operation and support. These latter costs of procuring support system resources and the future costs of operation and support are known as the Life Support Cost (LSC).

3.5.5.4 Optimising the Support System with Respect to Availability and Cost

The main product of the APP is the design of a logistics support system which is optimized with respect to other aircraft requirements, in particular availability. The proposed logistic support system is first outlined in a support system concept document, and is later recorded in progressively more detail as the design of the aircraft and support system proceed (Figure 3-23). The final documentation describes in full detail how logistic support is to be organised and what resources will be required.

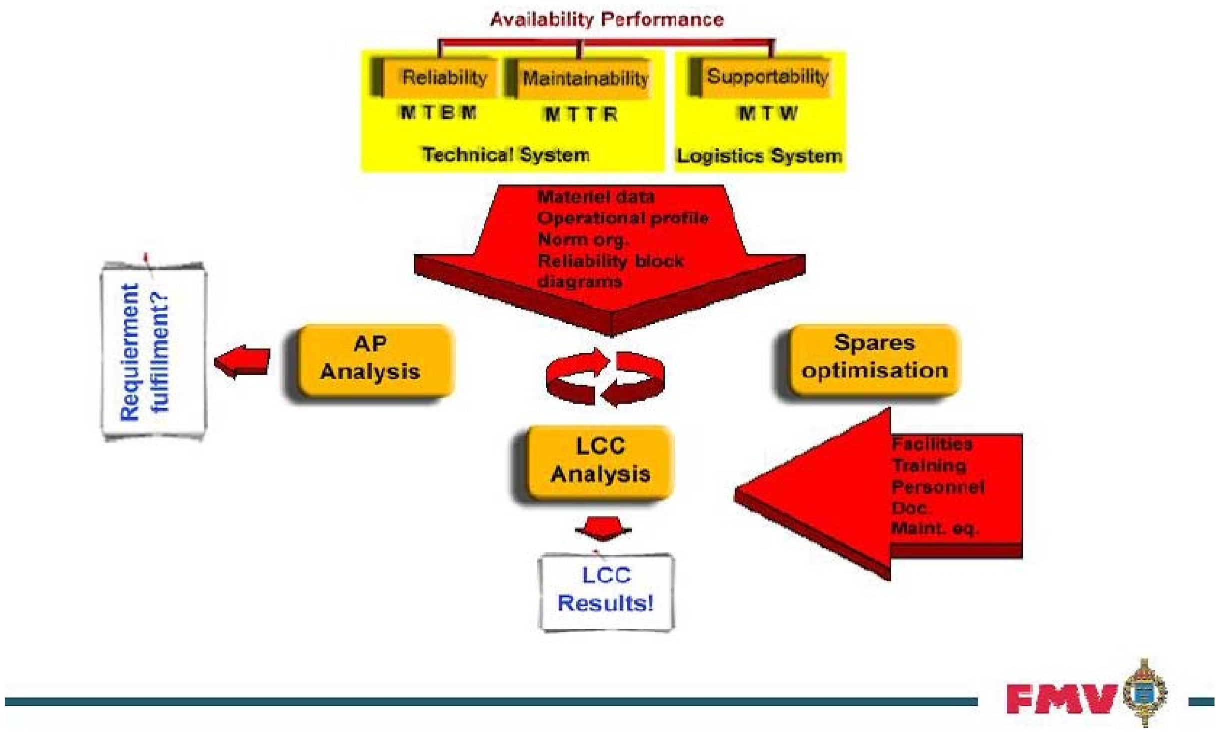


Figure 3-23: Part of the Iterative Process Involving the Optimization and Acquisition of Maintenance Resources.

3.5.6 The Application of FMV's APP to Recent Aircraft Programs

3.5.6.1 The Jas 39 Gripen

When studies to replace the Viggen started in the 1970s, the Swedish government demanded that the new aircraft have a much lower life-cycle cost, despite the new and more sophisticated technologies involved. The result was the Jas 39 Gripen (Figure 3-24). The Jas 39 (Figure 3-24) is one of the most successful projects in FMV's history with respect to aircraft availability and life-cycle cost. Figure 3-25 shows how the increasing trend in life-cycle cost over previous fighter aircraft programs was broken.

Figure 3-24: Jas 39 Gripen Aircraft – Replacement for the AJ 37 Viggen.

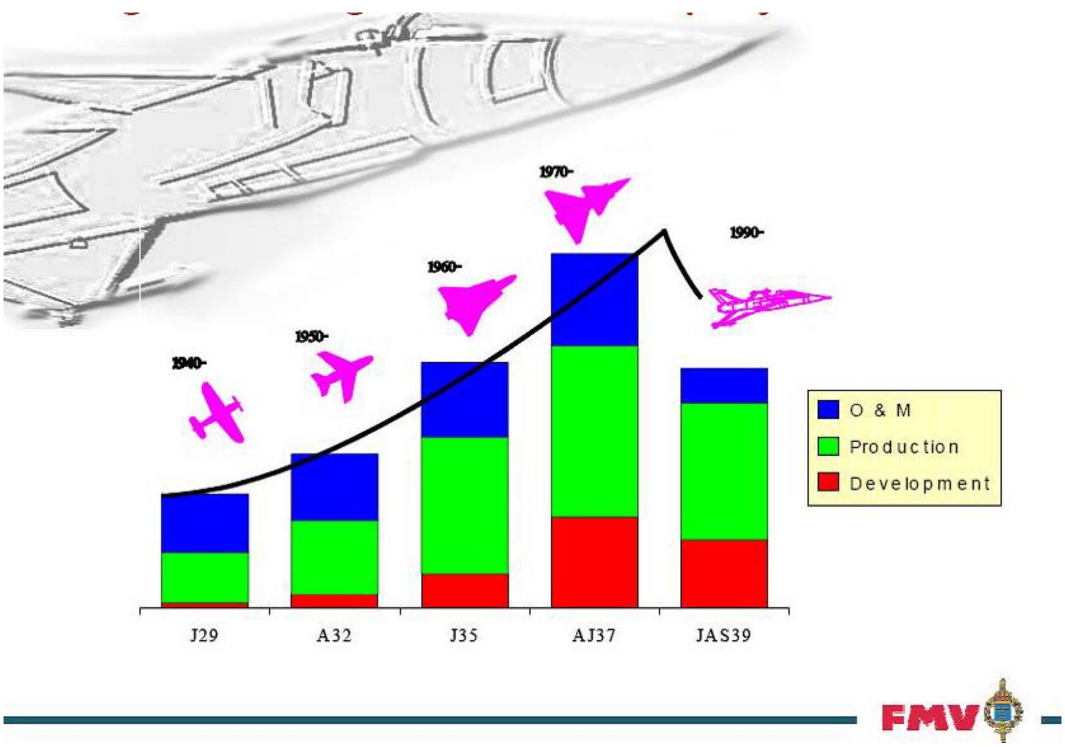


Figure 3-25: Trends in Swedish Fighter Aircraft Development, Production and O&M Costs.

At the beginning of the project the availability and capability requirements for the Jas 39 Gripen were described in a "System Development Plan". This effectively became the Swedish Air Forces order to FMV. The System Development Plan was detailed to the extent of specifying what analyses were required, and included the following:

- References to contractual requirements.
- A model organization and other prerequisites regarding operations and maintenance.
- Formulae and rules for calculations such as life-cycle cost.
- The contractual status of all input parameters.
- Definitions.
- Requirements breakdown.
- Predictions.
- Maintenance needs studies.
- Maintenance task analyses.
- LORA.
- Repair/discard analyses.
- Life support cost analyses.
- System analyses.
- Development process for the maintenance plan.
- Recommendations to guide the planning of spares, ground support equipment, packing, training, etc.

In other words, FMV's full Availability Performance Program was adopted as the System Development Plan for the Jas 39. This was the first time the full AAP was applied to any program.

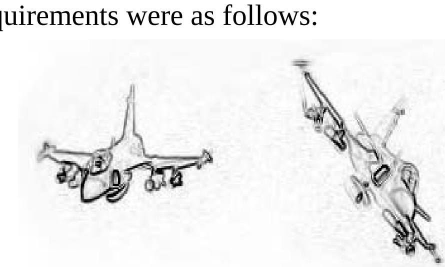
The availability requirements in the contract were geared to wartime, and were expressed in the following general form:

> *"A squadron JAS39 with X a/c shall be able to produce Y missions of Z ordered with a probability of P%."*

The availability requirements breakdown was structured so that the contractor had some flexibility, and so that the most cost effective solution for the Swedish Air Force would also be the most profitable solution for the contractor.

Some of the metrics used in formulating the contractual availability requirements were as follows:

- Total failure rate (failures/fh).
- Mission success probability.
- Downtime (h/fh) – particularly important in wartime.
- Maintenance work load (mh/fh) – particularly important in peacetime.
- Turn-around times.
- Life support cost – used in incentive clauses, and carefully formulated to avoid unintended consequences.



The contract incorporated even some warranties:

- Design guarantee.
- Production guarantee.
- Special guarantee on the control system.
- User cost guarantee during the initial period of operation (500 fh per a/c).
- *Options:*
  - Maintenance cost at central workshop.
  - Turn around times at the central workshop.

The approach to verification was as follows:

- Mainly a theoretical verification.
- Some practical demonstrations.
- Verification to start after 3000 fleet hours.
- Discrepancies to be fixed by the contractor through modifications at no charge to FMV.

Availability and support costs are formally reviewed by the Government at least annually at special meetings. As a result of the AAP the achieved maintenance costs per flight hour of the Jas 39 Gripen have been drastically reduced compared to earlier Swedish fighter aircraft, and this reduction has so far been sustained (Figure 3-26 and Figure 3-27). The estimated life support cost has been sustained at a level about 15% lower that the contract requirement (Figure 3-28). The contractor has qualified for corresponding bonus payments. Average availability, as measured by downtime per flying hour, has been much better than specified, while mission success rate (mission reliability) has been slightly lower than specified (Figure 3-29).

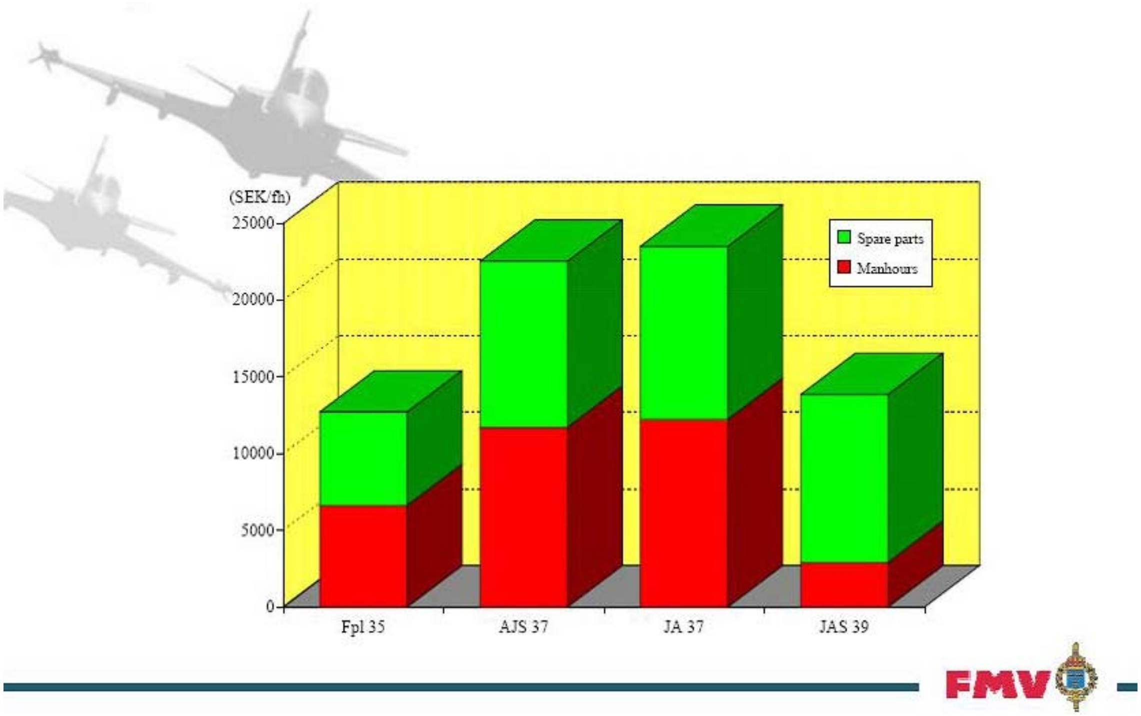


Figure 3-26: Historical Trend in Maintenance Cost in Kronor (SEK) per Flight Hour of Swedish Fighter Aircraft.

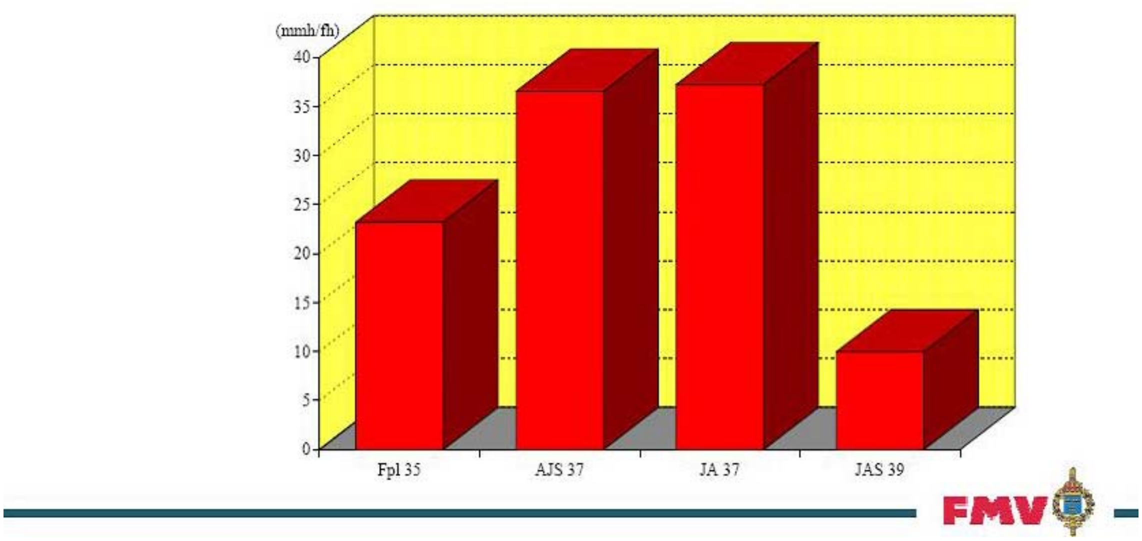


Figure 3-27: Historical Trend in Maintenance Cost in Man-Hours per Flight Hour of Swedish Fighter Aircraft.

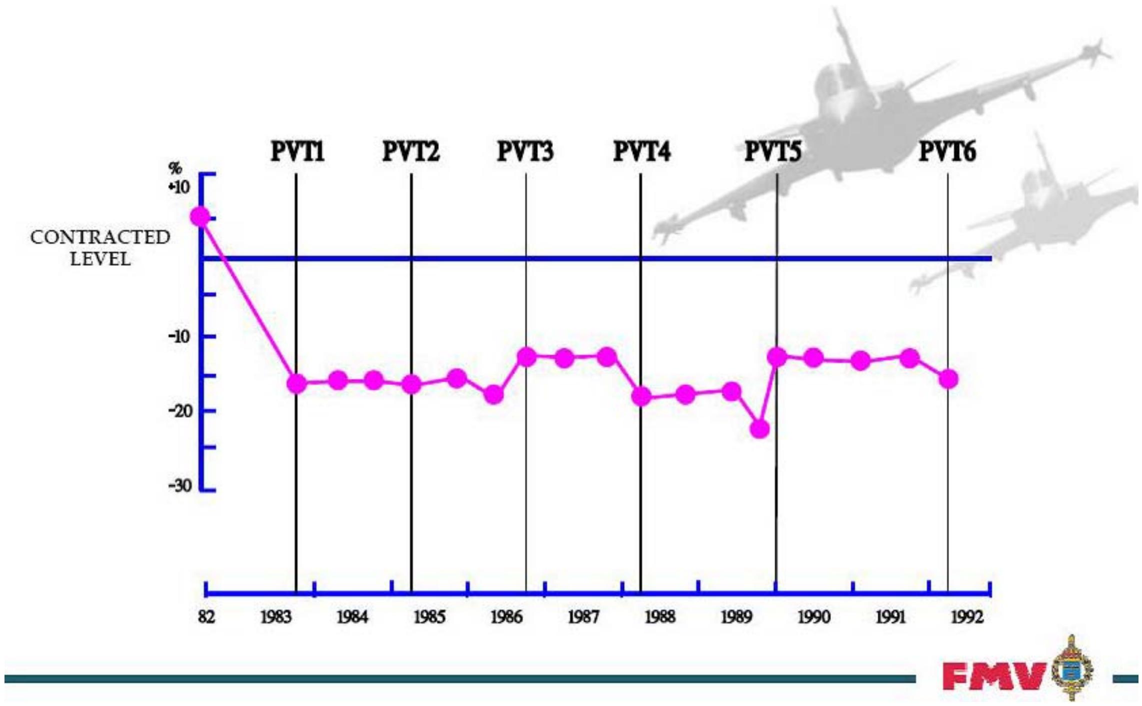


Figure 3-28: Ongoing Estimates of Life Support Cost (LSC) Compared with the Contracted Level.

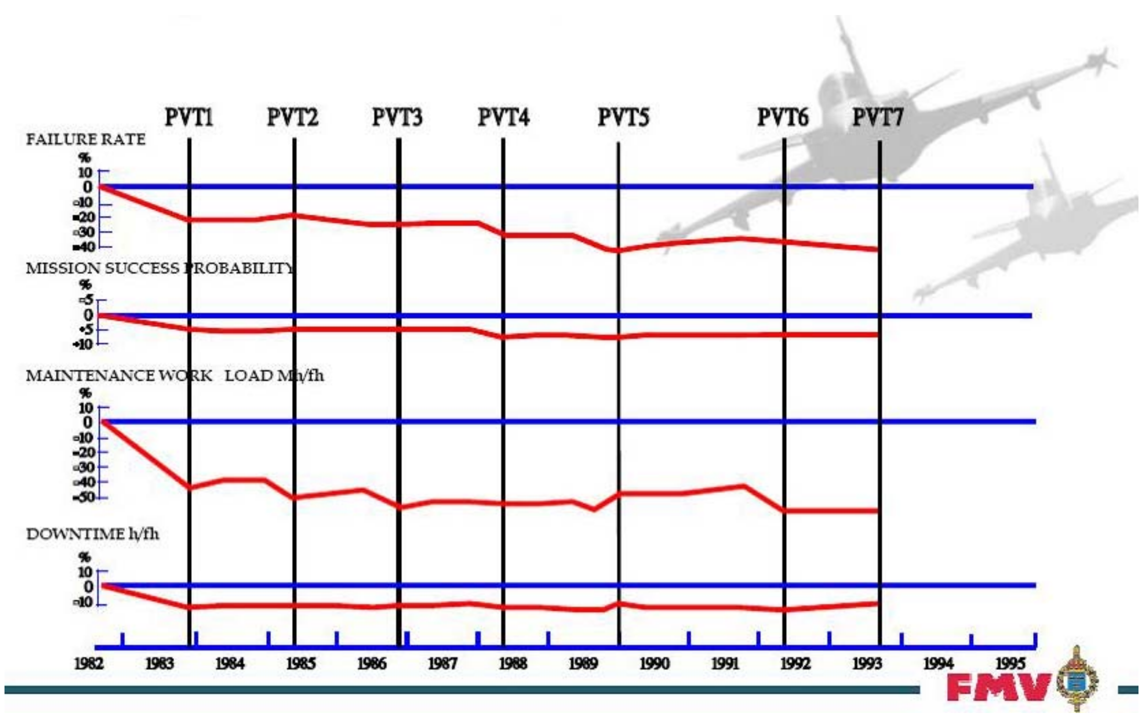


Figure 3-29: History of Achievement/Shortfall in Key Availability Related Metrics on the Jas 39 Gripen Program Compared to the Aircraft Specification.

3.5.6.2 Nordic Standard Helicopter Program (NSHP)

In 1999 the Armed Forces of Denmark, Finland, Norway, and Sweden decided to purchase a multi-purpose, medium to heavy lift helicopter that could be equipped for the different missions required by each country. The intention was to achieve economies in procurement and support and to improve operational effectiveness by enhancing interoperability between Nations and between different Services and agencies within each Nation. A common Nordic Standard Helicopter Program (NSHP) was defined, and it was agreed that FMV would act as the executive agency for the negotiation of the basic procurement contract. Swedish laws and regulations were applied to the contract.

The NH 90 helicopter by NHIndustries – owned by Agusta, Eurocopter and Stork Fokker Aerospace – has won the order, but Denmark has left the program. Sweden has ordered 18 NH 90s with an option on a further seven. These aircraft will replace the Air Force's Hp 3 and the Navy's Hp 4. Norway has ordered 14 NH 90s with an option on a further 10, while the Finland has ordered 20 NH 90s.

Figure 3-30 shows the different helicopters that were considered for the NSHP.

Figure 3-30: Candidate Aircraft for the Nordic Standard Helicopter Program (NSHP).

Figure 3-31 shows the different variants that were required by each Nation. The acronyms used in the figure are as follows:

- TTT (Tactical Troop Transport).
- OTT (Operational Troop Transport).
- SAR (Search And Rescue).
- CSAR (Combat Search And Rescue).

- ASW (Anti Submarine Warfare).
- MEDEVAC (MEDical EVACuation).
- CG (Coast Guard = Norway).
- National Fixed (national variant).
- National CP (Complete Provision, national variant).

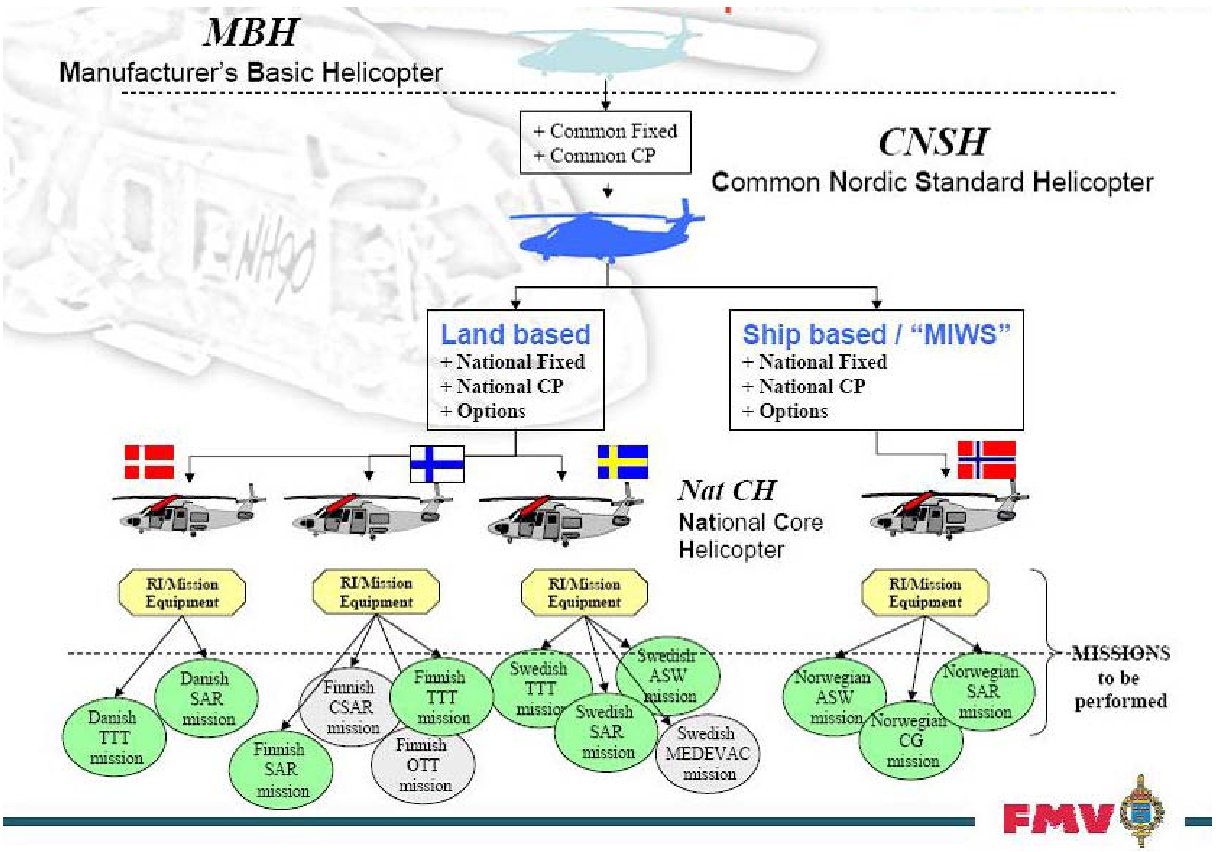


Figure 3-31: Originally Proposed Variants of the Nordic Standard Helicopter.

All the participating Nations' requirements were implemented in a common "Nordic Requirements Document". This document defined those requirements that were considered common and those which were specific to a particular Nation. The bidding prime contractors were required to provide detailed data in their quotations for the evaluation of performance, reliability, availability, and life-cycle cost. They were required to evaluate aircraft availability and life-cycle cost separately for each Nation, according to their individual operational, availability, and life-cycle cost models. Based on these analyses they were required to offer optimised solutions. All aspects of FMV's LCM and AAP processes were included in the analyses, including a full RCM study of preventive maintenance requirements and a full analysis of the supply chain needed for new and repaired/restored spare parts. FMV subsequently performed similar analyses to identify the key drivers of cost and availability, and verify and compare the competing proposals. An aggregate model of life-cycle cost for all four Nations was used in the evaluation of the proposals (Figure 3-32). To facilitate an equitable evaluation of proposals with regard to life-cycle cost, FMV's models assumed a common aircraft fleet availability requirement of 80% (Figure 3-33).

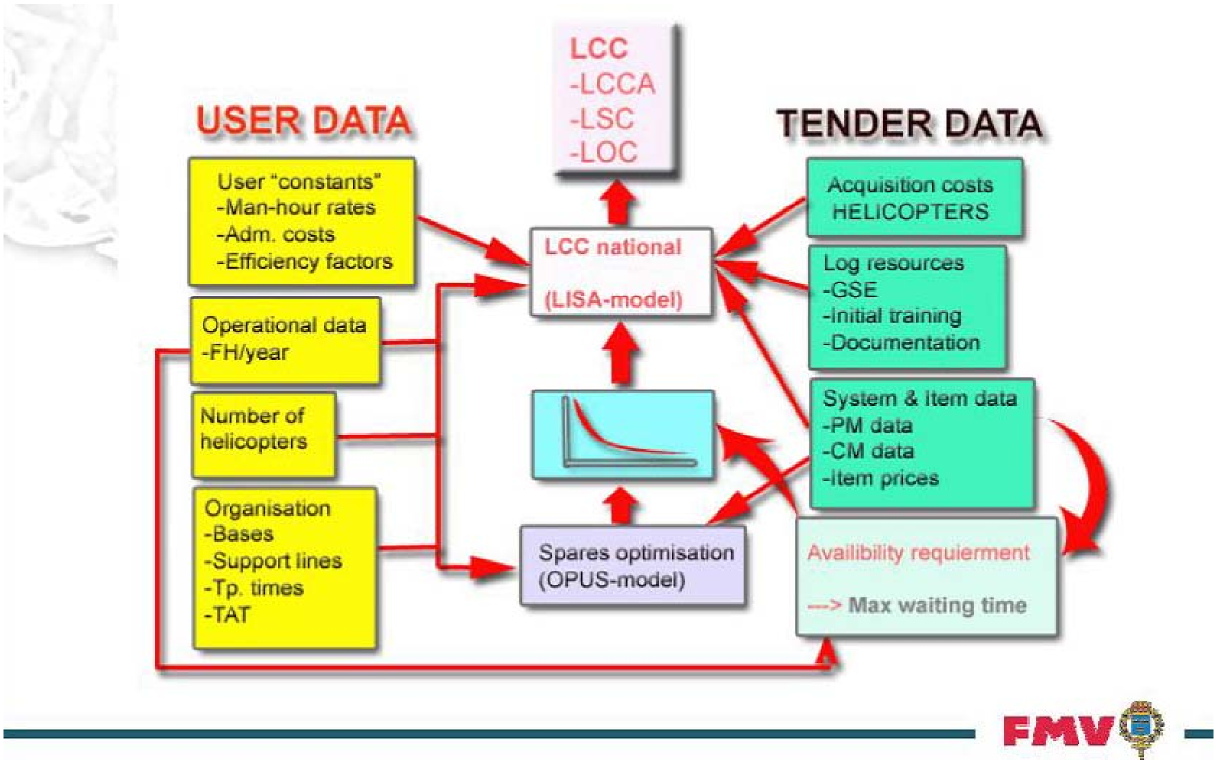


Figure 3-32: Schematic of the Aggregate Life-Cycle Cost (LCC) Model for the Nordic Standard Helicopter Program (NSHP). Aircraft availability, expressed as the maximum allowable waiting time, is an important input to the model.

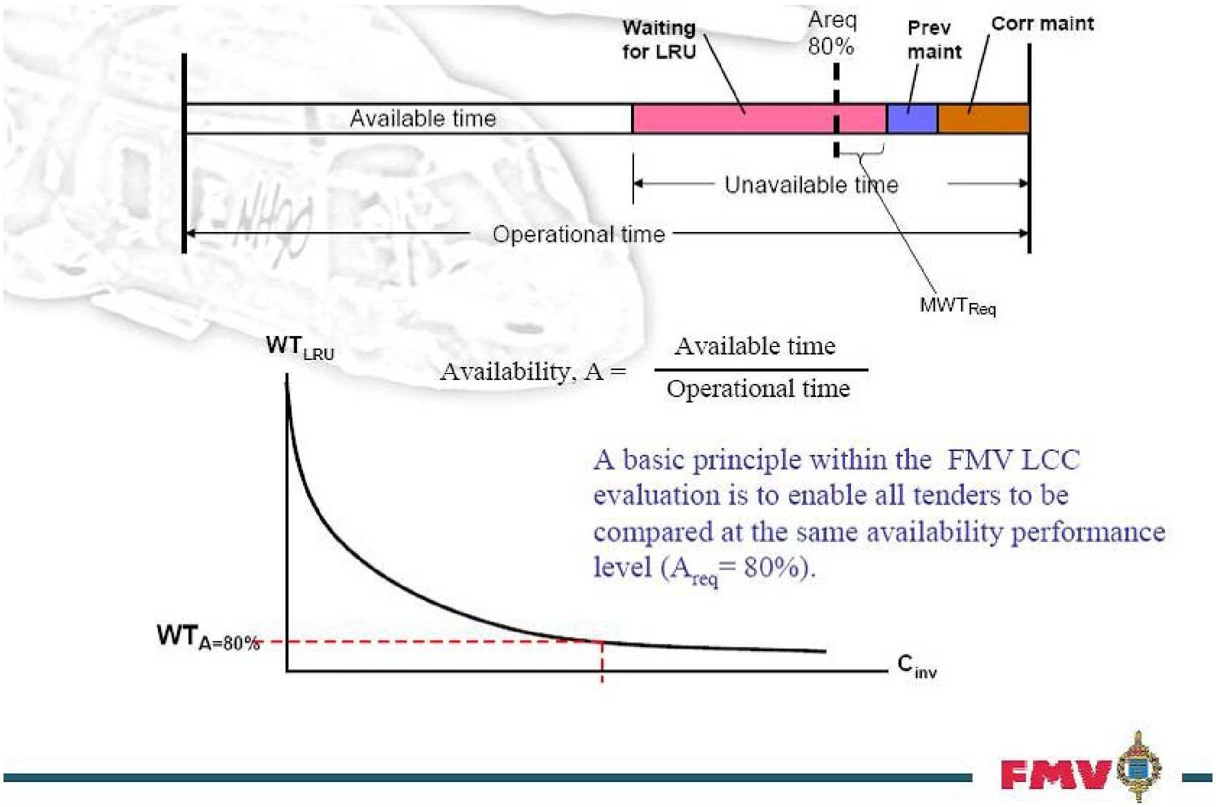


Figure 3-33: For Evaluating Tenders for Spare Parts, the Life-Cycle Cost of the Aircraft was Estimated for an Aircraft Availability of 80%.

A comparison of the estimated life-cycle cost for each of the four proposals is in Figure 3-34. The costs have been normalised with respect to the life-cycle cost for tender F. This tender – for the NH-90 helicopter – was the winning tender, even though it did not have the lowest estimated life-cycle cost.

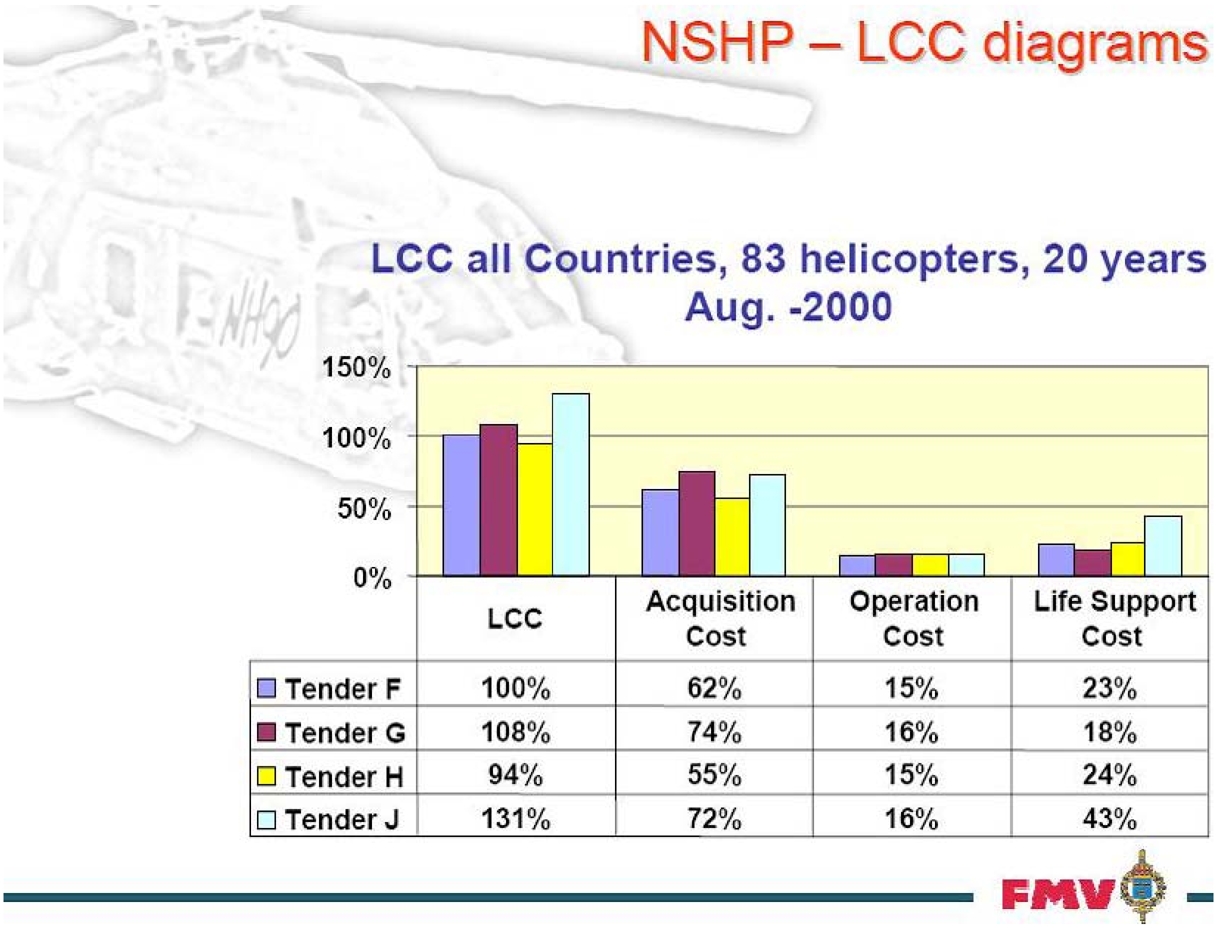


Figure 3-34: Comparison of Estimated Life-Cycle Costs for Four of the NSHP Tenders.

The proposal evaluation process generated considerable detailed data on cost drivers, which are not presented here. One observation was that the investment in spare parts differed significantly between the tenders. The difference was explained by the different maintenance concepts offered by each contractor.

The life-cycle cost analyses were used as a baseline for negotiating the acquisition and support contracts. Unlike the Jas 39 contracts, the Swedish NH-90 contracts do not contain incentive clauses related to life-cycle cost. However, they contain warranties on failure rate, Mean Time To Repair (MTTR), maintenance man-hours per flight hour, and other cost and downtime metrics related to aircraft-level preventive and corrective maintenance. The failure rates of approximately 25% of Line-Replaceable Units (LRU) are also subject to warranty. These were selected based on their potential impact on life-cycle costs.

Regular reviews of estimated life-cycle costs have now ceased for the NSHP as a whole, but FMV continues to update cost estimates for the SwAF.

3.6 UNITED KINGDOM

This section is based on Paper 1.7 by Elford.

3.6.1 Introduction

This section describes the transformation of UK military aircraft support concepts and activities under the auspices of the UK Ministry of Defence's Defence Logistics Transformation Programme (DLTP). It sets out some of the relevant historical context in terms of the main financial and political factors that are driving the change before describing some of the transformation activities that have been undertaken and the new support concepts that are emerging. The section concludes by illustrating some of the benefits that are being demonstrated through some aircraft-related DLTP change initiatives.

3.6.2 Historical Context

3.6.2.1 The Defence Logistics Organisation's Change Programme

The Defence Logistics Organisation (DLO) was formed in April 2000 as a result of some of the recommendations from the UK's 1998 Strategic Defence Review. The individual logistics organisations from the three Services were merged together and a new 4* level post, Chief of Defence Logistics (CDL), was created to lead the DLO. Upon its formation, Her Majesty's Treasury set the DLO a target to achieve a 20% reduction in total DLO operating costs by Financial Year 2005/2006 – this was referred to as 'the Strategic Goal'. The DLO Change Program was launched by CDL on the 26 September 2002 as a single, organisation-wide programme to deliver change in the DLO driven by specific requirements and generating measurable benefits.

3.6.2.2 The End-to-End (E2E) Programme

In May 2002, the UK MOD appointed the consulting firm McKinsey & Co to help in the identification of areas where the DLO could achieve the Strategic Goal target while safeguarding, and preferably enhancing, the support the DLO was providing to the front-line. The resulting 'E2E Study' report, delivered on 1 July 2003, broke the paradigm that Logistics Support is bounded by organisations and established principles showing that true logistics transformation could only be achieved by taking a holistic, whole supply chain (that is from production to point of use or '*end-to-end*') approach to optimising the delivery of logistics support.

3.6.2.3 E2E Study Recommendations for Logistics Support

The E2E Study recognised that future support strategy must be based on expeditionary operations, that is, short-notice operations in distant-overseas locations often with poor infrastructure. These operations require Joint logistic support that is tailored to the level at which the UK Armed Forces will be operating (the so-called '*most likely*' operational scenarios at lower intensity), is rapidly deployable and robust. Logistic support requirements should be driven from the front line back ('*customer pull*') and based on the effects that the operational commander wishes to achieve.

The E2E Study aimed to identify ways to deliver more effective logistic support for military forces at lower cost, where possible, but not at the expense of mandated or increased operational effectiveness. The proposals to improve logistic supply and equipment support for deployed forces arose as a result of a systematic analysis of existing logistic processes. The analysis considered both equipment and logistic support end-to-end, and addressed both non-deployed and deployed operations, for the UK's standing and crisis commitments. Future Support would be founded on the following three key principles:

- Configure logistic support for the most likely operational scenarios (medium scale), but create sufficient flexibility to cope with the most demanding. Previously, logistics support was largely geared towards fighting a major conflict, whereas modern expeditionary operations have generally been more frequent and of a smaller scale.
- Concentrate support facilities at the 'logistic centre of gravity'. Withdraw stocks held in remote warehouses, centralise stock holdings and support major training exercises and operations with '*Deployable Spares Packages*' (DSP – also known as '*Priming Equipment Packs*'), in line with Industry best practice. Hold only sufficient materiel for a unit, formation or squadron until the supply chain is established and where resources and materiel can deliver the required logistics support as effectively, flexibly and efficiently as possible.
- Streamline the supply chain and take a '*factory to foxhole*' perspective to synchronise all logistic efforts with delivering the final output. By applying 'Lean' principles (see below) to the end-to-end supply chain, excess capacity and duplication will be removed or reduced, defined organisational boundaries will be removed, and logistic support will flow more quickly, efficiently and effectively.

In sum, E2E sought to provide operational commanders with the materiel they need, where they need it and when they need it.

3.6.2.4 The Defence Logistics Transformation Programme

On 1 April 2004, the logistics elements of the DLO Change Programme and the End to-End Review were brought together under the Defence Logistics Transformation Programme (DLTP) to form a single coherent programme of logistics change initiatives across Defence. The DLTP soon developed the E2E Study's 3 principles above into 7 of its own:

- **Configure for the 'most likely' operational scenarios** – Formerly, logistics support was geared towards supporting major conflict, whereas modern expeditionary operations, although of a smaller scale, are greater in number, occur at shorter notice and require greater agility.
- **Concentrate resources and materiel** – More efficient and effective equipment support can be achieved if resources and materiel are concentrated at '*logistics centres of gravity*'. For example, in aircraft support, this means striving to put as many depth support activities in depth support Units ideally collocated at aircraft main operating bases thereby eliminating duplication of activity, overhead and infrastructure.
- **Apply the 'Forward/Depth' concept** – The traditional four '*lines*' of maintenance are replaced by the two-level construct known as '*Forward/Depth*'. Closely related to the previous principle, this rationalisation of overcapacity also helps to eliminate duplication of activity and infrastructure.
- **Minimise the 'deployed footprint'** – Today's relatively small-scale expeditionary operations occur at short notice and demand far greater logistics agility. Therefore, force elements must incorporate the smallest possible organic support arrangements fed by efficient and effective support chains.
- **Optimize asset availability** – More effective asset tracking reduces waste, stock holdings and cost and improves operational availability of war-fighting equipment.
- **Rely on an effective joint supply chain** – An effective, efficient and flexible end-to-end supply chain is essential to equipment support.

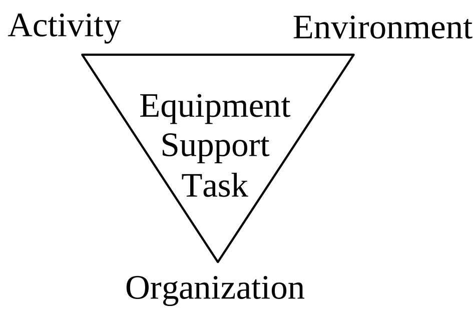
- **Access to timely, relevant and accurate information** – Timely access to relevant and accurate logistics information is another vital enabler to ensuring that logistics support in the military environment operates efficiently and effectively.

3.6.3 The Evolution of Aircraft Support Concepts

3.6.3.1 The Three-Attribute Model of Equipment Support

3.6.3.1.1 Equipment Support Tasks

Defence equipment is employed in operations to generate military effects. By its very nature, such equipment is complex, costly and must be supported during missions, for the duration of each campaign and throughout its useful life. Equipment support comprises a series of tasks each of which may be considered as having three distinct but inter-related attributes: '*activity*'; '*environment*'; and '*organization*', as illustrated below:



The E2E Study recommended that military equipment should be supported under a 2-level regime rather than the traditional 4 lines. This later became known as '*the Forward/Depth construct*' under which each of the attributes above has 2 levels, defined as follows:

- **Activity:**
  - Forward Support Activities (FSAs):
    - Flight servicing[1] (including preventative maintenance and replenishment activities) [37], re-fuelling, re-arming and role changing.
    - Functional testing and adjustment.
    - Minor modification.
    - Fault diagnosis and minor[2] corrective maintenance.
    - Scheduled maintenance.
    - Expedient repair[3] [37].
  - Depth Support Activities (DSA):
    - Scheduled maintenance (including bay maintenance, reconditioning and overhaul).

[1] Maintenance to determine aircraft condition prior to, or following, a period of flying – JAP100A-01 Ch 2.8.

[2] Achievable within notice to move times, for instance.

[3] Rapid repair solutions designed to restore operational capability at potentially reduced airworthiness levels – JAP100A-01 Ch 9.12.

    - Major[4] unscheduled corrective maintenance.
    - Modification and conversion.

- **Environment –** Support tasks can be considered to arise in one of 2 locations or '*environments*', referred to here as '*Forward*' or '*Depth*':

    - **Forward Environment –** Forward support locations will not always be predictable since they will be determined by the operational circumstances prevailing at the time. They will range from the operational elements of Main Operating Bases (MOB) and well-found deployed operating bases (including aviation-capable ships) to austere forward operating bases in the deployment theatre that may well be '*in harm's way*'. Such locations will always be under the command of an operational commander.

    - **Depth Environment –** The location of depth support will always be determined well in advance by the relevant commodity, weapon system or platform DLO Integrated Project Team[5] (IPT), often in partnership with industry, such that it is able to provide the level of support required as cost-effectively as possible.

- **Organization –** There are considered to be 2 *groups* of support organizations:

    - **Forward Support Units –** '*Forward Support Units*' (FSU) will belong to the Front Line Commands (FLC)[6].

    - **Depth Support Units –** Alternatively, IPTs will be responsible for delivering DSAs and so will form '*Depth Support Units*' (DSU) which will primarily deliver their capabilities in the more stable, UK-based depth environment. The sub-set known as '*Deployable Depth*' encompasses those logistic processes and functions that are optimized in peacetime within a DSU on grounds of effectiveness and efficiency and yet need to be configured as deployable to provide responsive DSA support to FSU when required.

3.6.4 Transformation Activities

3.6.4.1 Implementing the Forward/Depth Construct and Rationalising UK Military Aircraft Support

3.6.4.1.1 From Four Lines to Two Levels

Traditionally, four '*lines*' of maintenance have supported UK military aircraft. There were previously defined[7] [37] as follows:

- **First Line** – The maintenance organization immediately responsible for the maintenance and preparation for use of complete systems or equipment. For instance, aircraft squadrons.

- **Second Line** – The maintenance organization responsible for providing maintenance support to specified First Line organizations. For example, workshop facilities at aircraft MOB.

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[4] Not achievable within notice to move times, for instance.

[5] The DLO team charged with providing for the whole-life support of the platform, system or equipment.

[6] In UK military aviation, these are Strike Command, Fleet and the Joint Helicopter Command.

[7] JAP100A-01, Ch 0.4.

- **Third Line** – The maintenance organization within the Services (*sic*), but excluding the organizations within First and Second Line. For instance the MOD's own Defence Aircraft Repair Agency.
- **Fourth Line** – The industrial maintenance organization providing maintenance support to the Services (*sic*) under contract. Defence contractors such as BAE Systems and AgustaWestland, for example.

3.6.4.1.2 Rationalising to the Forward/Depth Construct

Under the Forward/Depth construct, these four '*lines*' have been reduced to two '*levels*'. Over the last 2 years, the DLO, in partnership with Industry and its FLC customers, has been transforming UK military aircraft support to align with the Forward/Depth construct. Since DARA still has significant capacity for airframe Repair and Overhaul (R&O)[8], there have been 2 principal routes to the Forward/Depth construct:

- 'Roll forward' where all DSAs are moved to a single DSU or 'hub'.
- 'Roll back' where all on-aircraft DSAs are moved from former aircraft Second Line facilities at MOB to consolidated facilities within DARA or Industry. This has the result that, in contrast to the roll-forward case, DSA for a given platform's on- and off-aircraft R&O are split. However, DARA Fleetlands, for instance, is able to derive certain economies of scale by effectively being a single on-aircraft R&O 'hub' for a total of 3 helicopter types[9].

3.6.4.1.3 Examples of Rationalisation under the Forward/Depth Construct

Roll forward examples include the following:

- A Tornado DSU hub has been formed at RAF Marham supporting all RAF Tornados.
- A Harrier DSU hub has been formed at RAF Cottesmore supporting all RAF and RN Harriers.
- The UK's Merlin helicopter fleet is supported from a DSU hub at RNAS Culdrose.
- All the UK's Puma helicopters are being supported by a DSU hub at RAF Benson.
- The UK's fleet of Gazelle helicopters is supported from a DSU hub at the British Army's Middle Wallop Station.
- A DSU hub for the UK Apache Attack Helicopter is being formed at the Army's Wattisham Station.

'Roll back' examples include the following:

- All on-aircraft R&O for the UK's Chinook, Lynx and Sea King helicopters is carried out at DARA Fleetlands with off-aircraft R&O activities taking place on MOB, in industry and at the DARA Electronics facility at Sealand.
- VC10 on-aircraft R&O work is now centralised at DARA St. Athan.
- All on-aircraft R&O work for the Hercules fleet is now conducted at Marshall Aerospace at Cambridge.

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[8] This is known as 'on-aircraft' activity as opposed to aircraft component repair and overhaul which is known as 'off-aircraft' activity.

[9] Chinook, Lynx and Sea King.

3.6.4.2 The Application of Lean Techniques

The ideas behind what is now termed '*lean thinking*' were originally developed in Toyota's manufacturing operations (where the company established the '*Toyota Production System*') and spread through its supply base in the 1970s. The term '*lean*' stems from the fact that Japanese business methods used less of everything: human resources; capital investment; facilities; spares; consumables; and time. In their book 'Lean Thinking' [38], James Womack and Daniel Jones proposed the following lean transformation process:

- Identify all the steps in the chain of events (or 'value stream') for each customer output.
- Whenever possible, eliminate those steps that do not add value (that is, eliminate 'waste').
- Ensure that the value-adding steps flow smoothly.
- Each successive step should trigger those that supply it with '*pull*' signals.

Lean tools have been used extensively over the last 3 years at every level within UK military aircraft support. Experience has shown that the tools and techniques have been particularly successful in driving out waste in the workshop and hangar environments. For example, all the various on-aircraft DSU have used Lean to establish so-called '*pulse*'[10] lines to replace the traditional bay approach to airframe R&O. As a result, the numbers of aircraft undergoing such work and the total time each spends being worked on have been reduced. The next section provides some more quantitative examples.

3.6.4.3 Partnering with Industry

In the UK, the MOD and the defence industrial base have recognised the mutual importance of working in close collaboration. The resulting strategy of '*partnering*' places very strong emphasis on developing an effective and co-operative working environment between the two parties, based on better transparency, increased openness and mutual respect. This represents an important culture change which is non-adversarial and through which both parties co-operate in meeting their respective aims.

The following lists some key tenets of the partnering approach:

- Joint planning and decision making in both programmes and finance.
- Information sharing.
- Joint risk and performance management.
- Joint continuous improvement of the delivery of products, services and capabilities.

It is considered that partnering with Industry will produce the following benefits:

- Improved speed of delivery of programmes.
- Reduced acquisition and support costs.
- Increased availability of aircraft to the front line.
- The retention and sustainment of the skills necessary to provide onshore military aircraft design authority, systems engineering and through-life support capabilities.

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[10] Lean manufacturing production lines flow continuously whereas, in the aircraft maintenance world, the best that can be achieved is a regular pulse between successive maintenance phases.

- Enhanced confidence and deeper mutual understanding.
- More assured revenue streams for Industry based on long-term support and ongoing development activities rather than a series of large new equipment procurements.

3.6.4.4 Contracting for Availability

3.6.4.4.1 The DLO's Transformation Staircase

Since shortly after its formation, the DLO has been transforming the support arrangements for its various defence platforms, systems and equipments in such a way that more of the risks are transferred to Industry. The so-called 'transformation staircase' illustrates successive steps in moving away from traditional support arrangements, where the DLO pays Industry to repair items and supplies it with the piece part spares to do so, ultimately to those where the UK MOD pays Industry to provide specified levels of military capability.

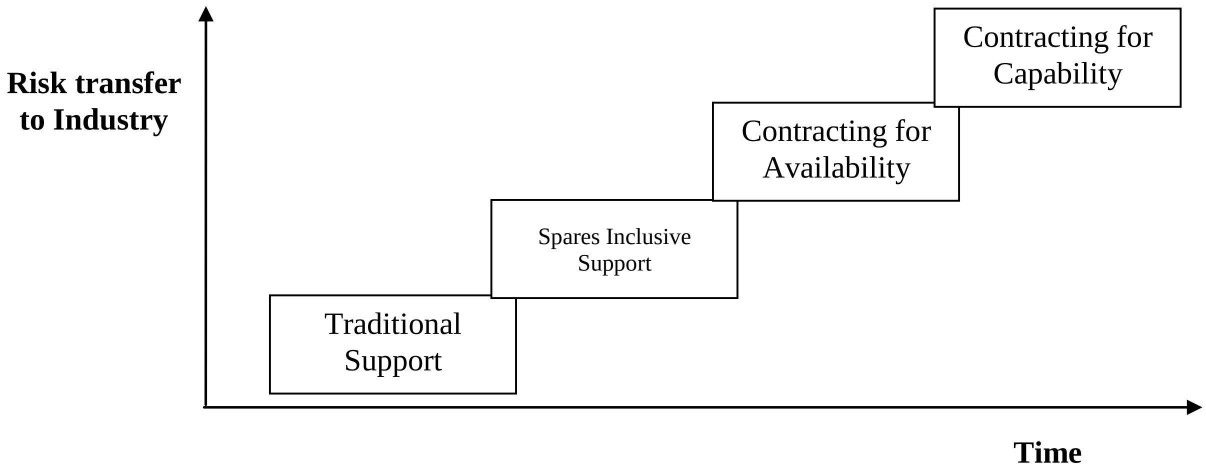


Figure 3-35: The DLO's Transformation Staircase.

- **Spares Inclusive Support** – Here, Industry is paid a fee to repair equipment, but it must source its own piece part spares and consumables.
- **Contracting for Availability (CfA)** – Under CfA arrangements, Industry's payment is linked directly to quantitative measures of the provision of a platform or equipment's availability for use. Such requirements are expressed in output terms which should be directly related to (and flow from) the relevant Customer/Supplier Agreement (CSA) that the DLO has with the FLC.
- **Contracting for Capability (CfC)** – CfA Key Performance Indicators (KPI) are measures of platform or equipment availability. Ultimately, however, the DLO is aiming to contract with Industry against measures of capability. One example is where the UK MOD pays for air-to-air refuelling capability and allows its contractor to benefit from aircraft not required by the RAF in peacetime by generating revenue through commercial use.

3.6.5 Aircraft Support Transformation Examples

3.6.5.1 Examples of Lean Transformation

3.6.5.1.1 Tornado Depth Support

Support for the RAF's Tornado fleet has been rationalised with the adoption of the Forward/Depth construct and the formation of a single DSU '*hub*' for the vast majority of Tornado DSA at RAF Marham, one of the RAF's largest Tornado MOB. Lean tools have been used extensively in establishing '*pulse lines*' at Marham including Combined Maintenance and Upgrade (CMU) work to the airframes and significant engine, hydraulic and avionic DSAs.

Expected benefits are listed as follows:

- A 50% reduction in operating costs per flying hour over 5 years.
- A £321 m (50%) reduction in the aircraft's support budget.
- The number of aircraft undergoing DSAs at any one time will be reduced from 22 to 16 by 2008.
- Approximately 500 fewer personnel will be required for Tornado GR4 support.

3.6.5.1.2 Tornado Forward Support

At RAF Lossiemouth, Lean tools have been used to improve many aspects of the way squadrons support their aircraft. For instance, a consolidated team of personnel has been formed to undertake FSA rectification work far more efficiently and dispersed operation of aircraft from hardened aircraft shelters has been ceased.

3.6.5.1.3 Harrier Depth Support

Support for the Harrier fleet has also been rationalised with the adoption of the Forward/Depth construct and the formation of a single MOB-based, Harrier DSU '*hub*' at RAF Cottesmore. Again, Lean tools have been used to establish on- and off-aircraft '*pulse lines*', and the CMU approach has also been adopted.

Expected benefits are listed as follows:

- A £4 m reduction in the aircraft's support budget over 4 years.
- The number of aircraft undergoing DSAs at any one time has been reduced from 9 to 6.
- The adoption of an on-aircraft pulse-line has reduced Harrier GR7 turn-round times from 120 days to 80 days.
- Approximately 310 fewer personnel will be required for Harrier support.

3.6.6 Next Steps

3.6.6.1 The Defence Industrial Strategy

Published in June 2006, the UK MOD's Defence Industrial Strategy (DIS) [39] recognised the important contribution that the UK's defence industry makes to delivering military capability and challenged the whole of the defence acquisition community, within both the MOD and Industry, to improve performance in the delivery of capability to the front line whilst increasing value for money. The DIS recognised that, with today's increasing emphasis on agility, the concept of Through Life Capability Management would need to be adopted in order to ensure that military capability is built from the most cost-effective mix of components and is both affordable to operate through life and readily adaptable.

3.6.6.2 Through Life Capability Management

The traditional approach to defence equipment procurement has been to design and manufacture successive generations of platforms (or at least to fund major upgrade packages) each with step changes in capability. The concept of Through Life Capability Management (TLCM) centres on support, sustainability and the incremental enhancement of existing capabilities from technology insertions. In TLCM, the emphasis will be on developing the systems engineering competencies necessary to facilitate gradual capability evolution. For its part, Industry will benefit by having longer, more assured revenue streams based on long-term support and ongoing development rather than a series of large new equipment procurements.

3.6.6.3 Enabling Acquisition Change

The Enabling Acquisition Change (EAC) Report [40] was commissioned to advise what changes should be made to the UK MOD's organisational structures, processes and behaviours in order to achieve the goals of TLCM. Whilst recognising that the UK's track record in delivering for its Armed Forces highly capable, battle-winning equipment within available resources was excellent, the report also observed that the UK MOD's acquisition system has a history of suffering from what it called '… *a conspiracy of optimism* …': targets and incentives are often poorly aligned; behaviour is stove-piped; and boundaries between organisations make the achievement of a through life approach difficult.

The report made a significant number of recommendations including the following:

- The establishment of an integrated procurement and support organisation by merging the UK MOD's Defence Procurement Agency and the Defence Logistics Organization to be led at 4-star level, or equivalent. It has recently been announced that the new organization is to be known as '*Defence Equipment and Support*' lead by the '*Chief of Defence Materiel*'.
- The reinforcement of the notion of through life delivery by setting targets for the delivery of a defined level of project performance and its cost effective sustainment through life.

3.7 CANADA

The Canadian national perspective was provided by Beland and Hollick in Paper 3.1. The information in their paper has been used in Chapters 4 and 5. The following additional notes on maintenance/support in the Canadian Forces were prepared by the AVT-144 Technical Team.

In Canada, the Army, Navy, and Air Force were unified in the late 1960s, and so any benefits associated with integrated logistics systems have presumably been realized. The benefits of RCM were recognized some time ago, and all Canadian Forces aircraft are now maintained using schedules developed using MSG-3 maintenance analysis, which is discussed in Chapter 5. Aircraft structure is also subject to maintenance policy defined by a standard Aircraft Structural Integrity Program (ASIP) comparable to the USAF program set out in Mil-Std-1530. Failure management policy for structure also draws on the experience of the UK and Australia.

The Canadian Forces have been among the pioneers of risk analysis and damage tolerance analysis in engines. Significant savings have been realized on the T-56 engine that powers the CP140 (P-3) and C-130 fleets, and more are forecast as a result of this investment.

There is strong interest in improving methods of partnering and contracting with industry for aircraft support. In this regard, Canada's efforts are comparable with those of other NATO countries. Difficulties have been experienced in applying performance-based contracts to existing programs, but the concept of availability-based contracting has been fully embraced in Canada's new Maritime Helicopter Program (MHP). In this program, twenty-eight CH148 Cyclone helicopters, which are based on the S-92, have been ordered from Sikorsky to replace the current Sea King fleet. An account of the availability-based contracting used for the acquisition and support of the CH148 Cyclone maritime helicopters is given as a case study in Chapter 5. The way that availability metrics will be used to manage these contracts is described in Chapter 3.

Several other major aircraft acquisitions are in process for the Canadian Forces. The Boeing C-17 has been selected to provide strategic airlift. Probably four C-17 will be purchased. An advance contract is in place to procure 15 Boeing Chinooks to meet a new requirement for a medium lift helicopter. A major portion of the current Hercules fleet will be replaced with Lockheed Martin C-130J aircraft. Finally, a replacement is being sought for the Buffalo in the fixed wing Search And Rescue (SAR) role.

Performance-based contracting is just one aspect of an Optimised Weapon System Management (OWSM) process currently being introduced by the Canadian Forces. This process is being developed and implemented by the Assistant Deputy Minister (Materiel) (ADM(Mat)), which is an organisation that integrates all materiel life-cycle management for all three Services.

The element of ADM(Mat) that deals with aircraft is the Aerospace Equipment Project Management (AEPM) Division. As well as providing project management of new and existing fleets, this organisation also provides a central focus on aircraft availability, comparable to that provided by SIMMAD in the French Air Force. It also contains an independent military airworthiness authority that does not share staff with the project management and engineering authorities for each aircraft type. Through policy and audits, this Directorate of Technical Airworthiness has considerable influence and control over the content of maintenance documents.

3.8 UNITED STATES OF AMERICA

A national perspective from the USA was not presented at the Workshop. However, considerable information on the development of acquisition and maintenance/support concepts in the US DoD and the Services is available from public sources. Some of this information is included elsewhere in this report. The following brief comments were prepared by the AVT-144 Technical Team.

In the USA, the Office of the Deputy Under Secretary of State for Logistics and Material Readiness provides a strong focus on readiness through its Material Readiness and Maintenance Policy and associated education and publicity. An overview of US managerial and technological initiatives in the areas of material readiness and maintenance can be obtained via Internet site www.acq.osd.mil/log/mppr. There are also high-level departments in the various services dealing specifically with readiness. In addition, there are other high level departments dealing with related issues such as corrosion and aging equipment.

The key measures of aircraft availability currently include the percentage of time that an aircraft can perform at least one or all of its assigned missions, termed the "Mission Capable" (MC) rate and "Full Mission Capable" (FMC) rates, respectively. Statistics on availability tend to be expressed as the percentage of the fleet meeting MC or FMC goals, and/or as the average MC and FMC rates for a fleet or organization. The MC and FMC measures are not being used on the F-35 Joint Strike Fighter (JSF). Examples of availability statistics and targets for US Department of Defence (DoD) aircraft were given in Chapter 2.

The US Navy has been closely involved with the development of Reliability Centred Maintenance (RCM) for aircraft in collaboration with the US-European Maintenance Steering Group (MSG). Most US Navy aircraft have undergone RCM analysis.

The design, manufacturing, and maintenance/support organisations for US military aircraft have undergone “Lean” analysis. A cooperative effort in this regard was set up in 1992 under the “Lean Aircraft Initiative”. This lean program addresses availability as well as cost. Dramatic reductions in cost and cycle times for depot maintenance have been achieved. For example, the average time to overhaul C-5 transport aircraft at the Warner Robins Air Logistics Center has been reduced from 339 days to 160 days. The average time to overhaul KC-135 tanker aircraft at Oklahoma City Air Logistics Center has been reduced from 380 days to 205 days.

Alternative, performance-based contracting methods are being tried out, in which the contractor – usually the OEM – assumes responsibility for all depot maintenance and maintenance logistics and for providing the required aircraft availability.

The US Congress maintains a close interest in the availability of military equipment through its sub-committee on Readiness, and has sponsored major studies by the General Accounting Office (GAO) on issues related to aircraft availability. As mentioned in Chapter 2, several of these reports have described difficulties experienced by the US Armed Forces in meeting MC goals. The causes have been a combination of interrelated logistical and operational factors, with no dominating single problem. The GAO has also identified a need for a review of availability goals and associated metrics for aircraft.

Chapter 4 – METRICS, MODELLING, AND KEY PERFORMANCE INDICATORS OF AIRCRAFT AVAILABILITY

4.1 INTRODUCTION

Availability and its relationship to military capability, readiness, and effectiveness was defined and explained in Chapter 2. Since aircraft availability is a key measure of force readiness and effectiveness, lower formations are required to report their availability routinely to higher formations. When availability is reported in this manner, it is usually stated as the number of aircraft that are immediately available and the number that can be recovered within a specified time frame. These reports also include a statement of the number of aircraft that are not available and why. A limited set of standard metrics are usually used for this purpose.

When availability is used as a performance parameter, it is usually expressed as a probability (i.e. a stochastic variable) or equivalent metric. In this form, availability can be included as a parameter in models of force effectiveness and readiness, aircraft in-service support, aircraft life-cycle cost, and so on. Such models allow the relationship between aircraft availability and other parameters of interest to be studied in different contexts, so that well-informed trade-offs can be made during the design and management of the aircraft and its in-service support system and during the planning of operations.

This chapter first examines the metrics and key drivers of aircraft availability. It then outlines some advanced models of aircraft availability, including the results of some case studies. The chapter concludes with a detailed case study in the application of metrics and models to availability-based contracts for aircraft acquisition and support.

4.2 METRICS OF AIRCRAFT AVAILABILITY/READINESS

To distinguish between inherent availability and availability in an operation situation, where maintenance may be delayed for lack of resources or for administrative reasons, the term "operational availability" is sometimes used. The definition of operational availability A_O in MOD UK's R&M terminology [41] is given in metric form as follows:

> "The proportion of the defined operational period during which the equipment is available for use without any performance limitations.
>
> i.e. A_o = uptime measured over an operational period / (uptime + downtime)
>
> Operational availability may be expressed by the formula:
>
> $A_o = (OT + ST)/(OT + ST + TPM + TCM + ALDT)$
>
> where: OT = operating time; ST = standby time; TPM = total preventative maintenance time; TCM = total corrective maintenance time; ALDT = administration and logistics delay time spent waiting for parts, maintenance personnel or transportation."

In Paper 1.5, Andela gives several definitions based on mathematical formulae that are used by the Royal Netherlands Air Force (RNLAF):

- Inherent availability (A_i): $$A_i = \frac{MTBF}{MTTR + MTBF}$$

- Operational Availability (A_o): $$A_o = \frac{MTBMA}{MTBMA + MMT + MLDT}$$

  This definition of A_o is mathematically equivalent to the MOD UK one given above.

- Scheduled availability (A_s) is defined as the portion of time, in which a weapon system fulfils the needed function:

  $$A_s = \frac{FMC + PMC}{FMC + PMC + NMC_{scheduled}}$$

  In this definition only scheduled maintenance is 'planned'. A precondition is that unscheduled maintenance is not calculated. The availability is calculated only to take into account preventive maintenance action.

- Unscheduled Availability (A_u) is defined as the portion of time that a weapon system fulfils the required function, assuming there is no scheduled maintenance:

  $$A_u = \frac{FMC + PMC}{FMC + PMC + NMC_{unscheduled}}$$

Legend:
MTBF= Mean Time Between Failure
MTTR= Mean Time To Repair
MTBMA= Mean Time Between Maintenance Actions
MMT= Mean Maintenance Time
MLDT= Mean Logistic Delay Time
FMC= Full Mission Capable
PMC= Partly Mission Capable
NMC= Not Mission Capable due to scheduled maintenance

The two definitions that refer to "operational availability" and use the abbreviation A_0 describe the fraction of total time that an aircraft is available for operational use without limitations. They embrace all parameters that might affect average availability. The other definitions of availability ignore one or more time periods included in the "operational availability" A_0. They have value in specific contexts.

In this report, the broadest definition of average availability is generally implied, i.e. "operational availability" A_0. The two fundamental metrics of availability so defined are the time the aircraft is available and the time it is unavailable. Thus, our task is to identify the parameters that govern the lengths of these two periods. For this purpose, these two periods can be divided into smaller periods, each of which is governed by its own set of parameters. For modelling purposes, these parameters must in turn be definable, individually or collectively, by a metric.

The various formulae above already illustrate different ways of dividing the period of unavailability, also known as "downtime", into smaller periods. The choice of sub-division depends on the purpose of the exercise. For example, in Paper 3.1, Andresen gives a breakdown of periods used in the System Health Operational Analysis Model (SHOAM) designed by the Boeing Company's Integrated Vehicle Health Management (IVHM) Center (Figure 4-1).

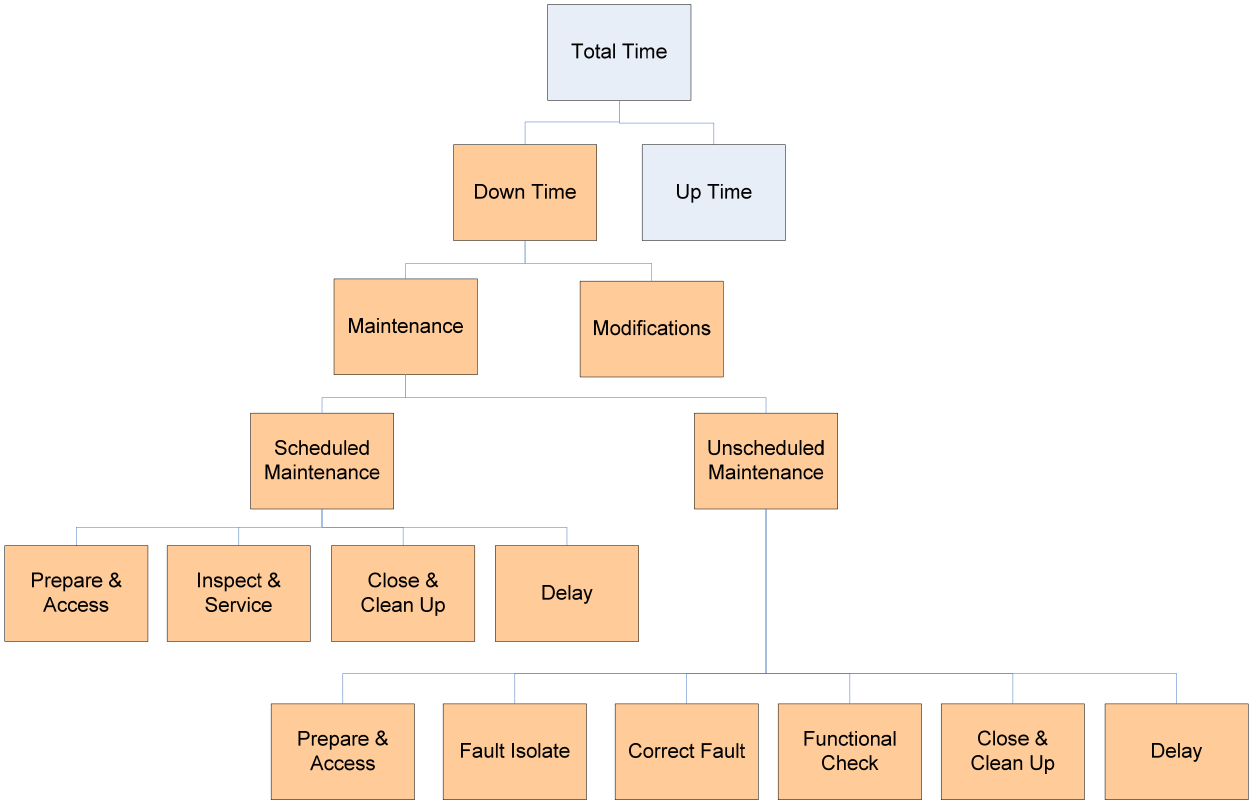


Figure 4-1: Sub-Division of Aircraft Downtime Used in Boeing IVHM Center's SHOAM Model.

Some of the downtime metrics used by the USAF, which are plotted in graphs later in this chapter, are presented by Hart in Supplementary Paper #3 as follows:

- The fraction of total time that an aircraft at an operating unit is unavailable is referred to as the "non-mission-capable rate", which is abbreviated to NMC. The Mission Capable (MC) rate is defined as MC = 1 – NMC.

- NMC, a measurement of field-level scheduled and unscheduled maintenance and supply issues, is sub-divided into:

  - NMC = NMCM + NMCS + NMCB.
  - NMCM = NMCMS + NMCMU + NMCMSA + NMCMUA.
  - NMCS = NMCS + NMCSA.
  - NMCB = NMCBS + NMCBU + NMCBSA + NMCBUA.
  - Thus, NMC = NMCMS + NMCMU + NMCMSA + NMCMUA + NMCS + NMCSA + NMCBS + NMCBU + NMCBSA + NMCBUA.

- These various NMC categories are defined as follows:

  - NMCMS: Not Mission Capable Maintenance Scheduled – The aircraft cannot do any assigned missions because of scheduled maintenance. The aircraft cannot fly (restricted from use).

- NMCMU: Not Mission Capable Maintenance Unscheduled – The aircraft cannot do any assigned missions because of unscheduled maintenance. The aircraft cannot fly (restricted from use).
- NMCMSA: Not Mission Capable Maintenance Scheduled Airworthy – The aircraft cannot do any assigned missions because of scheduled maintenance. The aircraft can fly (not restricted from use).
- NMCMUA: Not Mission Capable Maintenance Unscheduled Airworthy – The aircraft cannot do any assigned missions because of unscheduled maintenance. The aircraft can fly (not restricted from use).
- NMCS: Not Mission Capable Supply – The aircraft cannot do any assigned missions because of supply. The aircraft cannot fly (restricted from use).
- NMCSA: Not Mission Capable Supply Airworthy – The aircraft cannot do any assigned missions because of supply. The aircraft can fly (not restricted from use).
- NMCBS: Not Mission Capable Both Maintenance and Supply Scheduled – The aircraft cannot do any assigned missions because of supply and scheduled maintenance. The aircraft cannot fly (restricted from use).
- NMCBU: Not Mission Capable Both Maintenance and Supply Unscheduled – The aircraft cannot do any assigned missions because of supply and unscheduled maintenance. The aircraft cannot fly (restricted from use).
- NMCBSA: Not Mission Capable Both Maintenance and Supply Scheduled Airworthy – The aircraft cannot do any assigned missions because of supply and scheduled maintenance. The aircraft can fly (not restricted from use).
- NMCBUA: Not Mission Capable Both Maintenance and Supply Unscheduled Airworthy – The aircraft cannot do any assigned missions because of supply and unscheduled maintenance. The aircraft can fly (not restricted from use).

In the USAF and some other NATO Air Forces, assessments of aircraft availability usually refer only to the portion of a fleet that has been assigned to active duty, i.e. to operating bases. A full explanation of USAF status reporting and maintenance codes can be found in [42] and [43].

As mentioned in Chapter 2, The US Navy is reportedly moving away from the MC and FMC goals in newer aircraft, such as the Joint Strike Fighter. This is because the average availability metrics currently used in targets and status reports (MC and FMC) provide only a limited historical perspective and do not address issues that are important to war-fighting commanders such as how often an aircraft can fly missions over the course of a day and the probability that the aircraft will complete its mission.

4.3 DRIVERS OF AIRCRAFT DOWNTIME

4.3.1 Boeing Analysis of the Downtime of a Long Range Transport Aircraft

Andresen provides some statistics for the actual downtime due to scheduled and unscheduled maintenance of a fleet of long range transport aircraft in the United States Air Force (Figure 4-2 and Figure 4-3).

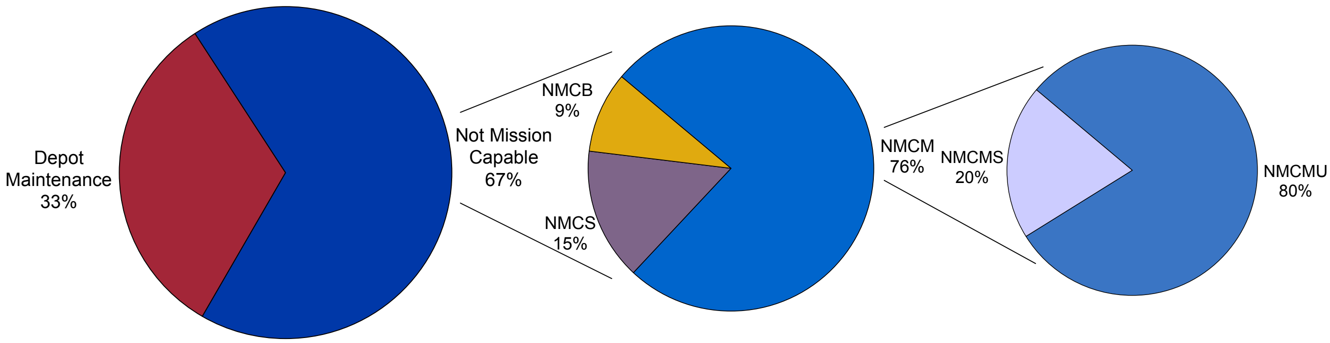


Figure 4-2: Long Range Transport Aircraft Downtime Distributions.

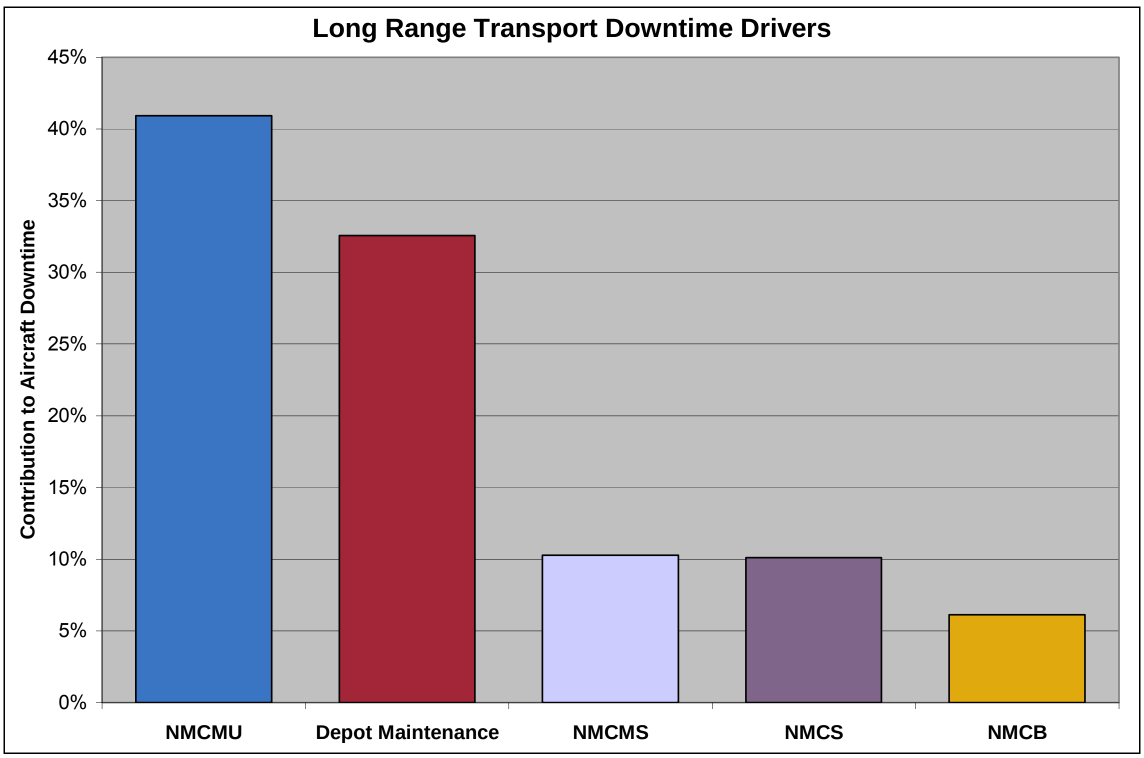


Figure 4-3: Long Range Transport Aircraft Downtime Drivers.

The charts show that 33% of total downtime is due to maintenance at depots, which is presumed to be mostly scheduled preventive maintenance. The remaining 67% of total downtime occurs at operating units. This portion of total downtime is categorised as Not Mission Capable (NMC) time. It attributed in the maintenance records to maintenance tasks (NMCM, 76% of NMC), supply only (NMCS, 15% of NMC), and both maintenance tasks and supply (NMCB, 9% of NMC). The unit level maintenance statistic (NMCM) is further sub-divided according to whether the maintenance is unscheduled (U, 80% of NMCM) or scheduled (S, 20% of NMCM).

It can be inferred from the charts that scheduled and unscheduled maintenance tasks each account for approximately 40% of total downtime due to all causes. When the aircraft are at operating units, unscheduled maintenance tasks are by far the largest contributor to aircraft downtime. Nevertheless, supply delays and scheduled maintenance tasks also have a significant impact.

4.3.2 USAF Analysis of Key Drivers of Availability

In Supplementary Paper #3 Hart provides statistical data for the C-5 aircraft that could be used to identify key drivers of aircraft availability and to validate models. Nine graphs from his paper indicating the trends in aircraft downtime over a period of 15 years from 1991 to 2006 and the main drivers by system are reproduced below.

Firstly, Figure 4-4 and Figure 4-5 show that during the (fiscal year) period 1991 – 2006, C-5 aircraft at operating units were unavailable (NMC) for on average 37% of the time. AMC's NMC target is 25% [44]. The downtime increased from a low of 29% in 1991 to a high of 44% in 2006. This represents an average loss of almost 1% per year in aircraft availability over a period of 15 years. The statistics on downtime drivers in the figures require some careful interpretation, but it seems that almost all of the downtime at operating bases was attributed to maintenance tasks and supply. The data indicate that average annual downtime due to supply delays alone varied between 5% and 10% during the period. This is a large portion of the total downtime. Unscheduled maintenance tasks and related supply delays accounted for significantly more downtime than scheduled maintenance tasks and related supply delays. Moreover, the contribution of unscheduled maintenance tasks rose by about 10% from 1991 to 2006, while the contribution of scheduled maintenance tasks remained relatively flat.

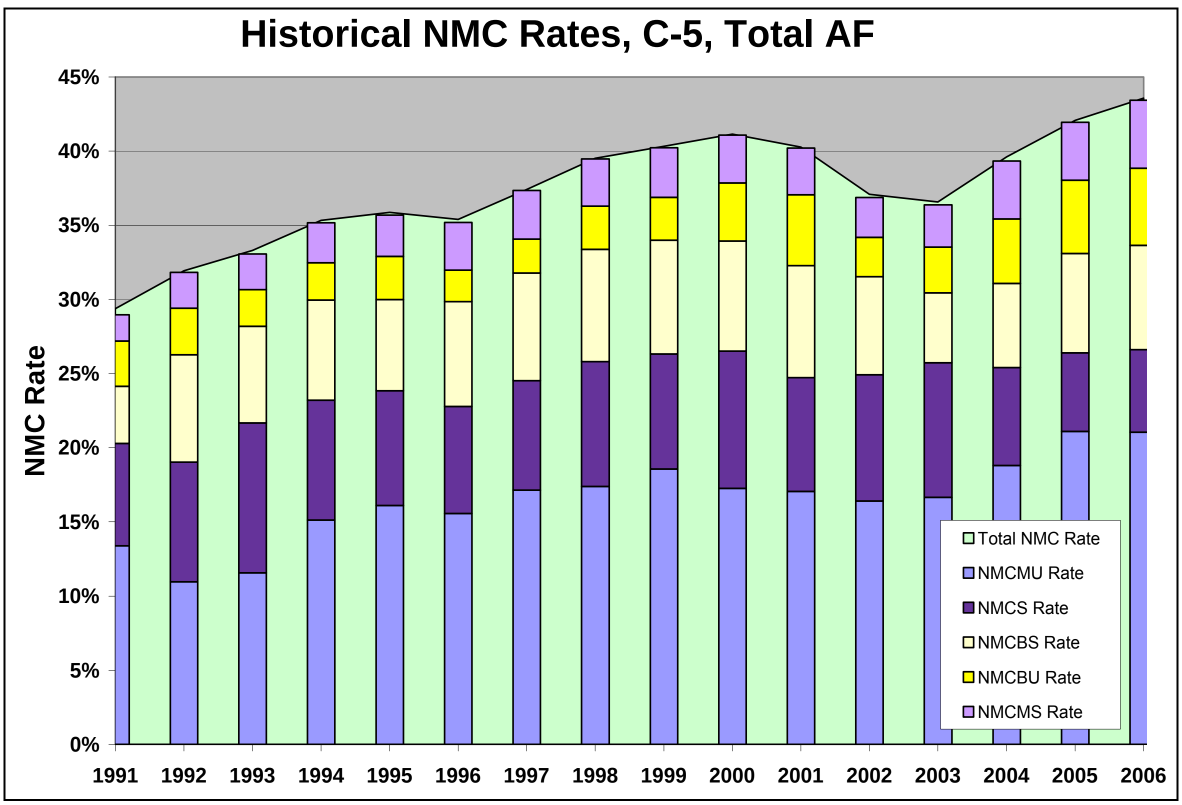


Figure 4-4: Relative Contributions of Scheduled and Unscheduled Maintenance Tasks and Supply Delays to the Downtime of C-5 Aircraft at Operating Units.

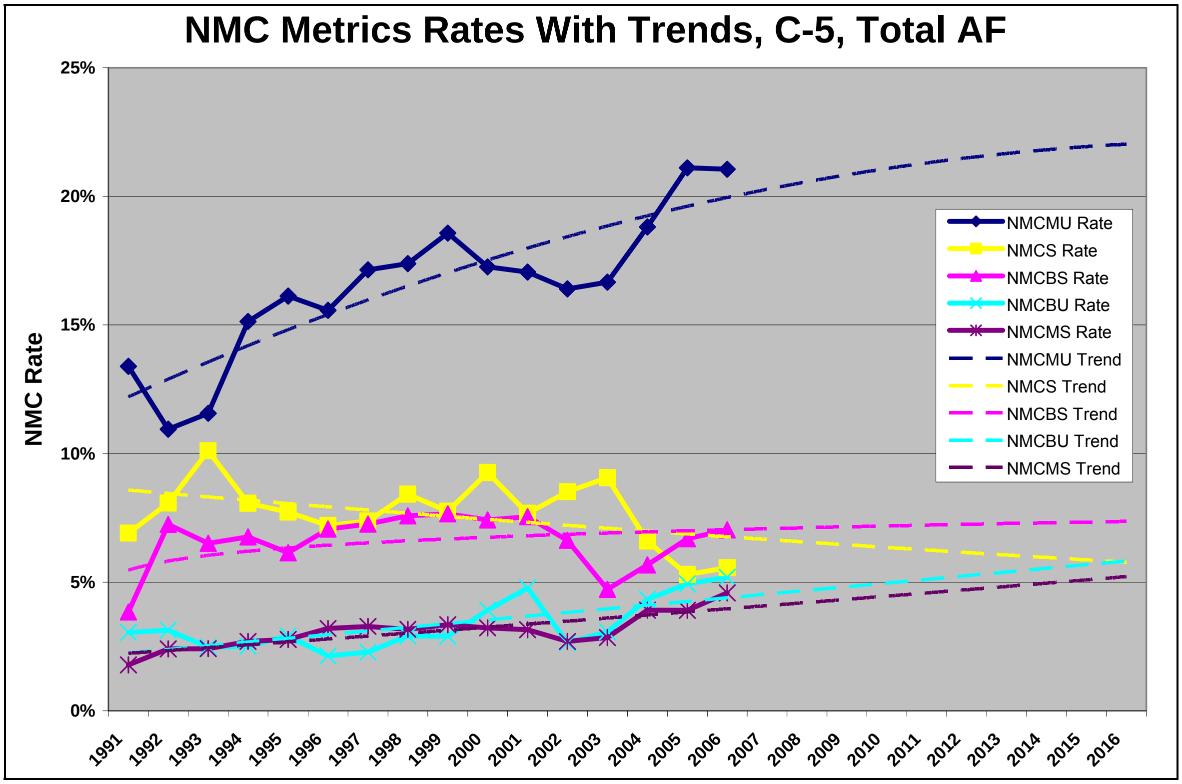


Figure 4-5: Trends in the Contributions of Scheduled and Unscheduled Maintenance Tasks and Supply Delays to the Downtime of C-5 Aircraft at Operating Units.

Secondly, Figure 4-6 and Figure 4-7 show the contribution of various systems on the aircraft to downtime, based on an analysis of two-digit Work Unit Codes (WUC) in maintenance data records. The systems shown in the graphs account for most of the total downtime at operating bases. As stated before, this downtime varied from 29% in 1991 to 44% in 2006. Downtime due to scheduled inspections varied between 5% and 12% during this period. Other maintenance work, probably mostly unscheduled, accounted for the remaining downtime (24% to 32%). Engines, landing gear, airframe, and flight controls were the most significant systems, each consistently accounting for roughly 5% throughout 1991 – 2006. Other systems were less significant. Interestingly, the proportion of downtime due to scheduled inspections increased from 5% to 12% from 1991 to 1996, and gradually returned to 5% over the next 10 years. Other maintenance work was less variable, but there was a slight overall increase in downtime for airframe, engines, and flight controls over the 15-year period. The graphs do not break out the inspection downtime by system.

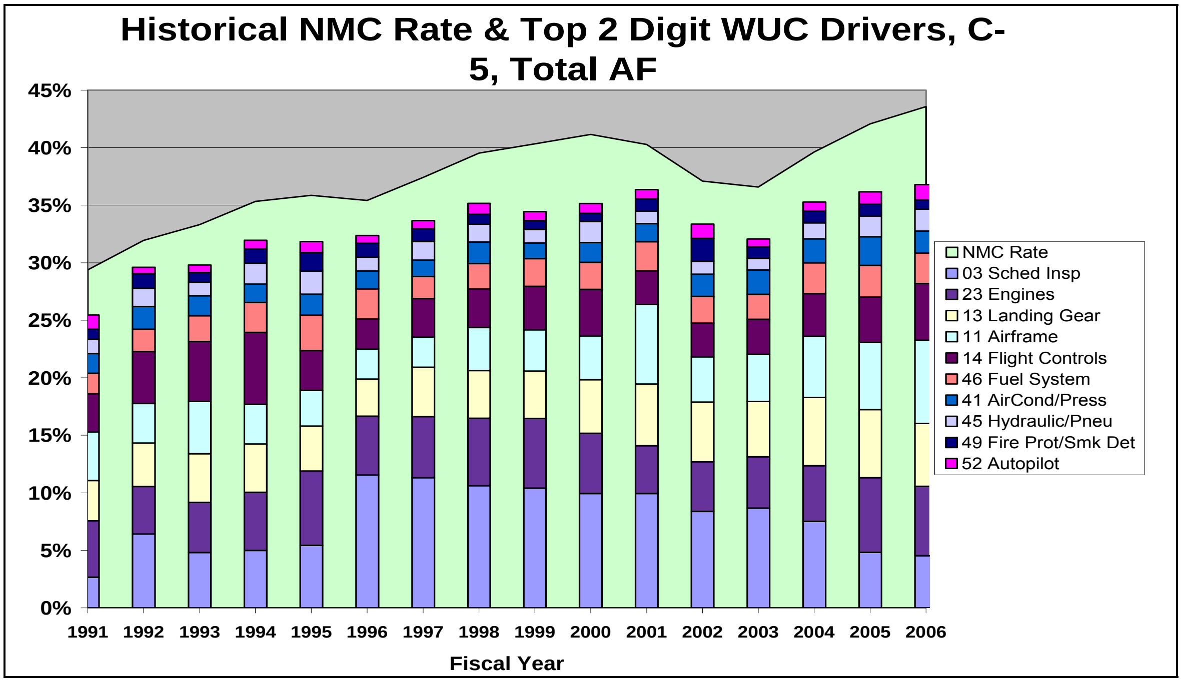


Figure 4-6: Relative Contributions of Airframe, Engines, and Systems to the Downtime of C-5 Aircraft at Operating Units.

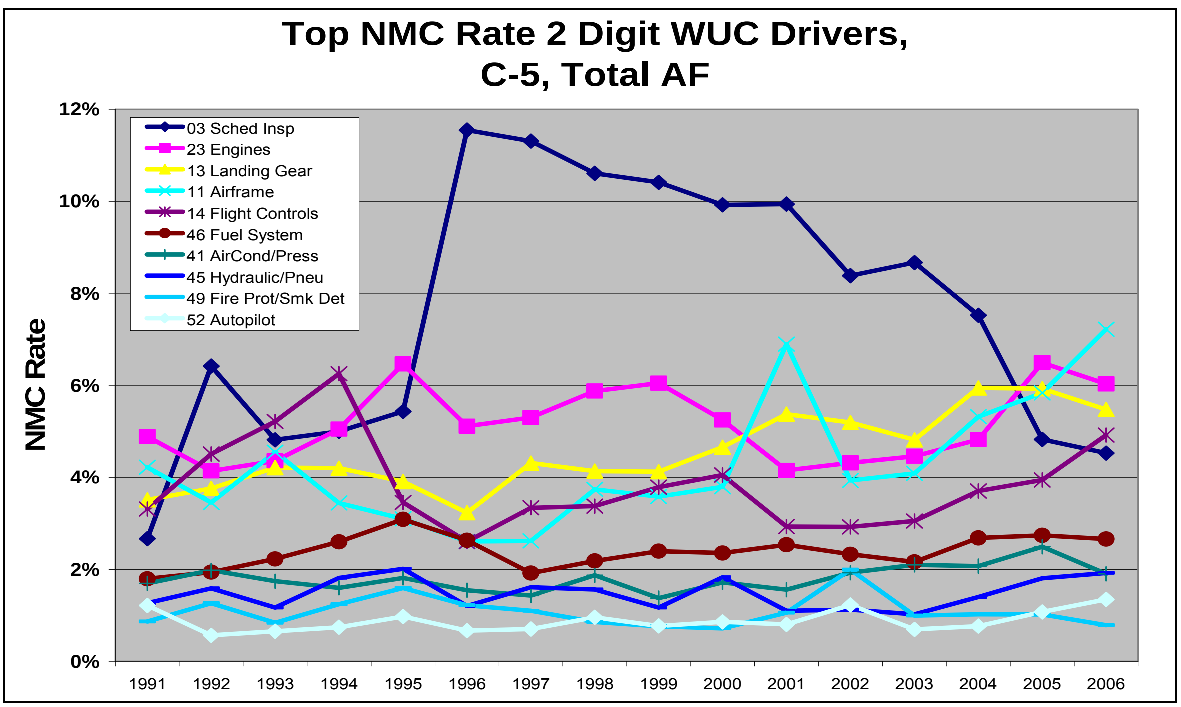
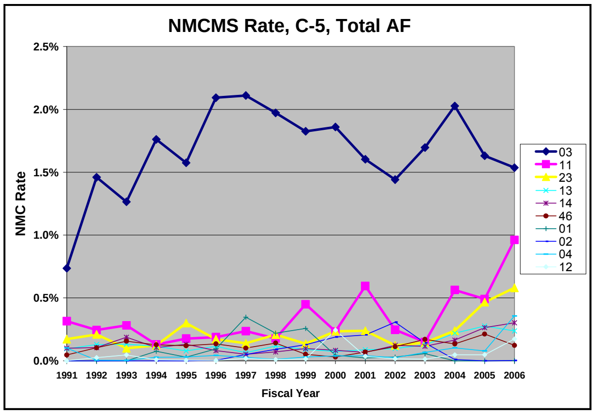
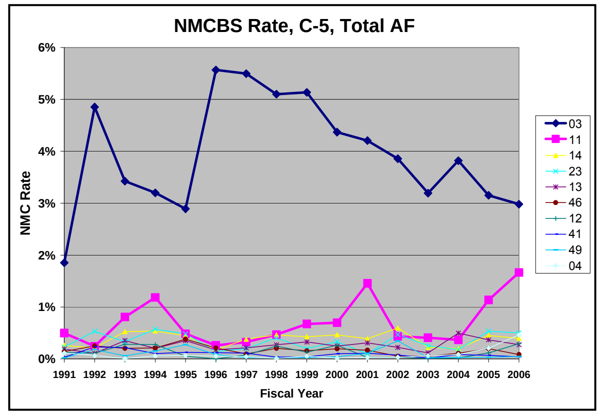


Figure 4-7: Trends in the Contributions of Airframe, Engines, and Systems to the Downtime of C-5 Aircraft at Operating Units.

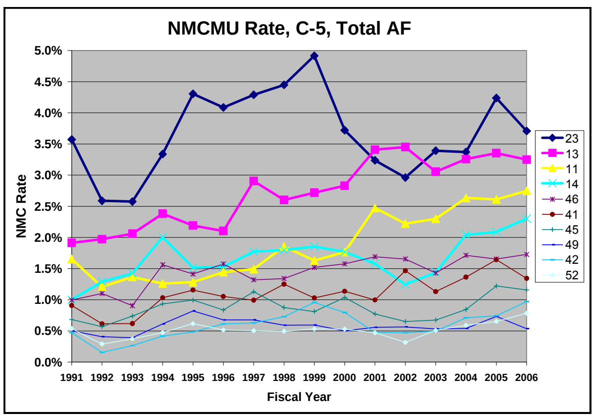
Finally, the five graphs in Figure 4-8 a) to e) provide some additional breakdown of the downtime associated with each system mentioned previously. Graphs a) and b) show that inspections (code 03) accounted for most of the downtime for scheduled maintenance. As before, the graphs do not break out the inspection downtime by system. Graphs b) and c) show that engines, landing gear, airframe, and flight controls, in that order, dominated unscheduled maintenance, but that the downtime due to other systems was also significant. Graph e) indicates that supply delays in all systems directly impacted downtime to a measureable extent. They were particularly significant in flight controls and landing gear.



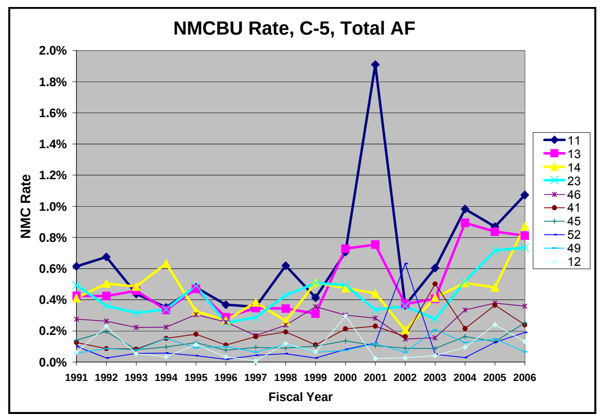
a) Scheduled maintenance



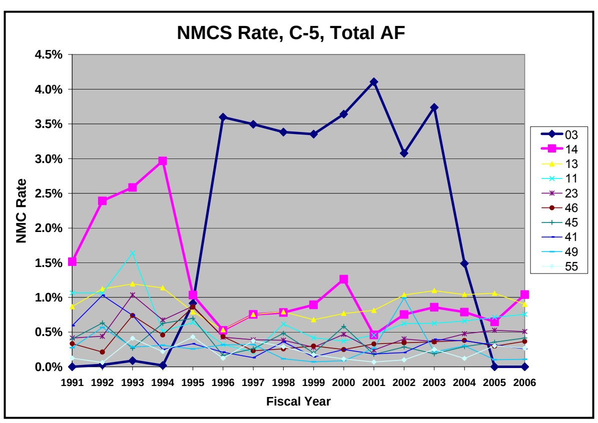
b) Both scheduled maintenance and supply



c) Unscheduled maintenance



d) Both unscheduled maintenance and supply



e) Supply only

Numerical Codes in Graphs

These are the same as standard USAF Work Unit Codes (WUC) for the systems in question.

03 – scheduled inspection
11 – airframe
13 – landing gear
14 – flight controls
23 – engines
41 – air conditioning
45 – hydraulic/pneumatic
46 – fuel system
49 – fire protection / smoke detection
52 – autopilot

Note that colour codes vary between graphs

Figure 4-8: Maintenance and Supply Downtime for Various Systems on USAF C-5 at Operating Units.

4.4 MODELLING OF AIRCRAFT AVAILABILITY/UNAVAILABILITY

4.4.1 Simple Parametric Model

In Supplementary Paper #4 Hurst describes a simple parametric model that is used by the Canadian Air Force to examine the effect on operational availability A_O of changes in the maintenance/support system.

The division of time used by the Canadian Air Force for measurements of operational availability is given in Figure 4-9.

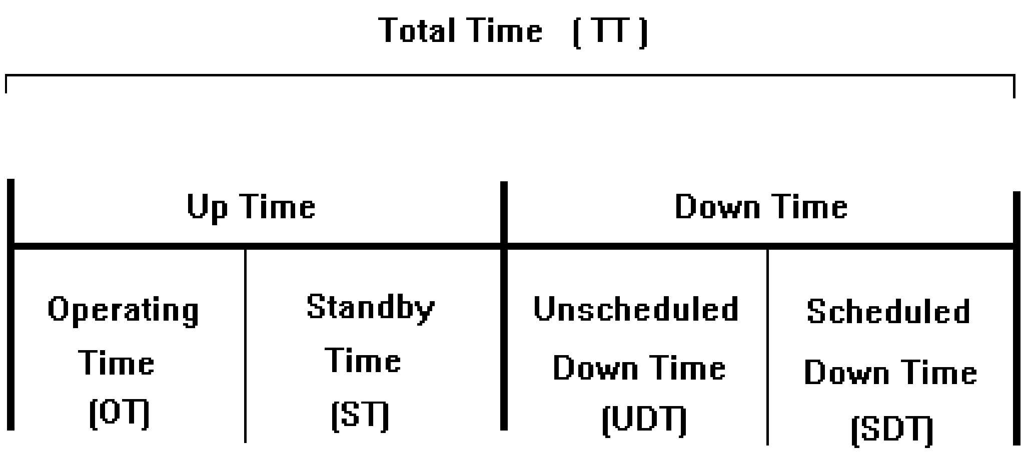


Figure 4-9: Division of Time Used by the Canadian Air Force for Operational Availability Measurements.

Using the breakdown of time given in Figure 4-9, A_O is given by:

$$A_o = \frac{OT + ST}{OT + ST + SDT + UDT} \tag{1}$$

In the maintenance data system currently used by the Canadian Air Force, logistic and administrative delay time is incorporated in both Scheduled Downtime (SDT) and Unscheduled Downtime (UDT).

It is easier in maintenance data systems to identify downtime rather than up time. Unavailability is given by:

$$\overline{A_o} = \frac{SDT + UDT}{OT + ST + SDT + UDT} \tag{2}$$

The parameter used to express the occurrence of unscheduled maintenance is the Mean (flying) Time Between Downing Events (MTBDE). For Canadian Air Force fleets, MTBDE is exponentially distributed. Therefore, MTBDE can be estimated by dividing the total airframe or flying hours by the total number of unique downing events which occur during a stated period of time, as given in Eqn. (3):

$$MTBDE = \frac{\text{Total Flying Hours For Period}}{\text{Total Number Of Downing Events}} \tag{3}$$

There may be several sequential or parallel unscheduled maintenance tasks following a downing event. The Mean Time To Restore (MTTR) the aircraft after a downing event ($MTTR_{DE}$) is the difference between the start of the first maintenance action and the end of the last one. It has been found that in Canadian Air Force fleets the distribution of the restoration time after a downing event is lognormal. Consequently, $MTTR_{DE}$ can be estimated from Eqn. (4), where the lognormal mean restoration time μ_L and standard deviation σ_L are estimated from historic data:

$$MTTR_{DE} = \exp^{\mu_L + \frac{\sigma_L^2}{2}} \quad (4)$$

If YFHPAC is the number of flying hours in a given calendar period, Eqn. (3) gives:

$$N = \frac{YFHPAC}{MTBDE} \quad (5)$$

Unscheduled downtime for the same period is given by:

$$UDT = N \times MTTR_{DE} \quad (6)$$

Substituting for N:

$$UDT = \frac{MTTR_{DE} \times YFHPAC}{MTBDE} \quad (7)$$

$$UDT = \frac{MTTR_{DE} \times h}{MTBDE}$$

Eqn. (7) allows the total unscheduled downtime in a given period to be estimated using parameters that can be obtained from existing maintenance data systems.

Scheduled downtime can be calculated by estimating the number of scheduled maintenance events and multiplying each event by its expected completion time. In the Canadian Air Force, there are three types of scheduled maintenance events:

- Supplementary inspection – comparable to the civil aviation "A" check;
- Periodic inspection, which includes a supplementary; and
- (Major) Structural inspection, which may or may not include a periodic inspection – comparable to the civil aviation "C" check.

Maintenance programs are developed using Reliability Centred Maintenance (RCM) principles and processes. The downtimes for these scheduled inspections have been found to have normal distributions. Therefore the expected downtime for future inspections is the arithmetic mean of historic downtimes.

For a fleet that does not include a periodic inspection in a major structural inspection, the downtimes over a given calendar period for scheduled inspections are:

$$\text{Periodic Downtime} = \frac{YFHPAC}{Per} \times MPT \quad (8)$$

$$\text{Supplementary Downtime} = \left(\frac{\text{YFHPAC}}{\text{Supp}} - \frac{\text{YFHPAC}}{\text{Per}} \right) \times \text{MST} \tag{9}$$

$$\text{Structural Downtime} = \frac{\text{YFHPAC}}{\text{DLM}} \times \text{MDLMT} \tag{10}$$

where:

- Per = Periodic inspection frequency
- Supp = Supplementary inspection frequency
- DLM = Major structural inspection frequency
- MPT = Expected downtime for periodic inspection
- MST = Expected downtime for supplementary inspection
- MDLMT = Expected downtime for major structural inspection

Thus, the total expected downtime for an aircraft due to scheduled inspections:

$$\text{SDT} = \left\{ \frac{1}{\text{Per}} \times \text{MPT} + \left(\frac{1}{\text{Supp}} - \frac{1}{\text{Per}} \right) \times \text{MST} + \frac{1}{\text{DLM}} \times \text{MDLMT} \right\} \times \text{YFHPAC} \tag{11}$$

Having estimated unscheduled and scheduled downtime (UDT and SDT) using equations (7) and (11), operational availability A_O is estimated from:

$$A_o = 1 - \left(\frac{\text{SDT} + \text{UDT}}{\text{TT}} \right) \tag{12}$$

where TT is the total time, i.e. the calendar period.

Table 4-1 illustrates the use of equations (7), (11) and (12) in calculating operational availability from information obtained from a maintenance data system.

Table 4-1: Illustrative Example of Prediction of Operational Availability from Historic Data from a Maintenance Data System, Using Equations (7), (11), and (12).

MTBDE (Measured mean time between downing events)	10 flying hours
$MTTR_{DE}$ (Measured mean time to restore after a downing event)	30 calendar hours
YFHPAC (Planned aircraft utilisation)	1000 flying hours per year
Predicted Unscheduled Downtime (UDT) from Eqn. (7)	**3000 hours (3 hours per flying hour)**
Supp (Specified frequency of supplementary inspection)	450 flying hours
MST (Measured mean downtime for supplementary inspection)	75 calendar hours
Per (Specified frequency of periodic inspection)	900 flying hours
MPT (Measured mean downtime for periodic inspection)	300 calendar hours
DLM (Specified frequency of major structural inspection)	3600 flying hours
MDLMT (Measured mean downtime for major structural inspection)	1600 calendar hours
Predicted Scheduled Downtime (SDT) from Eqn. (11).	**861 hours (0.861 hours per flying hour)**
Predicted Operational Availability (A_O) from Eqn. (12)	**56%**

To validate the model, the predicted steady state A_O was compared to the actual value for all Canadian Air Force fleets for one year. The predictions were within ±10%.

The model can also be used to examine the effect on operational availability of changes in the frequency or duration of the various scheduled inspections, the reliability (expressed as MTBDE), and the maintainability and effectiveness of the maintenance/support system (expressed as $MTTR_{DE}$). Hurst provides several examples of such studies. In one case, the model helped to demonstrate that a difference in A_O between two units operating the same aircraft was due primarily to differences in utilisation/tasking. In another study it was noted that reductions in the frequency of scheduled inspections gave diminishing returns. Beyond a certain point cost would be the only significant incentive to reduce inspection frequency.

4.4.2 Discrete Event Simulation (DES) Modelling

A time-based model of aircraft maintenance can be constructed by characterising the aircraft, the operating environment, and the support system by certain stochastic (probabilistic) parameters, by defining a set of discrete events, such as missions and component failures, and by defining rules that cause the events to occur.

The rules would incorporate the parameters, previous events, and the passage of time. Examples of stochastic parameters are the probabilities of failure of components, the elapsed times to repair failed components, and the elapsed times to resupply parts. The model would be repeatedly incremented in time, the values of stochastic parameters would be reset at each time increment to values generated from their probability distributions and the output of a random number generator, and events would "occur" according to the rules. The events would be monitored and used to calculate statistics of interest, including, of course, aircraft availability and support cost broken down as desired. By varying the rules and parameters, the sensitivities of the statistics of interest to these variations could be determined. This type of model is known as a Discrete Event Simulation (DES). It is a well-established tool of operations research, and commercial software is available for constructing and running the models.

4.4.3 System Health Operational Analysis Model (SHOAM) by the Boeing IVHM Center

With an understanding of the historical drivers of long range aircraft downtime, the parameters affecting these drivers can be modelled to analyze the system's sensitivity to these parameters. The Boeing Company's System Health Operational Analysis Model (SHOAM) model is a stochastic Discrete Event Simulation (DES) tool, to analyze system sensitivities and predict performance for various health management solutions.

In his description of SHOAM, Andersen points out that the design of the aircraft plays a significant role in its operational availability. In the area of unscheduled (corrective) maintenance, design factors include the inherent reliability of the aircraft, which is influenced by the system's complexity and technology. The primary metric in the SHOAM model for quantifying the inherent reliability of a component or system is "*Mean Time Between Failures (MTBF)*". The design's diagnostic capability, including the ability to accurately detect failures and isolate them, also has a major influence on availability. The number of "*Can Not Duplicate (CND)*" arisings, discrepancies that maintainers cannot detect during fault isolation, and "*Retest OK (RTOK)*" arisings, on-equipment component malfunctions that cannot be duplicated during off-equipment testing, are key metrics for quantifying its ability to accurately detect and isolate faults. Increased CND and RTOK rates lower the effective MTBF of the system below that of the design's inherent reliability, resulting in reduced aircraft availability.

Fischer mentioned during his presentation 1.4 that he had heard reports of a 50% rate of "No Fault Found (NFF)" in avionic LRU removals. Therefore, the issue of NFF arisings (referred to in the SHOAM model as CND and RTOK arisings) is a significant one. Technologies to improve diagnostic capability are included in Chapter 6.

In the SHOAM model, scheduled maintenance, or preventive downtime, can be quantified as a combination of the "*Mean Time Between Preventive Maintenance (MTBPM)*", the interval between scheduled maintenance, and "*Mean Preventive Maintenance Time* (M_{pt})", the time required to complete the scheduled maintenance. The amount of maintainer accessibility in a design contributes to the amount of downtime for both scheduled and unscheduled maintenance. The maintainability of a system can be expressed as the metric "*Mean Time To Repair (MTTR)*".

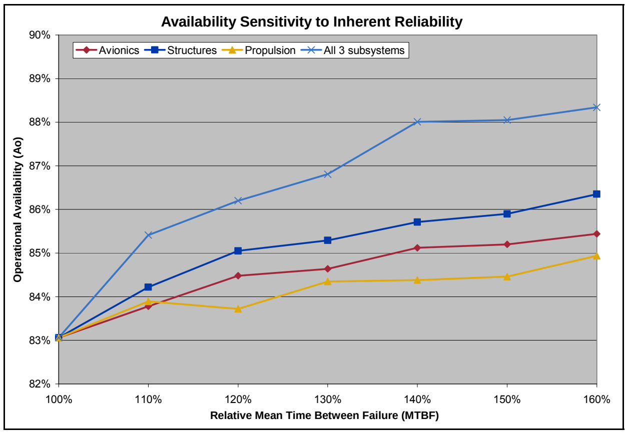
The maintenance infrastructure is also a major factor in overall fleet availability. The predominant parameter in this area is the maintenance workforce. This is quantified in SHOAM as the metric "*Number of Maintainers Available*". Currently, SHOAM uses the metric "*Mean Administrative and Logistic Delay Time (MALDT)*" to input the combined effects on availability of supply chain and administrative delays. This is the delay time spent waiting for parts, maintenance personnel, transportation, etc.

The conditions in which an aircraft operates also play a part in its ability to perform consistently. For example, aircraft operations at great distances from established bases increase the proportion of critical failures that occur in unsupported locations where repair capability is limited or non-existent. Therefore, such operations are likely to increase significantly the maintainability metric "*Mean Time To Repair (MTTR)*". In the SHOAM model, the metric used to input the level of off-station maintenance is the "*Probability of Remote Maintenance (P_{remote})*".

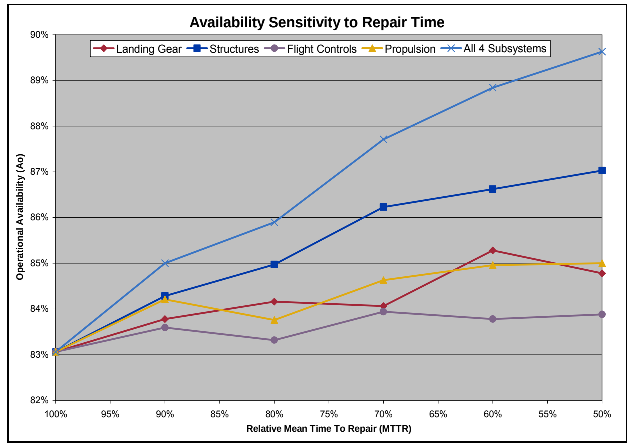
Table 4-2 contains a summary of the parameters and metrics associated with system availability that are included in the SHOAM model. The sensitivity of availability to some of these parameters for the case of a long range strike aircraft is presented in Paper 2.1. Some examples of the model output are in Figure 4-10. Graphs a) and b) indicate that an increase of 50% in MTBF or a reduction of 30% in MTTR could increase operational availability by about 5%. The potential impact of different systems is also shown. Graph c) indicates that a manning level of about 50% of that needed to cope with maximum operational tempo would achieve a good trade-of between availability and efficiency. At this level, the average utilisation of the available manpower would be just under 50%. Graph d) indicates that a comparable trade-off between spares stocks and aircraft availability might also be possible. These data from Boeing for a long range aircraft contain simplifications, but illustrate the potential utility of stochastic discrete event simulation.

Table 4-2: Parameters and Metrics Used in Boeing's System Health Operational Analysis Model (SHOAM).

Category	Parameter	Metrics
Design	Inherent Reliability	MTBF (Mean Time Between Failures)
	Fault Detection and Isolation	CND (Cannot Duplicate) RTOK (Retest OK)
	Scheduled Maintenance	MTBPM (Mean Time Between Preventive Maintenance) M_{pt} (Mean Preventive Maintenance Time)
	Maintainability	MTTR (Mean Time To Repair)
Maintenance Infrastructure	Maintenance Workforce	No. of Maintainers
	Spares Availability	MALDT (Mean Administrative and Logistic Delay Time)
	Administration Time	
Operation	Remote Maintenance	P_{remote} (Probability of Remote Maintenance)



a)



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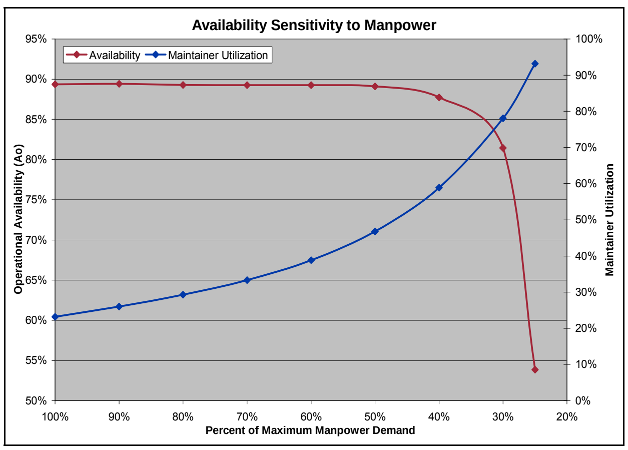

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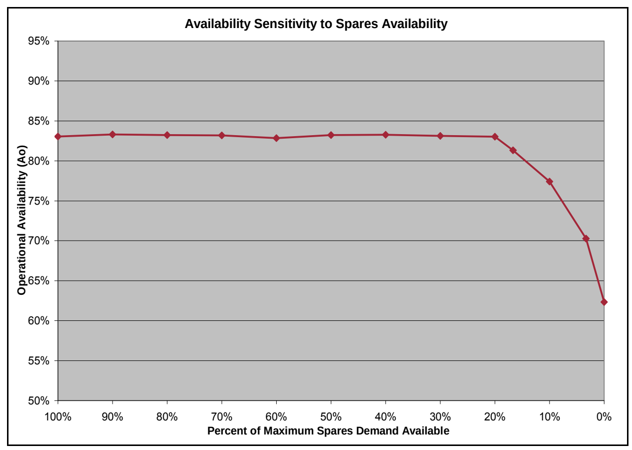


d)

Figure 4-10: Illustrations of Sensitivity Studies Performed Using the SHOAM Model for a Long Range Strike Aircraft.

4.4.4 UK Ministry of Defence Model for Evaluating Prognostic Health Management Systems

Andresen points out that one of the main purposes of the SHOAM model just described is to help in the design of integrated vehicle health management systems. Another model for this purpose was described by Cook of MOD UK in Paper 4.6. In this project, Discrete Event Simulation (DES) models were developed to estimate the improvements possible through:

a) Providing maintenance time-windows in which Corrective Maintenance (CM) could be safely performed, enabling resource levelling.

b) Predicting CM requirements to allow maintenance stockholding to be minimised.

Current supply chain data is used to define:

- Major components fitted;

- International deployments;
- Stockholding levels;
- Component transport times;
- Component failure rates;
- Component replacement durations;
- Mechanical technicians required for maintenance types; and
- Mechanical technician availability.

Where possible, the data was cross-checked against other supply chain information to verify the integrity of the information being used to define the simulation parameters. The outputs from the DES models were also assessed against expected model results in order to verify the integrity of the simulations. Sensitivity analyses were subsequently conducted against the prognostic interval and the mechanical technician availability; two essential model parameters for which no definitive values exist. Finally, some degree of model validation was achieved by comparing supply chain parameter predictions from the simulation with independently measured values from the real supply chain.

Activity Cycle Diagrams (ACD) are a useful way of defining the structure and elements required for Discrete Event Simulation (DES) modelling. They are constructed from alternating queues and activities and arrows show the flow of entities such as aircraft and stock through the diagram. The ACD in Figure 4-11 illustrates the activities, queues and entity flows in major-component Corrective Maintenance (CM) *without* use of data from the on-board Health and Usage Monitoring System (HUMS) for a single Chinook deployment. This diagram shows the system as two cycles – one for aircraft and one for stock – intersecting at the point of corrective maintenance activity. The diagram highlights important points for the mathematical modelling process, some of which are listed below:

- The limited availability of mechanical technicians due to non-CM tasks.
- The call for stock at component failure, which is defined here as the point at which the aircraft becomes unserviceable due to component damage.
- The division of the queue for corrective maintenance into aircraft waiting for technicians and D state aircraft (aircraft grounded whilst waiting for spares).
- The simplifications introduced (grey elements in ACD) in not modelling the stock sources other than repair and overhaul through the Defence Aviation Repair Agency (DARA), the full cycle of component rejection and repair and the possibility of urgent 1-day supply of components through dedicated military transport.

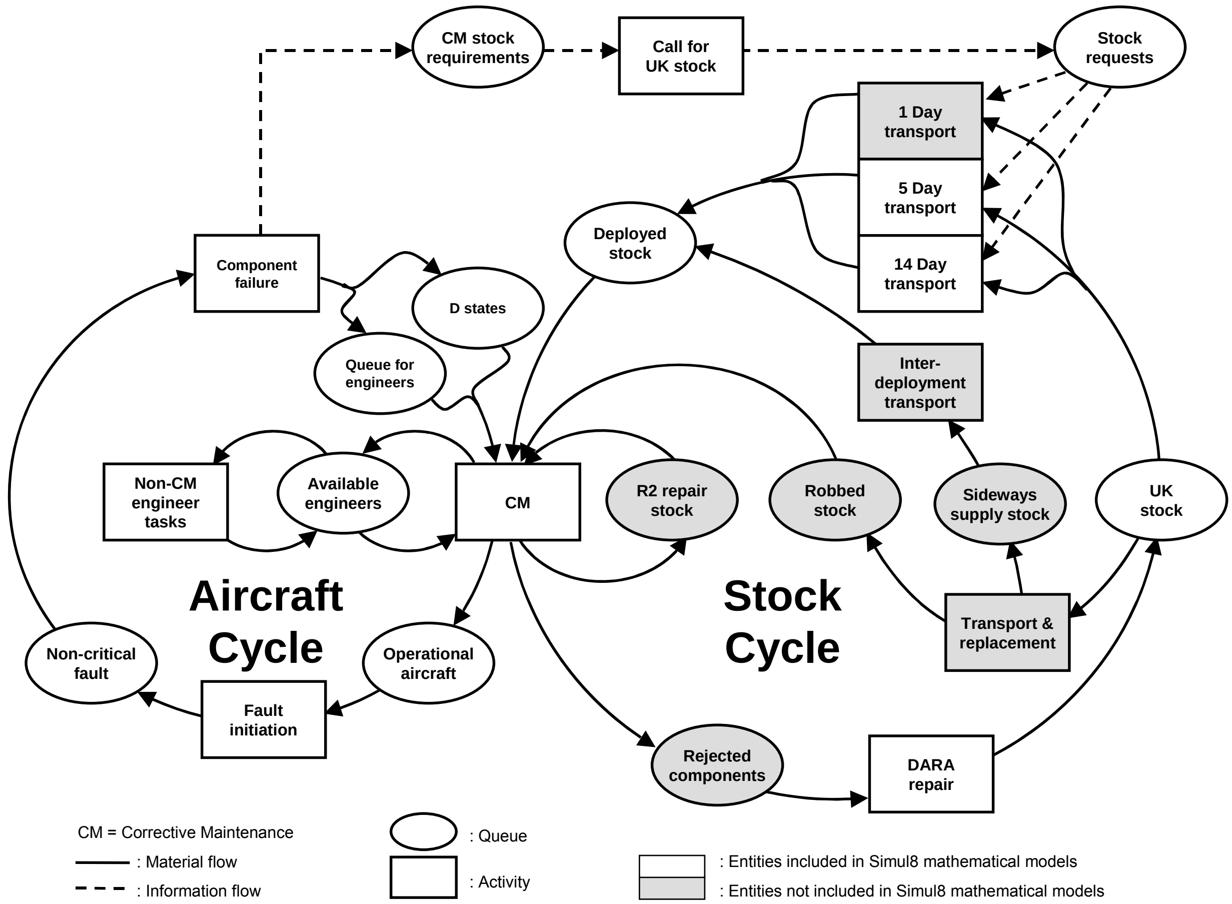


Figure 4-11: Activity Cycle Diagram (ACD) for a Single-Deployment of Chinook Helicopters *Without* HUMS. (Note: "Engineers" should be interpreted as technicians)

The ACD in Figure 4-12 illustrates the activities, queues and entity flows in major-component corrective maintenance *with* the benefit of HUMS data for a single Chinook deployment. Cook explains that there are two improvements in the maintenance and supply processes. Firstly, replacement components (if not in deployed stock) can be called for at the time of fault detection rather than when the aircraft becomes unserviceable. Secondly, a Predictive Maintenance Window (PMW) can be defined from the point of detection to the point of compulsory aircraft grounding. This window allows required corrective maintenance to be scheduled around constraints such as technician availability, stock availability and other maintenance activity.

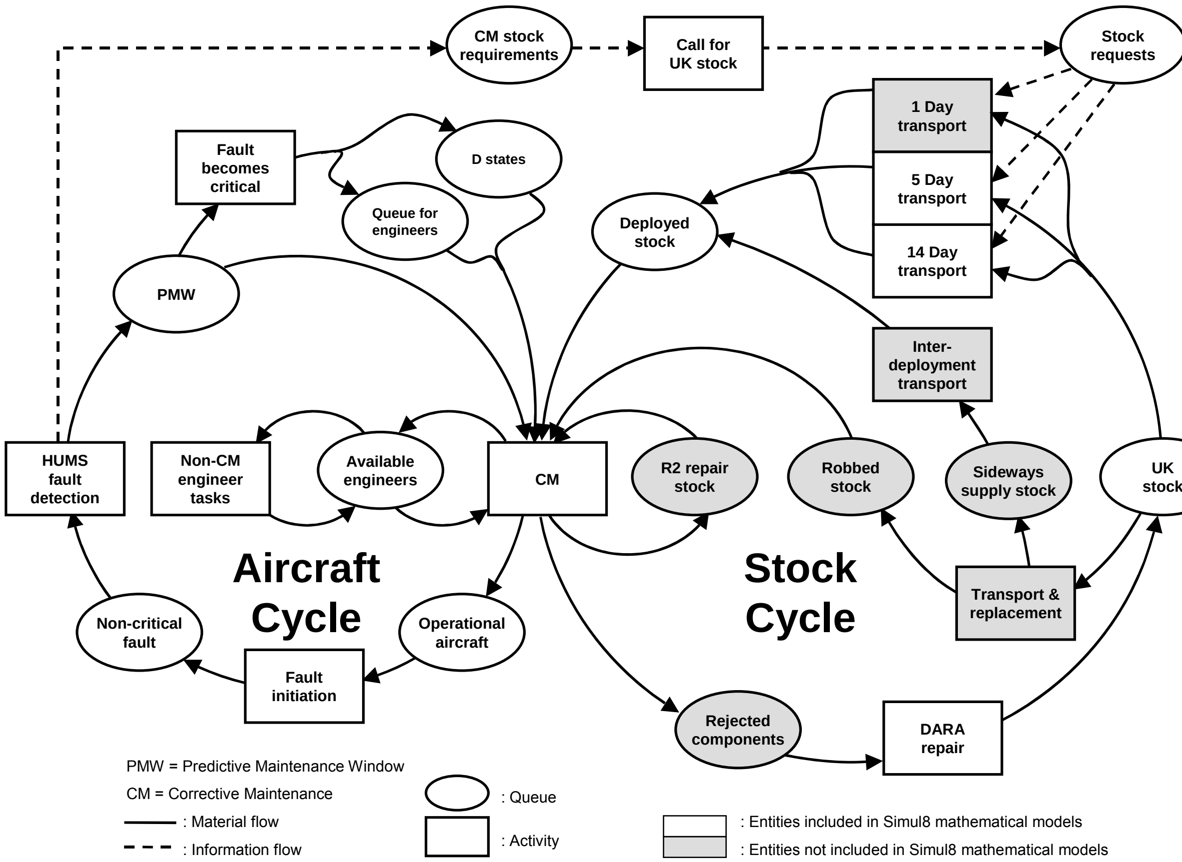


Figure 4-12: Activity Cycle Diagram (ACD) for a Single-Deployment of Chinook Helicopters *With* HUMS. (Note: "Engineers" should be interpreted as technicians)

Cook's term "Predictive Maintenance Window (PMW)" is important to an understanding of how advanced technology can be used to make full use of the RCM concept of on-condition tasks in preventive maintenance. As explained in Chapter 5, the purpose of a scheduled on-condition task is to detect potential failure before actual functional failure occurs. The interval between the point at which a potential failure becomes detectable and the point at which it degrades into a functional failure is known in RCM terminology as the "Potential Failure interval (PF interval)". In general, advanced technology is employed in the design and inspection of an aircraft to make this PF interval as long as possible: firstly to enable the use of an on-condition task instead of a hard time task; and secondly to reduce the frequency and cost of the on-condition task. In so doing, there are trade-offs between the cost of developing and implementing advanced technology, the cost of performing scheduled inspections, and other factors. If the PF interval can be made long enough, it may be economically feasible to use part of it as a PMW. One way of doing this is to perform continuous inspections using on-board sensors instead of periodic inspections using ground-based NDE. The concept of a PMW is particularly attractive for components that have relatively short lives, are of high value, and are in short supply. Examples of such components can be found in the drive trains and rotors of helicopters. Even for such components, there have been technical, economic, and regulatory hurdles in implementing a PMW. Nevertheless, there have been valuable intermediate gains from related R&D. For example, sensors onboard Chinook and other helicopters are used to supplement ground-based inspections by providing early warning of degradation that endangers flight safety. This has significantly improved the safety records of the aircraft types in question.

For the full models used in Cook's project, 11 major transmission components of the Chinook helicopter were considered, each with characteristic replacement duration and requirement for mechanical technicians based on operational data. The full models also considered 6 simultaneous deployments. On each of the 6 deployments the aircraft numbers, major component stockholding, technician numbers and characteristic failure rates for each of the 11 components are configured from operational data.

The DES models produced in this work were developed in the Simul8™ modelling package, which was found to be suitable for the requirements of the simulation. In a Simul8™ model, there are six main elements:

a) **Work Items –** These are the elements that are individually tracked through the model to determine the system behaviour. Work items are defined here for helicopters, stock items and component failure events (virtual work items).

b) **Work Entry Points –** These are the elements through which work items arrive in the system with pre-determined stochastic (sampled from a statistical distribution) distributions. Work items are also defined to exist in models prior to start-up, such as the helicopters themselves and the known stock held on deployments.

c) **Work Centres –** These are the elements in which work is performed on individual work items. The duration of the work can be deterministic (zero or fixed duration) or stochastic and the item can be routed out from the centre on paths determined by work item labels or by the 'visual logic' programming language within Simul8™. In the models used here there are numerous work centres, including maintenance, HUMS fault detection and transport routing.

d) **Queues –** These are the elements in which work items are held while waiting to be processed. These can hold any number of work items simultaneously, for a pre-determined duration or until requested. Queues are used here for several purposes including aircraft awaiting maintenance and stock being transported from the UK to deployed operations.

e) **Resources –** These are mobile elements that are required by work centres in order to complete their tasks. In order to provide some simulation value, resources must be scarce to some extent, which may be due to work centre competition or to the defined availability of the resources. In the models used here, the only resource considered is mechanical technicians; a genuine constraint on maintenance activity.

f) **Work Exit Points –** These elements are used to allow work items to leave the system.

Table 4-3 illustrates the elements used to simulate the presence of a HUMS.

Table 4-3: HUMS Elements in Single Deployment Mathematical Model.

Model Element(s)	Element Type	Description
1	Work Centre	*HUMS fault detection*. This element calls for a stock check and component supply if required prior to component failure.
2	Queue	*Predictive maintenance queue*. In this queue, aircraft with known faults can continue to operate pending maintenance.
3	Work Centre	*Prognostics*. This centre uses Simul8™ visual logic to determine whether there are stock, technicians and work centre available for the relevant Corrective Maintenance (CM) action. If so, the fault is routed to CM and maintenance is performed. If the fault has become critical (i.e. the prognostic interval has elapsed), the aircraft is grounded. If neither of these is true, the pending fault is routed to the predictive maintenance queue.
4	Queue	*Aircraft grounding queue*. In this zero-duration queue, faults are held for allocation to operational aircraft. This is necessary to avoid problems associated with direct work-centre to work-centre connections.

Based on discussion with MOD HUMS engineers, a conservative prognostic interval of 10 days was assumed for the results shown here. Examples were cited in which faults were visible in the HUMS record for 10 to 100 days prior to failure or maintenance. However, these were insufficient in number to take a statistical approach, and so a worst-case assumption was made.

In the results presented here, multiple-run trials were used, in which 100 runs of the simulation were performed to obtain statistical results. Each run within a trial had a warm-up period of 20 days and a data collection period of 1 year. The trial results were analysed to determine the mean and 95% confidence intervals for key parameters. The 95% confidence intervals are shown in the figures as error bars or dashed boundary lines.

The simulations were run to produce a comparison between cases with and without the use of HUMS with a PMW, and between the zero-stock and current-stock scenarios. Figure 4-13 shows that the model with HUMS/ PMW predicted zero D state (aircraft grounded awaiting spares) aircraft across all six deployments for major components whether stock is held on deployment or not. This was partly due to the simplifications of the model, in which the 10-day fixed prognostic interval is invariably greater than the 5-day fixed transport duration and there is always a sufficient supply of components from the UK store. True D state levels would depend on how well the supply chain can be managed to meet these fixed assumptions, but it is certain that HUMS with a PMW would have its most pronounced effect in a reduction of downtime due to D states.

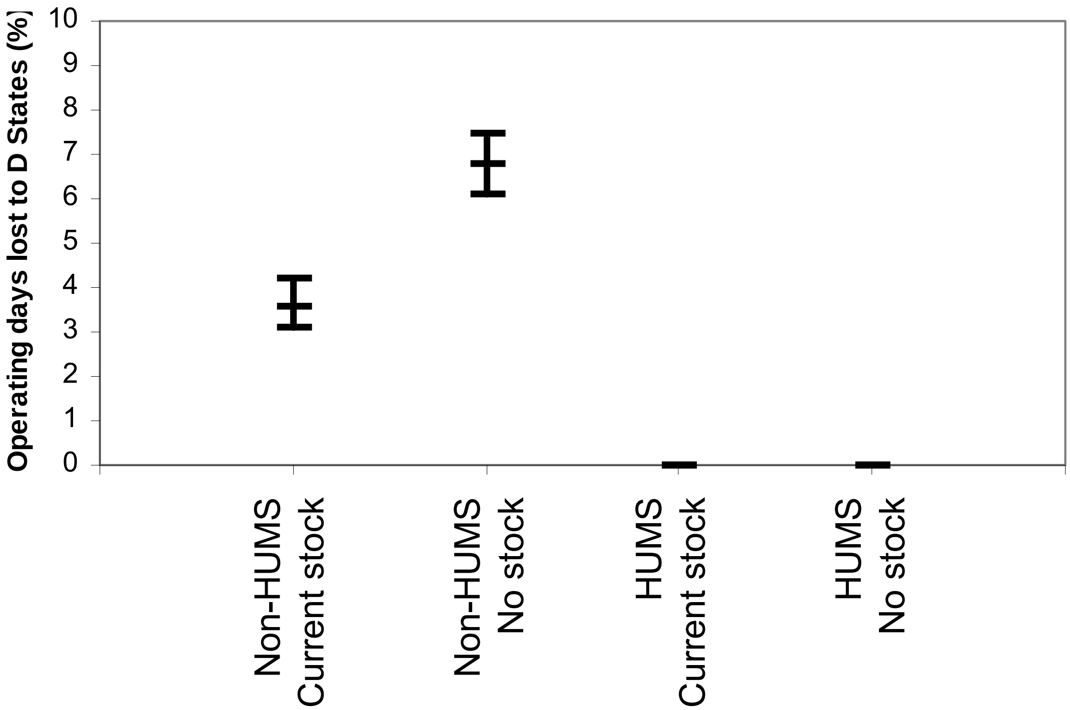


Figure 4-13: Prediction of Downtime Due to D States (Aircraft Grounded Awaiting Spares) – All Deployments.

Figure 4-14 illustrates the predicted percentage reduction in operating days lost to Corrective Maintenance (CM) across all six deployments through the use of HUMS and a Predictive Maintenance Window (PMW). It includes the effect of the PMW and associated pre-emptive stock requests. This figure shows that a HUMS used in this way could potentially reduce the downtime for CM from 11.0% to 6.2% under current stockholding levels. The reduction would be 7.0% with no deployed stockholding and a completely lean deployed supply process for major components.

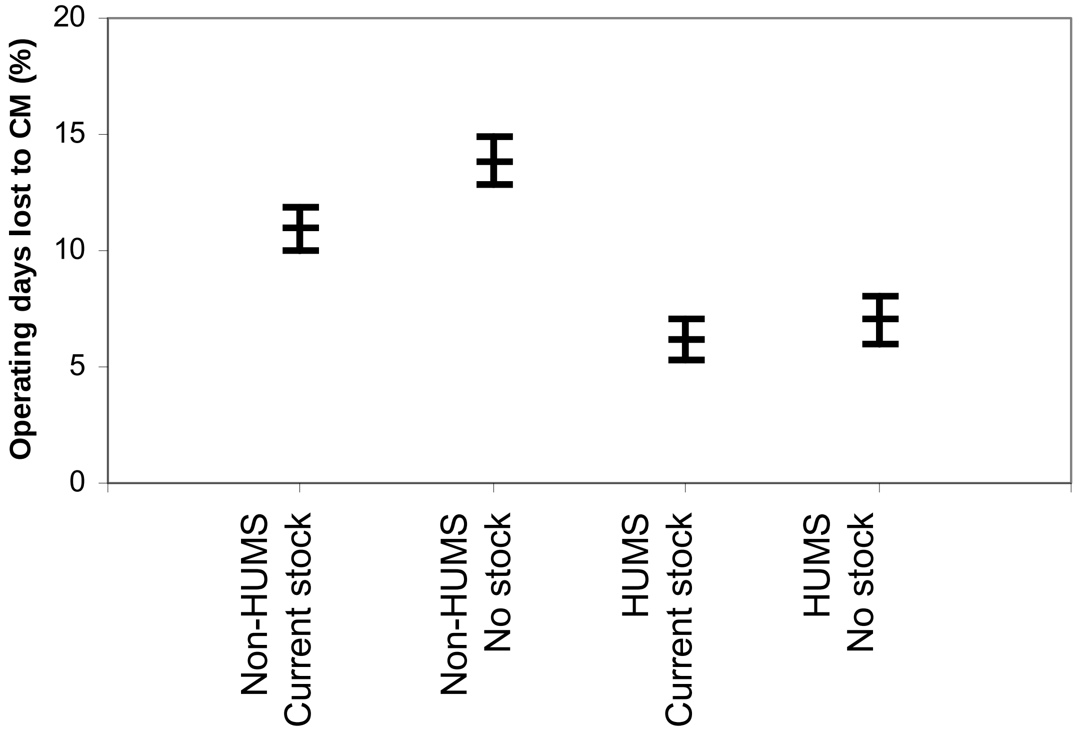


Figure 4-14: Prediction of Loss to Corrective Maintenance (CM) – All Deployments.

Two fixed parameters that were key to the model output were the Predictive Maintenance Window (PMW) and the mechanical technician availability. These two parameters were subjected to sensitivity analysis. To illustrate, the sensitivity analysis for PMW is shown in Figure 4-15. The figure shows the effect of PMW on aircraft availability for all 6 deployments. The PMW was varied from 0 – 30 days in 2-day increments and the zero-stock HUMS model trial was replicated for each. The results showed that for larger deployments, a window of 10 days is sufficient to gain most of the maintenance and supply planning benefits. For smaller deployments, such as the Falklands and Afghanistan, with limited number of aircraft and mechanical technicians, the benefit of a larger window is significant all the way to the 30-day maximum considered. This is because mechanical technician availability is a serious limiting constraint for these deployments. Thus, the flexibility of a broader predictive maintenance window is important. This analysis does demonstrate a clear dependence of the model's prediction of aircraft availability on the PMW.

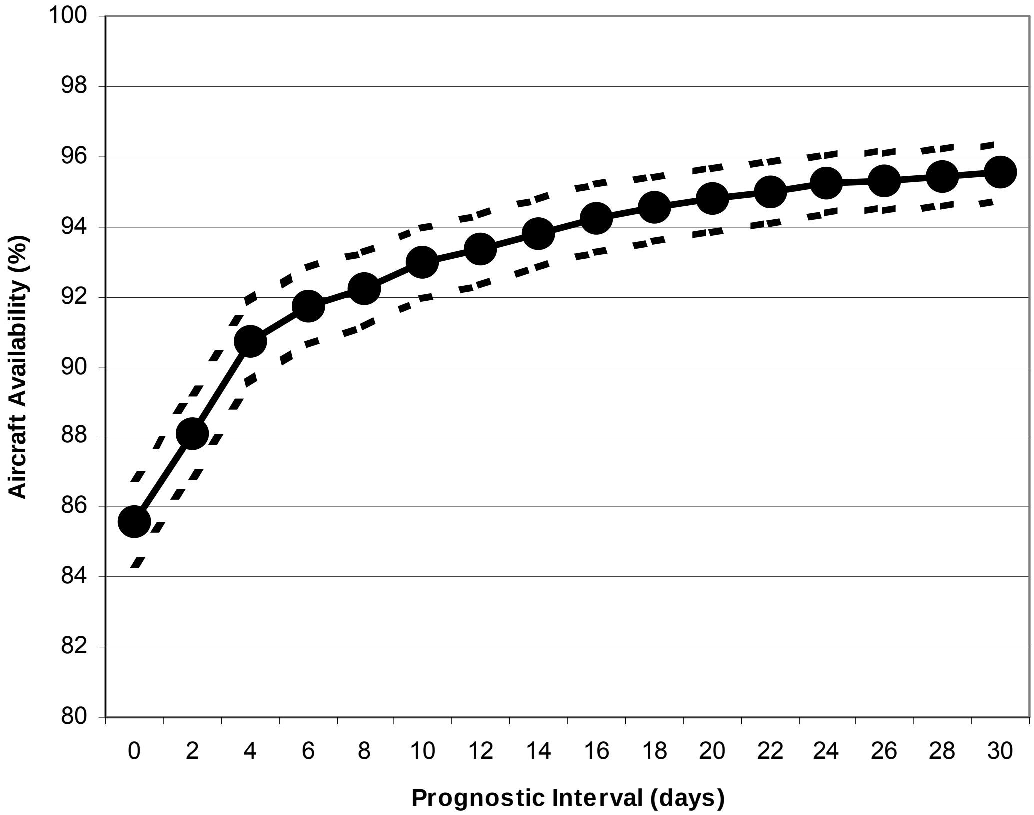


Figure 4-15: Model Prediction of the Variation of Predictive Maintenance Window (Prognostic Interval) on Chinook Helicopter Average Availability During 6 Different Simulated Deployments.

4.4.5 Other Modelling and Forecasting of Aircraft Availability

In supplementary Paper #3, Hart describes other work related to the area of Mission Capability (MC) rate forecasting and simulations, as follows.

4.4.5.1 Modelling Reliability and Availability Improvements Due to Modifications (USAF – Institute for Defense Analysis and HQ Air Force Materiel Command)

A straightforward method to forecast MC rates was cooperatively developed by the Institute for Defense Analysis and the Studies and Analysis Flight at Headquarters (HQ) AFMC. This approach was derived from a need to estimate the MC rate of different modernization proposals for the C-5. The result was a simulation model that considered the contributions of individual aircraft sub-systems that are being upgraded to overcome the C-5's aggravating reliability problems. The model is based on component failure distributions and actions and on component repair time distributions and actions [45].

4.4.5.2 Modelling for a Parametric Study to Reduce Downtime (Helsinki University of Technology – BAE Systems Hawk)

A discrete approach to simulate military aircraft maintenance and availability was developed by the Systems Analysis Laboratory at the Helsinki University of Technology. This model was constructed for use on the

BAE Systems Hawk Mk51 aircraft and describes the flight policy and maintenance, failure, and repair processes. It aims to shorten maintenance turnaround times and perform what-if scenarios for investigating ways to improve MC rates [46].

4.4.5.3 Model for Forecasting Availability and Long-Term Planning of Interrelated Factors (USAF – Air Force Logistics Management Agency and Air Force Institute of Technology)

An extensive analysis of MC rate forecasting was completed through a joint effort between the Maintenance Plans and Programs Branch of the Air Force Logistics Management Agency (AFLMA) and the Air Force Institute of Technology (AFIT) [47]:

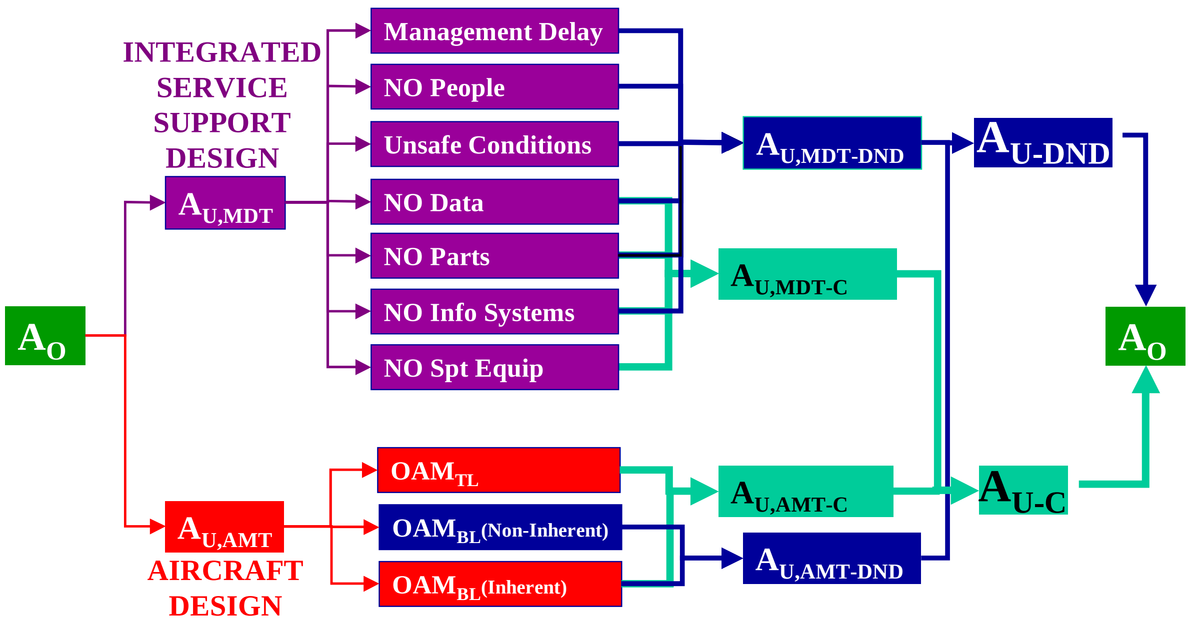
- The team first evaluated the AF’s Funding/Availability Multi-Method Allocator for Spares (FAMMAS) tool, a parametric model that forecasts MC rates by aircraft type based on funding projections of aircraft readiness spares and other associated planning factors. This effort discovered the FAMMAS model did not incorporate or explain the key logistics and operations drivers that influence MC rates. The researchers concluded that this limited its effectiveness as a management and decision-making tool.
- Second, the team sought to enhance the forecasting ability of MC rates by recommending the integration of significant factors besides funding. This was accomplished through the examination of over 600 variables from aircraft reliability, maintainability, operations, and personnel areas, and 10 years of data. The research acknowledged that MC rates are linked to logistics type factors including logistics operations, Reliability and Maintainability (R&M), and personnel, and operations type factors including aircraft operations, funding, and environment.
- The result was the development of two versions of an enhanced forecasting model that is a function of sorties, flying hours, average aircraft inventory, number of maintenance personnel assigned, and the interaction of the logistics and operations factors. The first version serves as a point estimator of an MC rate at a specific time in the future while the second version serves as a long-range planning model.

4.5 THE USE OF AVAILABILITY METRICS AND MODELS IN PERFORMANCE-BASED CONTRACTING – A CASE STUDY

4.5.1 The Availability Model and Process of Attributing Responsibility for Downtime for the New Canadian Maritime Helicopter Program (MHP)

In Paper 3.1, Béland and Hollick included a detailed explanation of the metrics and availability model used as the basis of the availability-based acquisition and support contracts that the Canadian Department of National Defence (DND) negotiated in 2006 with Sikorsky for a new Maritime Helicopter Program. In this program, Canada will replace its existing fleet of CH124 Sea King helicopters with a fleet of CH148 Cyclone helicopters.

The method developed for the performance measurement of the in-service support of the CH148 Cyclone helicopter is based on a top-down decomposition of operational availability A_O into mutually exclusive unavailability drivers, as illustrated in Figure 4-16. For ease of reference, Table 4-4 lists most of the metrics used in the Canadian DND’s availability model and the formulae used for attributing downtime to DND or the Contractor. The green shaded cells in the table and figure indicate the bottom line metrics on aircraft unavailability ($A_{U,MDT-C}$ and $A_{U,AMT-C}$) that will govern bonus payments and penalties. As Figure 4-16 indicates, the design and performance of both the aircraft and the in-service support system determine these metrics. Sikorsky, as prime contractor, has accepted responsibility for all these aspects for a minimum period of 20 years, including the design of a comprehensive information system to be used jointly by DND and the contractor. This information system is known as the Integrated Information Environment (IIE). The other metrics listed in the table help to explain or are used in deriving these bottom line metrics. The metrics in the pink shaded cells are the fundamental metrics that must be quantified and attributed to DND or Sikorsky for each individual maintenance task. The IIE is being designed to do this from simple inputs by the technicians.



$$A_O = 1 - A_U = 1 - (A_{U,MDT} + A_{U,AMT}) = 1 - (A_{U\text{-}DND} + A_{U\text{-}C})$$

Figure 4-16: Decomposition of Aircraft Operational Availability A_O by Design Attribute to the Organizational Level for the Canadian Maritime Helicopter Program (MHP).

Table 4-4: Metrics in the Availability Model for the Canadian MHP.

A_O	Operational availability.
A_U	Aircraft unavailability = 1 – A_O.
$A_{U\text{-}DND}$	A_U attributed to DND.
$A_{U\text{-}C}$	A_U attributed to the Contractor.
$A_{U,MDT}$	A_U due to maintenance delay time.
$A_{U,MDT\text{-}DND}$	A_U due to maintenance delay time attributed to DND = MMDT-DND$_{AMP}$/TPT.
$A_{U,MDT\text{-}C}$	A_U due to maintenance delay time attributed to the Contractor = MMDT-C$_{AMP}$/TPT.
$A_{U,AMT}$	A_U due to active maintenance time.
$A_{U,AMT\text{-}DND}$	A_U due to active maintenance time attributed to DND = MAMT-DND$_{AMP}$/TPT.

$A_{U,AMT-C}$	A_U due to active maintenance time attributed to the Contractor = MAMT-C_{AMP}/TPT.
TPT	Total program time (normally per year). This is a coordinated time base for the A_U computations.
OAM	On aircraft maintenance – preventive and corrective.
OAM_{BL}	OAM – base level (1st and 2nd Line).
$OAM_{BL(Non-Inherent)}$	OAM_{BL} which arises due to modifications, overload, accidental damage, battle damage, or other causes unrelated to inherent reliability. In general, the downtime non-inherent work is attributed to DND.
$OAM_{BL(Inherent)}$	OAM_{BL} related to inherent reliability. Normally inherent work is attributed to the Contractor.
OAM_{TL}	On aircraft preventive and corrective maintenance – 3rd Line.
$OAM_{TL(Non-Inherent)}$	OAM_{TL} which arises due to modifications, overload, accidental damage, battle damage, or other causes unrelated to inherent reliability. In general, the downtime for non-inherent work is attributed to DND.
$OAM_{TL(Inherent)}$	OAM_{TL} related to inherent reliability. Normally inherent work is attributed to the Contractor.
DE	Downing event.
OADE	Organizationally attributable downing event.
OAMT	On-aircraft maintenance task.
MMTT	Measured maintenance task time. Applies to a specific, isolated OAMT, and includes all active and inactive time for that task. MMTT = MAMT + MMDT for a specific task.
MDET	Measured downing event time.
MAMT	Measured active maintenance time. It is the total time a specific OAMT is reported as active, i.e. being performed. MAMT is normally attributed to the Contractor. When multiple OAMT are performed in parallel for a given Downing Event (DE), the MAMT for each task is normalized before use in further computations by factoring it by (MDET/$\sum_{DE}$MMTT). This apportions the downtime between successive flights in a logical way among all the overlapping maintenance tasks performed. If the task is performed by DND (onboard ship), the AMTBV (book value) for the task is the maximum downtime that can be attributed to the Contractor.
MAMT-DND	MAMT attributed to DND.
MAMT-C	MAMT attributed to the Contractor.
MMDT	Measured maintenance delay time. It is the total time a specific maintenance task is reported as inactive, i.e. not being performed. MMDT is attributed to DND or the Contractor, depending on the circumstances. Reasons for inactivity include lack of personnel, parts, data, management information, support equipment, and safe conditions. When multiple tasks are performed in parallel, the MMDT for each task is normalized before attribution by factoring it by (MDET/$\sum_{DE}$MMTT).

MMDT-DND	MMDT attributed to DND.
MMDT-C	MMDT attributed to the Contractor.
$\sum_{DE}$	Sum for a given downing event.
AMTBV	Active maintenance time – book value. Used to attribute downtime to the Contractor when DND performs the work. This is an agreed standard value for a given OAMT that is provided for all inherent base-level tasks ($OAM_{BL(Inherent)}$). It is the minimum elapsed time to prepare for, perform, and document a specific task.
BV	Same as AMTBV.
AMP	Annual measurement period.
$MAMT\text{-}DND_{AMP}$	Sum of MAMT attributed to DND within an AMP.
$MAMT\text{-}C_{AMP}$	Sum of MAMT attributed to the Contractor within an AMP.
$MMDT\text{-}DND_{AMP}$	Sum of MMDT attributed to DND within an AMP.
$MMDT\text{-}C_{AMP}$	Sum of MMDT attributed to the Contractor within an AMP.

The new maritime helicopters will be deployed on frigates, and most of the aircraft maintenance at shore bases and onboard ship will be performed by Canadian Forces personnel. This maintenance downtime will still be the responsibility of Sikorsky, but the downtime attributed to Sikorsky will not exceed an agreed book value.

During a pre-qualification process for bidders for the MHP, DND used advance information supplied by the bidders, together with historical data from comparable programs, to estimate the unavailability that would be attributable to DND ($A_{U,AMT\text{-}DND}$ and $A_{U,MDT\text{-}DND}$) and to develop a contractor-specific model of unavailability attributable to the contractor for active maintenance tasks ($A_{U,AMT\text{-}C}$). This model incorporated standard R&M performance attributes and those directly associated with the maintenance concept for the MHP. As part of their final proposals, the contractors were required to use this model to estimate the unavailability due to maintenance tasks attributable to the contractor. They were also required to provide their own estimate of unavailability due to maintenance delays attributable to the contractor. This aspect of the bidding process is illustrated in Figure 4-17, where the work done by DND for the final Request For Proposal (RFP) is highlighted in blue, leaving the data to be supplied by the contractors in red. This novel approach helped to ensure that the contractors would present a credible proposal that properly addressed DND's key requirements.

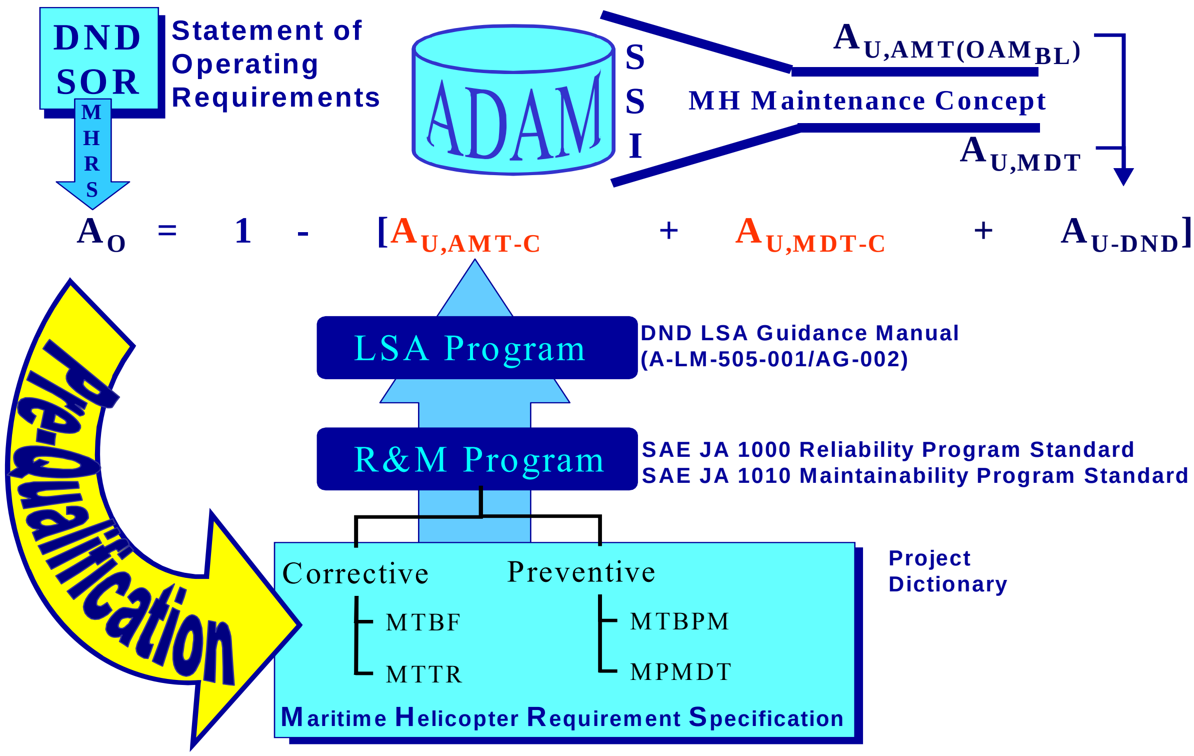


Figure 4-17: Data and Analysis Provided to Bidders by DND (Blue) to Bidders for the Canadian MHP as a Basis for Contractor Estimates of Aircraft Unavailability (Red).

In addition to meeting specific contractual requirements for aircraft availability, the prime contractor is required to follow the system engineering life-cycle processes prescribed in ISO/IEC 15288 [48] in developing and providing the integrated support solution. This means that Sikorsky must derive availability performance targets for aircraft sub-systems and contractor-supplied support, along the lines of Figure 4-18.

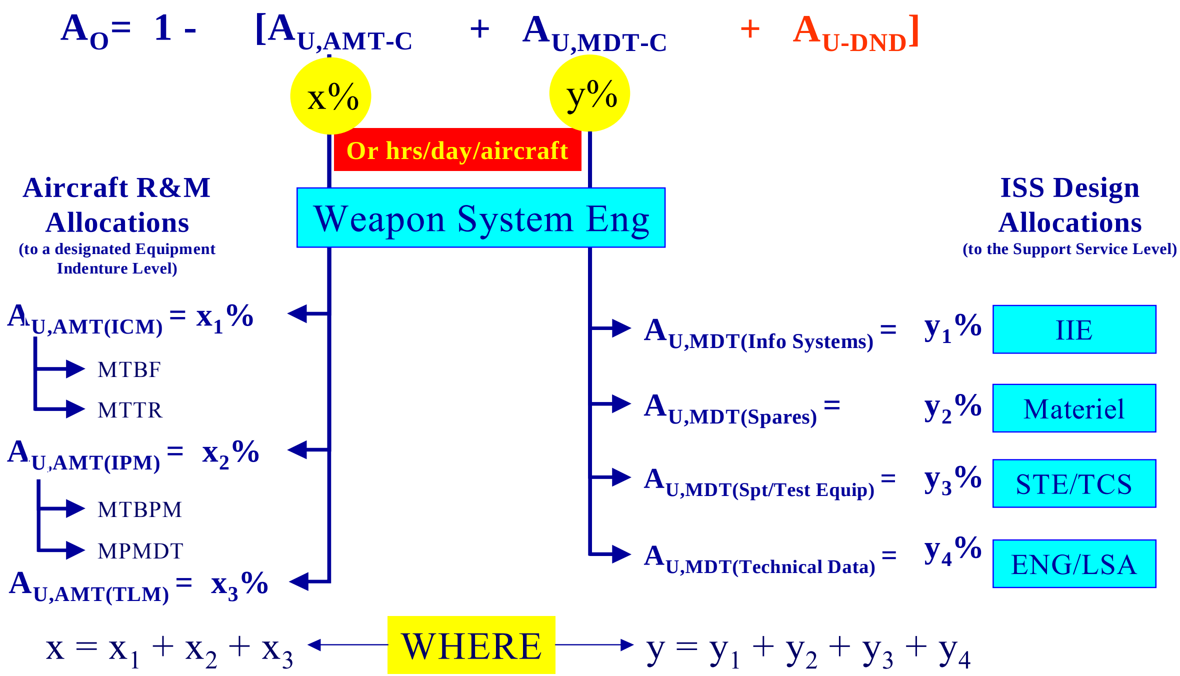


Figure 4-18: Systems Engineering Approach to the Provision of Availability Performance Targets for Aircraft Sub-Systems and Contractor-Supplied Support for the Canadian MHP.

Prior to acceptance by DND of the In-Service Support (ISS) system, Sikorsky is required to model aircraft availability in different operational scenarios and thereby demonstrate that the aircraft and the ISS will comply with the contract availability requirements.

A key enabling factor for an availability-based contract is the ability to measure organizationally attributable A_U performance in a manner that all responsible parties perceive as complete and accurate. This ability is a function both of the business rules or measurement process and the associated information system. As mentioned above, the measurement process was accepted by all bidders prior to release of the RFP. Since depot level (3rd Line) maintenance will be performed by the Prime Contractor or its sub-contractor, all the associated downtime will generally be attributed to the Prime Contractor. Since most maintenance at base/ship level will be performed by Canadian Forces personnel, the measurement and attribution process for this maintenance is more complex. Some additional insight into the base/ship level measurement process is given in Figure 4-19 to Figure 4-22. The symbols and abbreviations for all these figures are explained in Table 4-4.

The Base/Ship Level measurement process involves the tracking of the active and inactive periods of every individual on-aircraft maintenance task, and the causes of any inactive periods. This will be performed in real time on a Computerised Maintenance Management System (CMMS), which is an element of the IIE. The tracking will be performed using data inputs by technicians at “measurement points”. The overall up or down state of the aircraft will also be tracked, and all data inputs to the CMMS during a down period will be tagged to the “downing event” in question. The tracking of active and inactive periods is illustrated in Figure 4-19. The data inputs by technicians at the “measurement points” will be sufficient to allow all downtime to be attributed automatically to either the Prime Contractor or DND according to the established business rules.

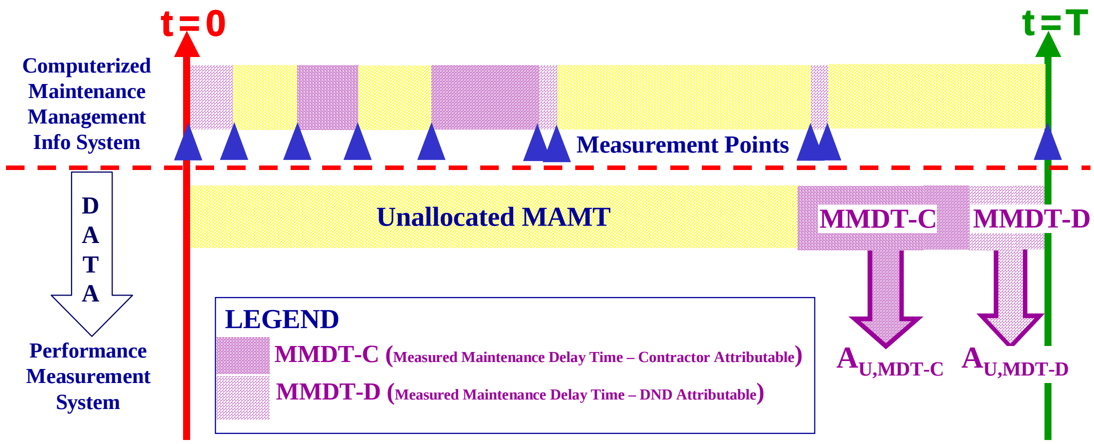


Figure 4-19: Tracking of the Active and Inactive Periods of Every Individual On-Aircraft Maintenance Task, and the Causes of Any Inactive Periods for the Canadian MHP.

These business rules include the following provisions:

- All downtime associated with modifications, overload, accidental damage, battle damage, or other causes unrelated to inherent reliability are automatically attributed to DND.
- There is a cap on the downtime to be attributed to the Prime Contractor for periods of active maintenance performed by Canadian Forces personnel. Such downtime will be capped at an agreed book value, as illustrated in Figure 4-20. The Prime Contractor benefits if the active maintenance time of Canadian Forces technicians is less than the book value, as illustrated in Figure 4-21.
- This book value and the attribution of delay time take into account that the Prime Contractor is responsible for the training of Canadian Forces personnel, integrated electronic manuals, the supply chain for aircraft parts, and the management and technical information systems.

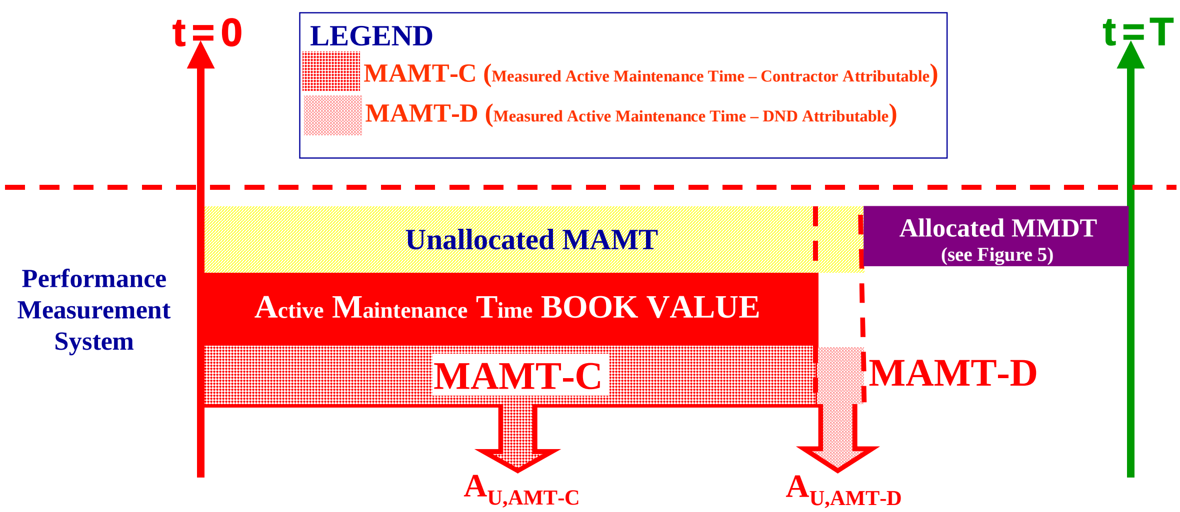


Figure 4-20: Use of a Book Value (BV) in Attributing Downtime to the Prime Contractor for Active Maintenance by Canadian Forces Personnel on the MHP (Case 1 BV < Active Maintenance Time).

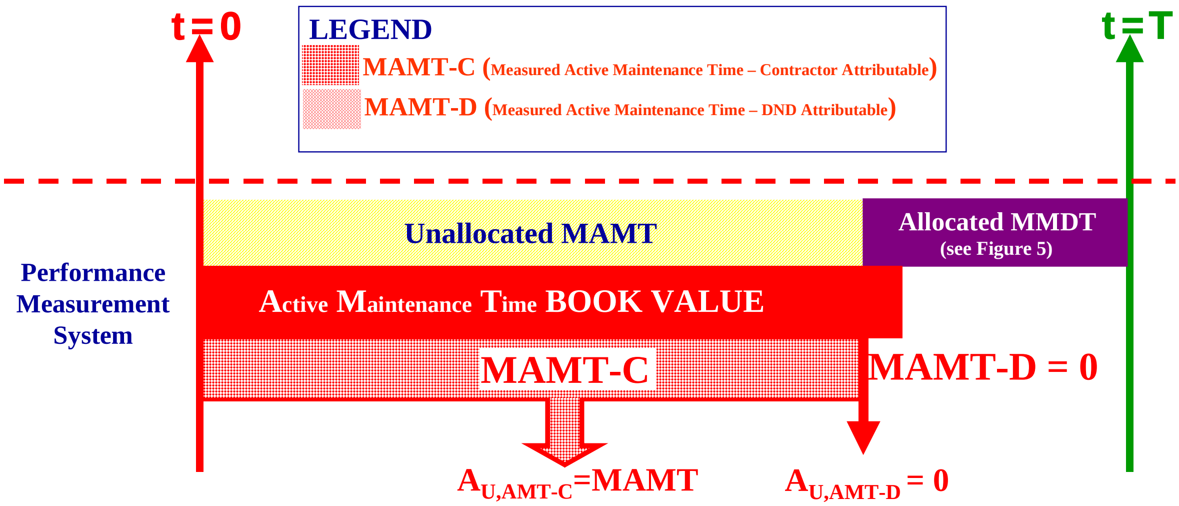


Figure 4-21: Use of a Book Value (BV) in Attributing Downtime to the Prime Contractor for Active Maintenance by Canadian Forces Personnel on the MHP (Case 2 BV > Active Maintenance Time).

The incentive payments in the prime contract related to aircraft availability are computed periodically from the data inputs just mentioned. The main metric for determining the level of incentive payments is the aircraft fleet unavailability attributable to the Prime Contractor. In computing this metric, the packets of downtime tagged to a given downing event are summed and then normalised to the overall duration of the downing event – known as the Measured Downing Event Time (MDET). This is a simple way of adjusting for the fact that active and inactive downtimes are tracked by individual maintenance task, while several tasks often occur in parallel. The summations and normalisation process for an individual downing event are illustrated in Figure 4-22.

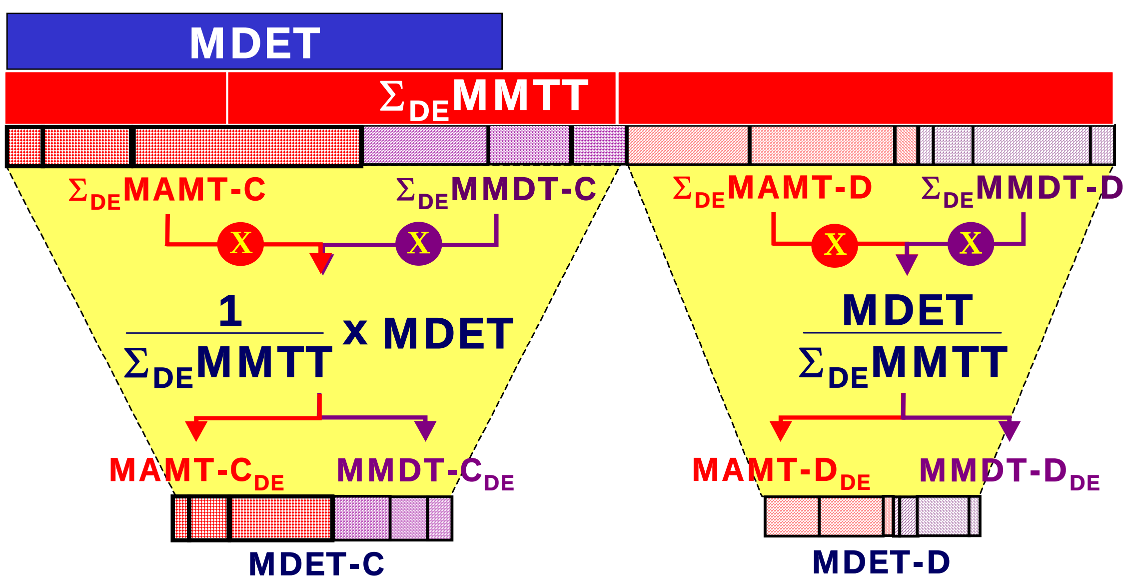


Figure 4-22: Summations and Normalisations of Downtime Attributed to the Prime Contractor and DND, Respectively, for an Individual Downing Event.

After normalisation, the downtime attributed to DND and the Prime Contractor, respectively, for individual downing events can be summed for any desired period. The unavailability attributable to the Prime Contractor, $A_{U\text{-}C} = (A_{U,AMT\text{-}C} + A_{U,MDT\text{-}C})$, is obtained by dividing the total downtime attributed to the Prime Contractor by the period of summation – known as the Total Program Time (TPT).

4.5.2 Contractual Accountability for Aircraft Unavailability in the Canadian MHP

The most basic accountability provision of the MHP ISS Contract is the scaling of ISS payments to the Contractor as a function of the number of hours flown by the MH fleet in a given fiscal year. This is known as Cost-per-Hour, or Power-by-the-Hour™ [1]. If the aircraft does not fly, the Contractor does not get paid. For planning purposes, DND has projected a nominal annual flying rate, and provides a guaranteed minimum.

The ISS Contract also incorporates a number of disincentive and incentive adjustments to Cost-per-Hour payments based upon levels of performance achieved relative to specified requirements for several performance measures. The key disincentive is that associated with a failure of the Contractor to satisfy the AU-C requirements; for each percentage point AU-C is above the specified requirement the Cost-per-Hour rate is reduced by one percent, to a maximum of 15.00%. Satisfaction of this key contractual requirement is also a gate through which the Contractor would be eligible to earn incentive payments against additional performance requirements that are incentivized.

Although performance measurement will begin upon DND acceptance of the MH, the financial accountability provisions of the Contract will not be enforced until the fiscal year following that in which the MH fleet has accumulated a grand total of 10,000 flying hours from the date/time of acceptance. This is intended to provide appropriate duration of time for initial learning related impacts on performance to be realized without formal consequences that would be inappropriate, and for the Contractor to fine-tune the PMS to provide the most-accurate outputs practicable.

As of January 2007, Sikorsky has achieved the critical design review milestone for the aircraft, and the preliminary design review milestone for the Integrated Support System. Over the next two years, the design of the Performance Measurement Service and its associated Integrated Information Environment Enabling System will be finalized and implemented. DND will participate in this process in an advisory capacity only to clarify stakeholder requirements, to witness iterative verification activities, and to conduct final scenario-based validations both of each individual support service, and of the entire integrated support system.

4.5.3 Summary of Case Study in Performance-Based Contracting

Béland and Hollick conclude that the Defence Industry within Canada and its Allies will perform an increasingly vital role in supporting DND's ability to achieve mission success. This role will be accomplished within contractual frameworks that are optimized to leverage commercial best practices in consideration of operational constraints. The MHP is a lead implementer in the Canadian Forces of a performance-based contract that is availability (A_O) centric.

As a key determinant of military mission success, fleet A_O is decomposable into organizationally attributable unavailability metrics. The MHP used such decomposition as the basis for specifying Contractor-attributable unavailability requirements in its In-Service Support Contract with Sikorsky Aircraft Corporation.

[1] Power-by-the-Hour is a registered trade name owned by Rolls-Royce plc.

Contractor-attributable aircraft unavailability requirements are divided into two groupings each of which is treated as system design attributes. Unavailability (downtime) due to active maintenance time is treated as a design attribute of the aircraft system, and unavailability due to maintenance delay time is treated as a design attribute of the contractor-supplied In-Service Support (ISS) system. For this reason, PMO MHP has required the Prime Contractor, Sikorsky, to apply a systems engineering approach to the design of these each of these entities, which will culminate in a demonstration of the design's compliance with the applicable availability requirements.

The main accountability provisions in the MH ISS Contract are financial in nature. The first is payment that is based on the product of the number of hours flown in a given fiscal year and the quoted rate per flight-hour. The second is a disincentive adjustment to the rate should aircraft unavailability exceed maxima specified in the ISS Contract. The last financial provision, eligibility for which is conditional on availability requirements being satisfied, is an incentive program based on levels of performance achieved relative to other performance requirements specified in the ISS Contract.

The factors that are critical to the successful implementation of the Canadian MHP measurement model have also been mentioned. Even more important than the various technical factors, which are mostly associated with the information technology enabling system, are the organizational/human factors. It is critically important to achieve cultural acceptance of transitioning to an environment that is quantifiably performance-oriented.

4.6 DISCUSSION AND CONCLUSIONS

In status reporting to higher authority, available and non-available aircraft are usually divided into sub-categories, so that commanders have a better picture of force capability. For example, available aircraft may be categorised as fully or partially capable of assigned missions. Unavailable aircraft may be divided into sub-categories that allow the unavailability to be attributed to particular aircraft systems and functions in the maintenance/support system, such as supply. This categorisation also allows the statistics to be used later to improve the design and management of the maintenance/support system.

At the highest level, the USAF coding system divides aircraft into two mutually exclusive categories: Mission Capable (MC), and Non-Mission Capable (NMC). At the next level down, MC aircraft are categorised as either Fully Mission Capable (FMC) or Partially Mission Capable (PMC). In NATO forces that use a set of codes for general status reporting similar to those of the US DoD, the statistics of aircraft availability usually refer only to the portion of a fleet that has been assigned to active duty, i.e. to operating bases. The UK has also recently adopted this practice.

An aircraft may be down for preventive (scheduled) maintenance, corrective (unscheduled) maintenance, or a combination of these. Moreover, it is quite possible that on-aircraft maintenance tasks or logistics delays may occur on several components in parallel at any given time. Therefore, it is not always possible to attribute an aircraft down state to one specific cause. On the other hand, in the case of specific components, it is often possible to attribute a down state to one cause. Therefore, if the serviceability state of every component and/or the general status of every maintenance task were tracked in time, the aircraft state at any point in time could be almost fully reconstructed from the data. Such an approach may be feasible with current technology in information systems.

Some Air Forces have operated maintenance data systems for many years. These systems are still evolving, and unfortunately do not yet allow the downtime history of individual aircraft or fleets to be reconstructed easily or fully. Therefore, statistics on downtime and availability tend to come from daily state reports from operational units to higher formations. As mentioned above, these contain limited detail on the causes of aircraft downtime. With a lot of effort, the USAF (Hart) extracted some useful data on the drivers of downtime in USAF C-5 long range transport aircraft from the USAF's maintenance data system. These showed that during the (fiscal year) period 1991 – 2006, C-5 aircraft at operating units were unavailable (NMC) for 37% of the time against a target of 25%. The total annual average downtime increased from a low of 29% in 1991 to a high of 44% in 2006.

Hart provided the breakdown of downtime by maintenance category. Unscheduled maintenance tasks on all systems and related supply delays accounted for significantly more downtime than scheduled maintenance tasks and related supply delays. Supply delays alone caused annual average downtime amounting to between 5% and 10% of the total operational period. This is a large proportion of the total annual average downtime of 29% to 44% at operating bases during 1991 to 2006. Hart also provided a breakdown of scheduled and unscheduled downtime by major system. Unscheduled maintenance work was the cause of between 24% and 32% annual average downtime at operating bases during 1991 – 2006. In this context, engines, landing gear, airframe, and flight controls were the most significant systems, each consistently contributing roughly 5% to annual average downtime. In contrast, the annual average downtime due to scheduled inspections on all systems varied between 5% and 12% during this period. A breakdown of this figure by system was not supplied.

Comparable data, but with less detail, for an unspecified long range transport aircraft was presented by Boeing (Andresen). Like Hart's data, these data showed that when the aircraft were at operating units, unscheduled maintenance tasks were by far the largest contributor to aircraft downtime. When depot maintenance was taken into account, scheduled and unscheduled maintenance each accounted for about 40% of the total downtime from all causes.

The downtime data just summarised appears to represent the maximum depth of historical analysis that is currently feasible. Future maintenance systems will hopefully permit greater ease and depth of analysis. When they have been in place for long enough, a better historical assessment of the actual drivers of aircraft downtime should be possible. The information in the current chapter indicates that scheduled and unscheduled maintenance are equal drivers of downtime for long range transport aircraft, and that supply delays alone account for a significant portion of this downtime. The main mechanical component groups/systems – engines, landing gear, airframe, and flight controls – are equal drivers of unscheduled downtime. Other component groups/systems contribute less downtime, but are nevertheless significant. Thus, to improve aircraft availability, broad-based action on all causes of downtime is needed.

Discrete event modelling is a useful method of investigating the effects of various parameters on the availability of fleets and individual aircraft. For this purpose, the time an aircraft is available (up time) is regarded proportionally as (1 – downtime), and available time is derived from a set of sequential and parallel models of elements of downtime. Each element of downtime is governed by relevant parameters of the aircraft, the operating environment, and the support system. The same elemental sub-division of downtime can be used retrospectively to measure the contribution of each element to the total downtime. However, human factors and the need for efficiency place practical limitations on the amount of detail that can be recorded in an information system.

Two Discrete Event Simulation (DES) models were discussed in this section, one by Boeing IVHM Center (Andresen) for an unnamed long range transport aircraft, and the other by MOD UK (Cook) for Chinook helicopters. Both were designed to model the impact on availability, cost, and other statistics of Integrated

Vehicle Health Management systems, and to assist with their design. Therefore, they are fairly detailed and complex models. Illustrative examples of model output were given.

The Boeing model of the maintenance of a long range transport aircraft predicted that an increase of 50% in MTBF or a reduction of 30% in MTTR could increase operational availability by about 5%. The potential impact of different systems is also shown. It also predicted that a manning level of about 50% of that needed to cope with maximum operational tempo would achieve a good trade-off between availability and efficiency. At this manning level, the average utilisation of the available manpower would be just under 50%.

MOD UK has used its model to investigate the effect of operational environments, logistics policy, and maintenance policy on the downtime of Chinook helicopters due to spares delays. Six different deployments were modelled, with and without deployed stocks of important components. Averaged over the different deployment scenarios, the local holdings of spares reduced the downtime due to spares delays from 7% to 3.5%. The model predicted that this downtime due to spares could be reduced to zero in both cases by including a Health and Usage Monitoring System (HUMS) and adopting a maintenance policy that allowed what Cook refers to as a Predictive Maintenance Window (PMW) of 10 days. The use of HUMS and a PMW was predicted to reduce the overall downtime due to corrective maintenance from 11% to 6.2%, a net reduction of 4.8%. For the larger deployments, a PMW of 10 days was sufficient to gain most of the maintenance and supply planning benefits. For smaller deployments with fewer aircraft and technicians, e.g. the Falklands and Afghanistan, a PMW of up to 30 days could be beneficial.

Cook's concept of a PMW is an important goal of current R&D in the automation of "on-condition tasks". On-condition tasks are designed to detect potential failure so that corrective action can be taken before functional failure occurs. As discussed in Chapter 2, they are a fundamental concept of Reliability Centred Maintenance (RCM). If a potential failure can be detected early enough, it may be feasible to defer corrective maintenance for a limited period – the PMW – without undue risk to the aircraft. A PMW can provide operational and logistical flexibility.

The implementation of a PMW would not always require automated, continuous inspection using on-board sensors; however, it would in the case of highly stressed, single load path mechanical components, such as helicopter rotor and transmission components. In such cases, a HUMS would be needed to provide signal processing, monitor the usage of the components in question, and provide outputs to the aircrew and groundcrew. In some cases, it may be necessary for the HUMS to provide updates of the remaining useable life of a component – known as prognostics. HUMS have been in use for many years on some helicopters, because they enable on-condition inspections as an extra measure of safety for components that are primarily managed by means of a safe life. However, it has not yet been possible to apply the PMW concept widely, because of technical, economic, and regulatory hurdles. As discussed later in Chapter 6, this may be changing with the development of new inspection technologies and the greater integration of vehicle health management systems with other aircraft systems.

The predictions by Boeing for long range transport aircraft and by MOD UK for Chinook helicopters presented in this chapter point to the potential value of operations research, in particular DES modelling technology, in finding managerial and technical strategies for increasing aircraft availability and reducing life-cycle cost. The AVT-144 Technical Team had difficulty in finding public examples of operations research into aircraft maintenance and availability. Consequently, it has not been possible to include much output from such models in this report.

Availability modelling and a robust maintenance data system are key enabling technologies for availability-based contracting, also known as Performance-Based Contracting/Logistics (PBC and PBL). In this case, the modelling is necessary to establish appropriate requirements for the aircraft and support system, to manage the support system throughout the life cycle, and to ensure that the prime contractor will make an adequate profit. This chapter has presented in some detail the measurement, modelling, and business approaches used recently in the acquisition and support contracts for the Canadian Maritime Helicopter Program (MHP), and has highlighted some of the technical and human factors essential to success in implementing these approaches. For purely contractual purposes, there is a need for metrics that allow responsibility for aircraft downtime to be allocated automatically using agreed business rules to either the customer or the prime contractor. The contractor may also need data that will allow him to attribute responsibility among his sub-contractors. Apart from these additional metrics, availability-based contracting requires similar metrics to those needed for managing maintenance more effectively from the perspective of aircraft availability and life-cycle cost. Therefore, the increasing use of availability-based contracting will provide considerable impetus to the development of better maintenance data systems and availability models.

Chapter 5 – MAINTENANCE/SUPPORT MANAGEMENT CONCEPTS AND TECHNOLOGIES FOR IMPROVING AIRCRAFT AVAILABILITY AND MISSION RELIABILITY

5.1 INTRODUCTION

It was pointed out in Chapter 2 that the improvement of aircraft availability required a dual approach of reducing the need for maintenance and the associated downtime, and some through-life goals were derived, as follows:

Through-life goals for minimising the need for maintenance are as follows:

a) Design to maximise the inherent (design) reliability and mission reliability.

b) Resolve any shortcomings in manufacture and maintenance that are inhibiting the achievement of the inherent reliability, or at least the specified reliability, in service.

c) Limit maintenance to essential tasks.

Through-life goals for minimising downtime are as follows:

a) Design the aircraft for maintainability (ease of maintenance).

b) Reduce the downtime for servicing (replenishments).

c) Reduce the downtime for replacement/restoration of lifed components by:

   1) Designing for aircraft maintainability with particular attention to the components in question;

   2) Extending remaining useful life;

   3) Improving the scope and accuracy of usage monitoring; and

   4) Using on-condition inspection instead of component replacement/restoration.

d) Reduce the downtime for inspections, i.e. on-condition and failure-finding tasks.

e) Reduce the downtime for "age exploration".

f) Reduce the downtime for diagnostics.

g) Reduce the downtime for failures that cannot be duplicated (CND).

h) Reduce the downtime for repair.

Making progress towards these goals is a complex managerial task. Some strategies were outlined in Chapter 2. This chapter describes some advanced maintenance/support management concepts and technologies that can help implement these strategies. Advanced concepts and technologies need not be new. They may be established concepts and technologies that have reached an advanced stage of development. The chapter covers the following categories of management concepts and technologies:

- Systems engineering and project management.
- Integrated Logistics Support (ILS).
- Availability-based contracting – also known as Performance-Based Logistics (PBL).
- Reliability and Maintainability (R&M) management.

- Aircraft/Engine Structural Integrity Program (ASIP and ENSIP).
- Total Life-Cycle Systems Management (TLCSM) and Through-Life Capability Management (TLCM).
- Integrated Project Teams (IPT).
- Technology Insertion (TI).
- Manufacturing management (primarily quality control).
- Reliability-Centred Maintenance (RCM) to determine essential maintenance and optimum failure management strategies.
- Lean and other enterprise management concepts.
- Maintenance management decision support.
- Integrating the maintenance/support system for a major program.

Modelling and simulation of the maintenance/support system is also an important maintenance/support management technology. It has already been covered in Chapter 4, and so is not listed above.

The scope of the chapter is limited to concepts and technologies for the planning, organisation, direction, and control of maintenance/support. Maintenance/support concepts and technologies that would be incorporated in the design of the aircraft or that would improve the execution of maintenance tasks and the supply of materiel to the aircraft are covered in the next chapter. This chapter breakdown is only for convenience in organising the material of the report, since the improvement of aircraft availability and mission reliability often requires integrated managerial and technical solutions.

The chapter does not cover all management concepts and technologies that could benefit aircraft platform availability. There are other relevant concepts and technologies that could not be covered in the time available to the AVT-144 Technical Team. We would like to have provided more information in the following areas:

- *Management concepts and technologies to improve the speed and reliability of the supply chain*, including the following: relevant Information and Communications Technologies (ICT); supply system modelling; Packaging, Handling, Storage, and Transportation (PHST) concepts for aircraft and components, particularly for deployments/expeditions; long-term storage concepts; the potential of Radio Frequency Identification (RFID); concepts and technologies to deal with parts obsolescence.
- *Concepts and technologies associated with the management of Human Factors Integration (HFI)* in maintenance/support, in particular those associated with training and modelling/simulation.

5.2 SYSTEMS ENGINEERING AND PROJECT MANAGEMENT

The design and management of an aircraft and its maintenance/support occurs in the context of many competing priorities for the available development and operating funds. Therefore, it is important that a systematic approach is followed that takes account of all important requirements and factors. A quotation from a United States Government Accountability Office (GAO) report on the F-35 Joint Strike Fighter (JSF) program [49] illustrates the point:

> "Increased program costs, delayed schedules and reduced quantities have diluted DoD's buying power and made the original JSF business case unexecutable. Program instability at this time makes the development of a new and viable business case difficult to prepare. The cost estimate to fully develop the JSF has increased by more than 80%. Development costs were originally estimated at roughly US$25 billion. By the 2001 system development decision, these costs increased almost US$10 billion,

> and by 2004, costs increased an additional US$10 billion, pushing total development cost estimates to nearly US$45 billion. Current estimates for the program acquisition unit cost are about US$100 million, a 23% increase to the estimated program cost. At the same time, procurement quantities have been reduced by 535 aircraft and the delivery of operational aircraft has been delayed. …………. The need for design changes largely resulted from the increased weight of the short takeoff and vertical landing variant and the impact it was having on key performance parameters. The other JSF variants' designs were affected as well."

Systems engineering is the systematic approach needed. Project management is the discipline used to manage the systems engineering process so that there will be a high probability of meeting the project requirements, including aircraft availability, within the required budget and schedule. Both disciplines are constantly evolving. It is important that the aircraft program employs the most advanced methods and that the senior engineers and managers are thoroughly trained and experienced in both disciplines. Despite our best efforts, programs still run into problems, particularly when they include some high risk elements, as illustrated in the JSF example above. However, these problems would be much greater, and the chances of success much less, if we did not use advanced systems engineering and project management methods.

Systems engineering is already widely used in the management of aircraft acquisition and in-service support and in many other engineering fields. ISO 15288 [50] provides a generic and detailed description of standard sub-processes that can be included, to the extent applicable, in a systems engineering process. In the context of military aircraft design and maintenance/support it can be described as the application of scientific and engineering efforts to transform an operational need into a description of a system configuration which best satisfies the operational need according to the measures of effectiveness. To this end, it integrates related technical parameters and ensures compatibility of all physical, functional, and technical project interfaces in a manner that optimizes the total system definition and design to provide a reasonable balance between performance, acquisition cost, and LCC. It also integrates the efforts of all engineering disciplines and specialties into the total engineering effort.

A more general definition based on a wide consensus has been provided by the International Council of Systems Engineers [51]:

> "Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle. This process is usually comprised of the following seven tasks: State the problem, Investigate alternatives, Model the system, Integrate, Launch the system, Assess performance, and Re-evaluate. These functions can be summarized with the acronym SIMILAR: State, Investigate, Model, Integrate, Launch, Assess and Re-evaluate. It is important to note that the Systems Engineering Process is not sequential. The functions are performed in a parallel and iterative manner."

Systems integration is a process within the systems engineering process and should not be confused with systems engineering.

The terminology, details, and rigour of the systems engineering process vary by Nation and organisation, and have evolved over the years. Its importance throughout the life-cycle is illustrated by the following quotation from the UK's 2005 review of defence industrial strategy [52]:

> "In a period when platforms are likely to remain in service for many years, unless systems engineering capability and vital long-term knowledge are maintained, it is little use investing in cutting-edge science.

New technologies will have less benefit without knowledge of how they might be exploited and inserted into existing equipment.

Although it appears to have been replaced by other DoD handbooks, Mil-Hdbk-502 [53] remains one of the best introductory guides to the use of systems engineering in the acquisition and support of military aircraft. This document provides a diagram of a generic systems engineering process (Figure 5-1). For the life-cycle management of a military aircraft, this can be applied to the aircraft and its maintenance/support system as a whole, in which case the process outputs would be capabilities that can be included in various force capabilities (see Chapter 2). The process can also be applied specifically to the design of the aircraft, its maintenance/support system, or to any element of these. When applying the process, it is important to define the boundaries of the system clearly. One of the most important concepts within systems engineering is functional analysis. This consists of defining the functions required to meet the requirements, decomposing them to an appropriate level, and then allocating them to groups of functions that will be embodied in an element of the system. The elements in question may be a mechanical component, an electrical component, electronic hardware, software, persons, some other resource, or some combination of these at any level in the system.

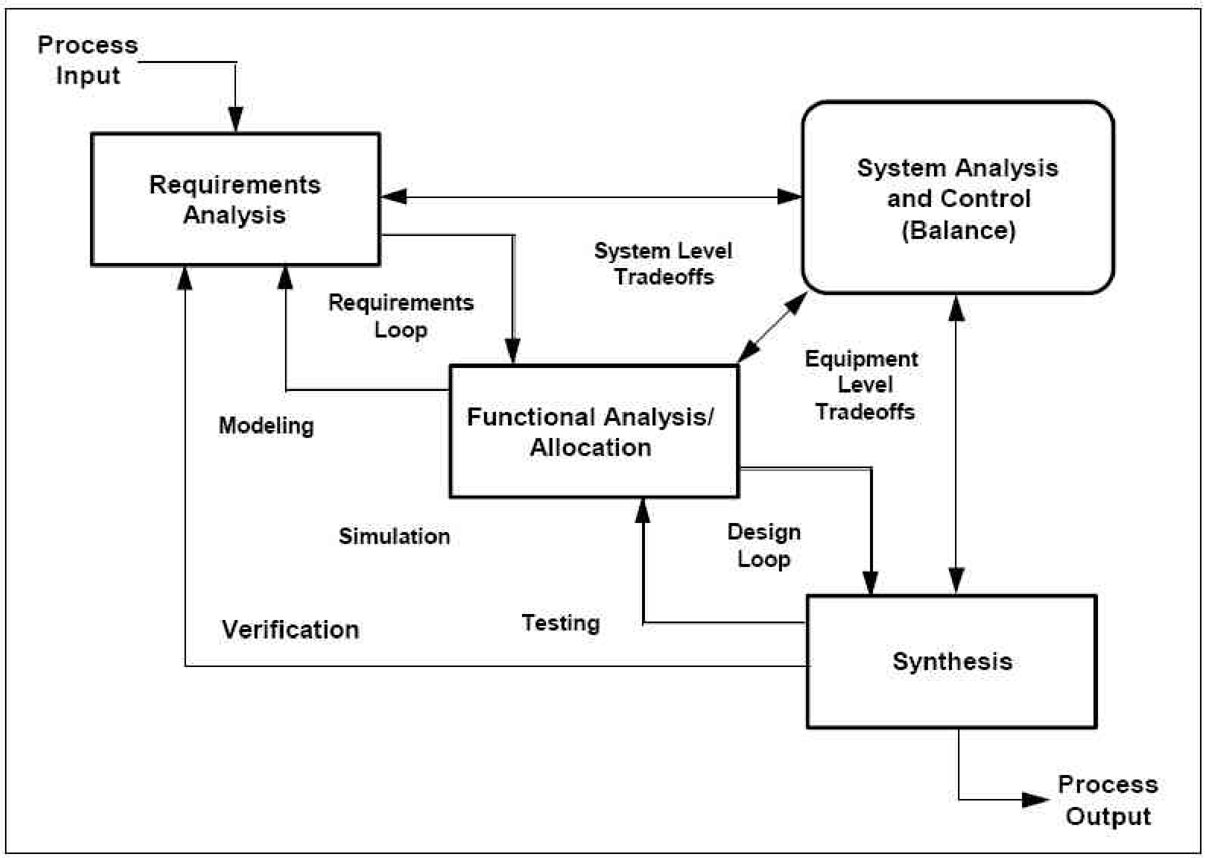


Figure 5-1: Systems Engineering Process Flow. (Source: Mil-Hdbk-502 [53])

Systems engineering has become an important engineering discipline over the past fifty years, and it is important that the best available concepts and technologies are used in the design and management of aircraft and their maintenance/support systems.

5.3 INTEGRATED LOGISTICS SUPPORT

Within the system life-cycle framework, many NATO Nations use a major sub-process known as "Integrated Logistic Support" (ILS) to co-ordinate the design of the aircraft and its in-service support to meet the aircraft specification at lowest cost.

Integrated Logistic Support (ILS) was first defined and implemented by the US DoD in the 1980s. Logistics Support Analysis (LSA) as defined in Mil-Std-1388 [21] is the core process of ILS. The ILS management concept was adopted by many other NATO Air Forces. The US DoD no longer mandates ILS by this name, but still promotes the use of robust systems engineering methodologies. The program manager and industry are now given the freedom to define their preferred approach within the policy laid out in the latest versions of DoD Directive 5000.1 [54] and DoD Instruction 5000.2 [55].

ILS provides the disciplines for ensuring that supportability and cost factors are identified and considered from concept and throughout the life of equipment, with the aim of optimizing the life-cycle cost. Supportability is defined as the degree to which system design characteristics and planned logistic resources, including manpower, meet the system peacetime and wartime availability requirements.

LSA is the principal tool of ILS. It is defined in NATO ARMP-7 as the selective application of scientific and engineering efforts undertaken during the acquisition process, as part of the system engineering process, to assist in:

- Causing support considerations to influence design;
- Defining support requirements that are related optimally to design and to each other;
- Acquiring the required support; and
- Providing the required support during the operational phase at minimum cost.

The UK, Germany, Canada, and other NATO Nations have continued with ILS based on approach to LSA in Mil-Std-1388. The UK has made considerable efforts to ensure that ILS and the associated Reliability and Maintainability (R&M) concepts are published in comprehensive, well publicized, and readable documents. These include Defence Standards 00-40 [56], 00-41 [57], and 00-60 [58]-[59] and the MOD Guide to ILS [60]. Canada's ILS manual, A-LM-505-001/AG-001 [61], is a comprehensive, self-contained document in English and French. It is well written, concise, and easy to read. It clearly explains the link between in-service support and weapon system effectiveness.

The importance of starting ILS management at the concept design stage is illustrated by Figure 5-2 and Figure 5-3, which are taken from Paper 3.3 by Buderath. The figures illustrate the distribution of expenditures during the life-cycle. Most of the expenditure (60%) occurs during the operation and support phase. Design and development account for only 7% – 12%, while production accounts for only 25% – 28%. However, the decisions taken during the design and development phase can determine about 95% of total life-cycle cost. A comparable expenditure profile has been published by the US GAO in [62], and is shown in Figure 5-4. To minimise life-cycle costs while designing to meet key requirements such as aircraft availability, it is important not only that ILS be started early, but that it be integrated closely with design in the manner illustrated by Buderath in Figure 5-5.

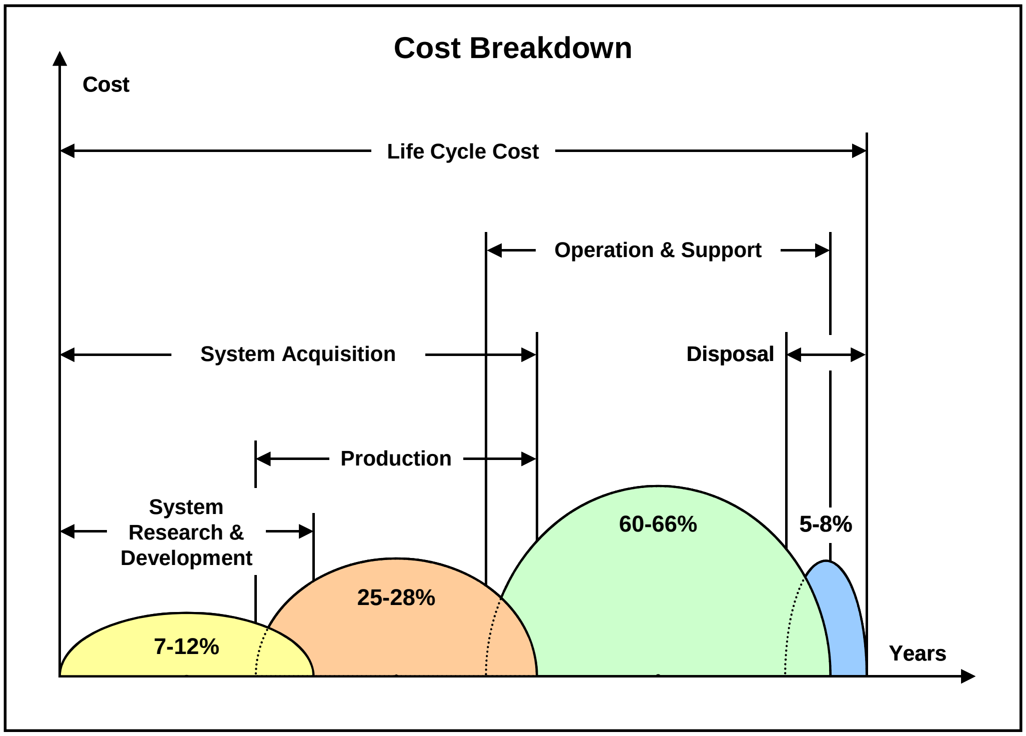


Figure 5-2: Current Cost Breakdown of Product Support in the Development Phase.

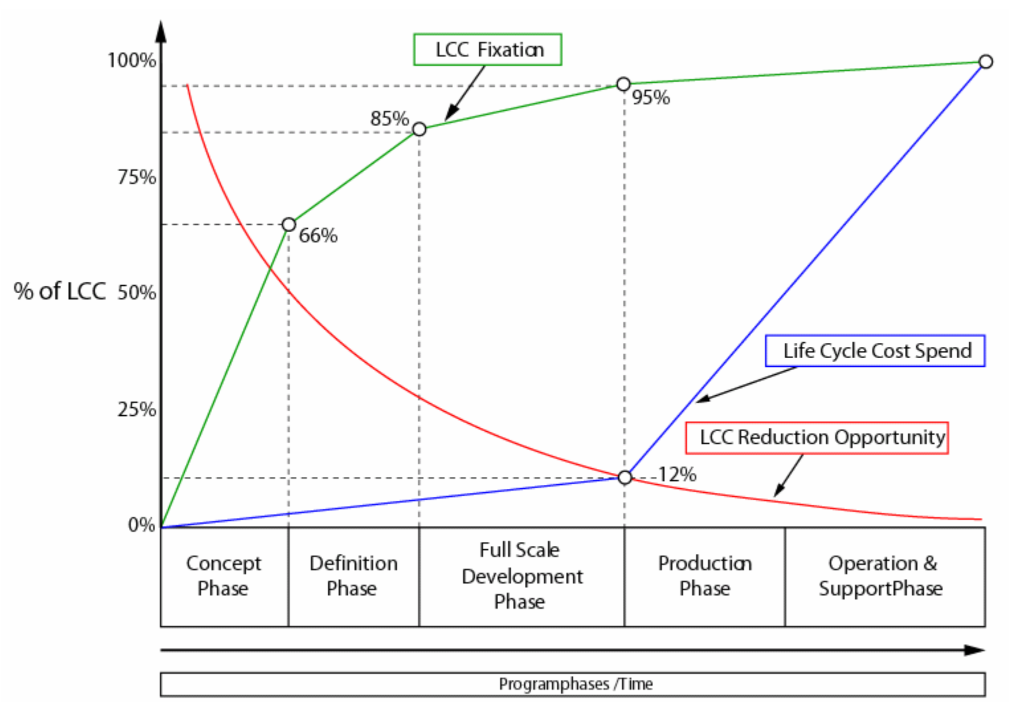


Figure 5-3: Illustration of How Most of the Life-Cycle Cost is Determined by Decisions Made Prior to Full Scale Development.

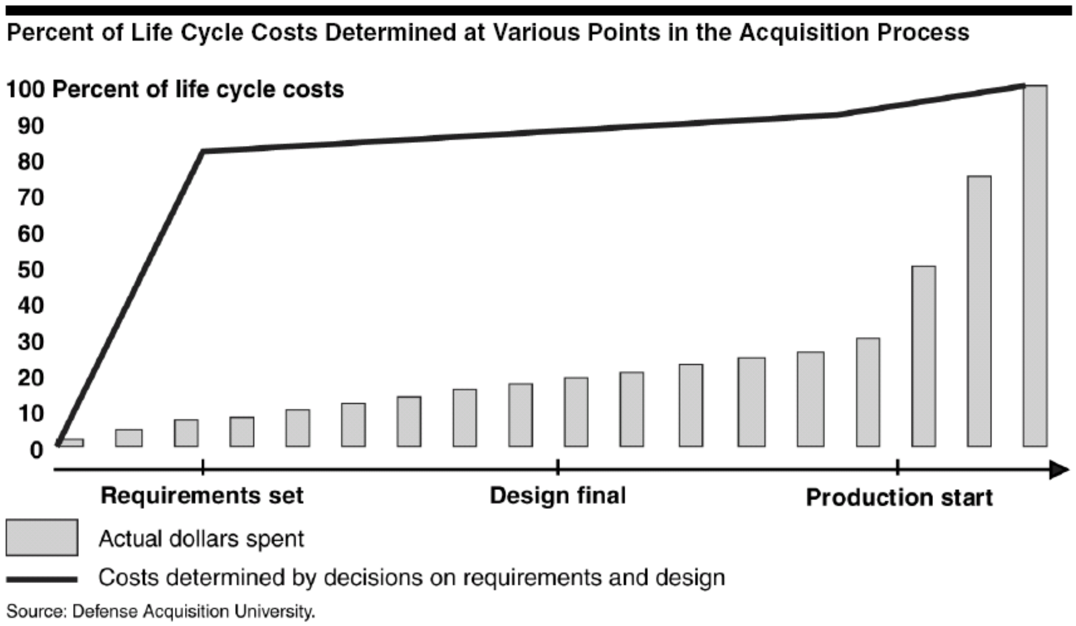


Figure 5-4: Illustration from a US GAO Report [62] of the Percentage of Life-Cycle Costs Determined at Various Points in a Typical Military Acquisition Process.

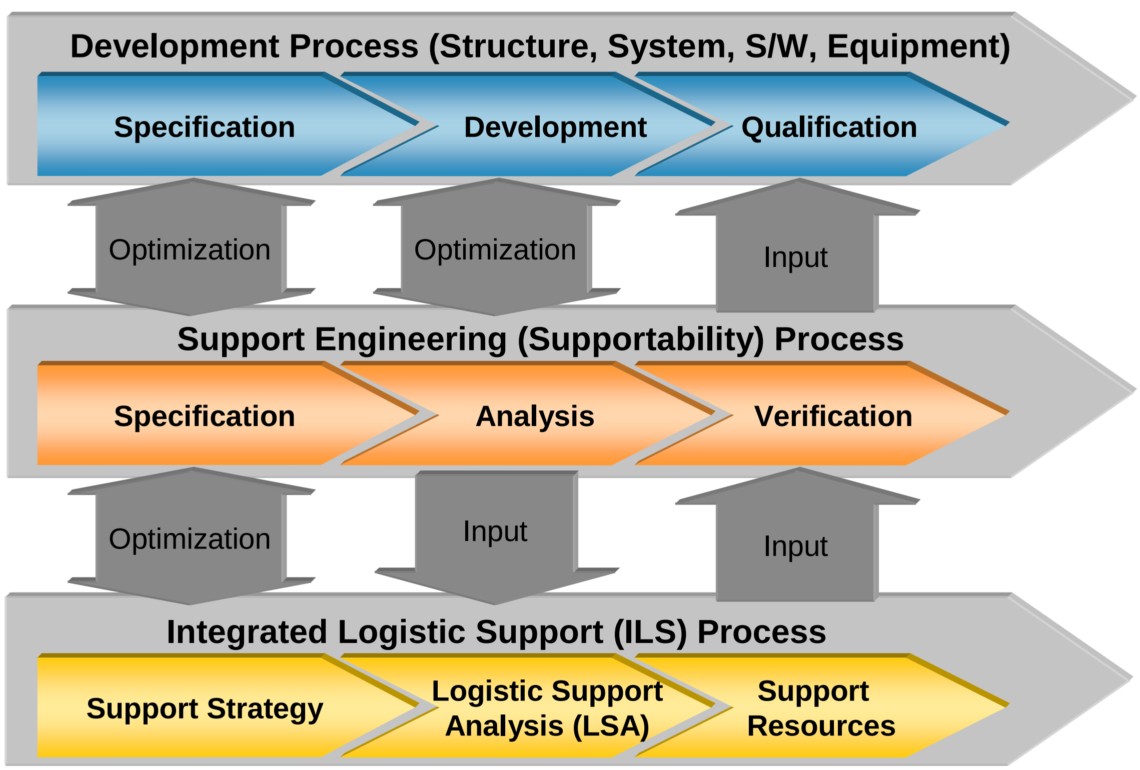


Figure 5-5: The Integration of Integrated Logistic Support (ILS) and Aircraft Design.

While the details of the ILS process vary between Nations, the general approach can be illustrated by the ILS process diagram in Figure 5-6, which is reproduced from MOD UK's Guide to ILS [60]. Reliability and Maintainability (R&M) analysis is not specifically shown on this figure. The UK manages R&M separately from ILS, but the results are recorded and used in the LSA. Failure Modes and Effects Criticality Analysis (FMECA) and RCM are shown as different activities within LSA. Some other countries / Armed Forces regard FMECA as an integral part of RCM.

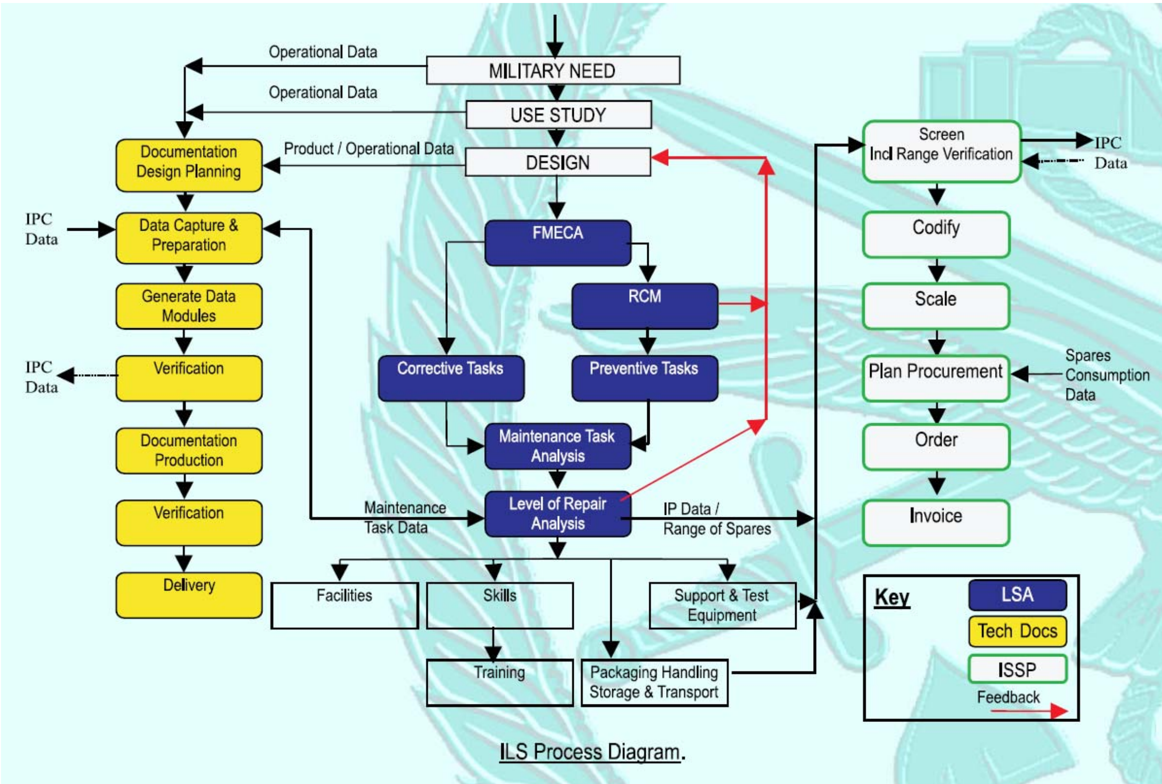


Figure 5-6: Process Diagram for ILS in MOD UK Guide to Integrated Logistic Support (IPC – Illustrated Parts Catalogue; ISSP – Integrated Supply Support Procedures; IP – Initial Provisioning).

ILS has both an influence on and draws information from the following disciplines and related elements:

- Maintenance planning.
- Supply support.
- Support and Test Equipment (S&TE).
- Computer resources support (Canada).
- Reliability and Maintainability (R&M), safety, testability and other design disciplines.
- Facilities.
- Manpower and human factors.
- Training and training equipment.

- Technical documentation.
- Packaging, Handling, Storage and Transportation (PHS&T).
- Disposal.
- Design interface (Canada).

Figure 5-7 shows how LSA and other ILS processes are intended to be performed iteratively to the appropriate depth throughout the system's life cycle. The iterations include updates of estimates of Life-Cycle Cost (LCC) for trade-off against availability and other parameters. The information generated during ILS activities is recorded in a computerised Logistics Support Analysis Record (LSAR). The life-cycle concept in Figure 5-7 is the UK's conceptual Defence Equipment Acquisition and Materiel Support (DEAMS) business process, which aims to provide and sustain equipment performance, and its availability, reliability and maintainability, at optimum LCC.

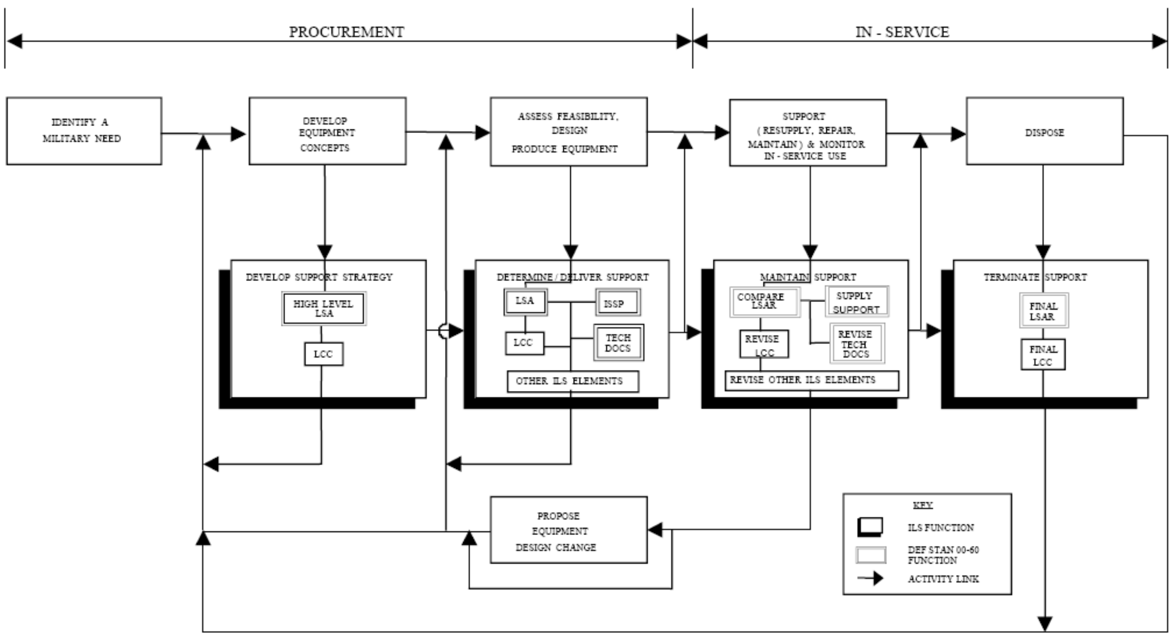


Figure 5-7: Illustration of ILS Activities Within MOD UK's Defence Equipment Acquisition and Materiel Support (DEAMS) Business Concept.

This has been only a brief overview of ILS, but it suffices to highlight what the most advanced practitioners of ILS regard as the most important elements of maintenance/support system and how they integrate the design of the design of the aircraft and the maintenance/support system. ILS management of this order is required to achieve the required aircraft availability with minimum risk and life-cycle cost.

5.4 AVAILABILITY-BASED CONTRACTING – ALSO KNOWN AS PERFORMANCE-BASED LOGISTICS (PBL)

In the past, governments tended to issue separate contracts for design/development, series production, and in-service support. Sometimes, parts of series production and in-service support were performed by contractors other than the OEM. Also, most of the heavy maintenance and supply management was performed by the services (i.e. organically). We have recently seen a dramatic transformation in this situation. Governments have started to enter into long-term partnerships with OEMs, whereby they are assured of contracts for series production and maintenance/support, including supply management. In some cases, the contracts hold the OEM accountable for the availability of the aircraft and other key performance parameters for periods of twenty years or more, and have provided incentives and penalties related to the achievement of the required availability at minimum life-cycle cost. This contracting approach is generally referred to as either "availability-based contracting", performance-based contracting", or "Performance-Based Logistics (PBL)", although other terms such as "power-by-the-hour™ contracting" are also used. It is sometimes used only for major sub-systems such as engines and landing gear.

The US DoD places great importance on PBL, and has defined the following five top level metrics that all PBL strategies should strive to maximize [63]:

- Operational availability;
- Mission reliability;
- Cost per unit of usage;
- Logistics footprint; and
- Logistics response time.

The UK National Audit Office (NAO) reports in [64] that platforms that are now handled under a full "future contracting for availability" full-life maintenance framework (i.e. pays for available aircraft rather than paying for spares) include the UK's CH-47 helicopters, E-3D Sentry AWACS radar surveillance aircraft, and Tornado fighters. Platforms that are using contracting for availability but are not yet through-life contracts, or are progressing via availability contracts for sub-systems, etc., as they work their way up, include the RAF's Hawk trainers, Harrier jets, VC10 aerial tankers, Nimrod maritime patrol aircraft, and others. Recent events include the signing of a Long-Term Partnering Agreement (LTPA) Foundation Contract with BAE Systems. It covers intended progress toward an eventual binding agreement that will provide effective through-life support to the RAF's entire fixed wing fleet for front line service.

Even if availability-based contracting is initiated after the design contract, and even well into an aircraft's life, it might nevertheless help to realise substantial benefits. For example, the same NAO reports indicates that, by greater partnering with industry, MOD UK has greatly reduced Tornado and Harrier operating costs, while maintaining the same number of flying hours:

> "The Tornado Integrated Project Team's costs have reduced from £601 million in 2001 – 02 to £258 million in 2006 – 07. The cumulative savings over the period amount to £1.3 billion. The Department projects that the annual cost will fall further, to £250 million by 2010 – 11. The Harrier Integrated Project Team's costs have reduced from £110 million in 2001 – 02 to £70 million in 2006 – 07, excluding the capital cost of the upgrade programme (Figure 7 on page 17). The cumulative savings over the period amount to £109 million. The majority of the cost reductions have been achieved through working with industry to reform traditional contracts, as the Department prepared for and introduced the Harrier Joint Upgrade and Maintenance Programme in November 2004, and the

> Tornado Combined Maintenance and Upgrade pulse line for the Tornado GR4 in December 2005. Over the same period, the Department has maintained a broadly similar level of flying hours and the cost per flying hour has reduced for both aircraft fleets."

These are impressive numbers, but it is difficult to assess the specific contribution of incentivised contracts compared with other managerial improvements, since the savings reported by the NAO occurred during a period of major transformational changes in the organisation of acquisition and maintenance/support and from a concerted effort to improve efficiency through Lean Enterprise Management. Moreover, depth maintenance of the Tornado and Harrier aircraft was not performed by industry during the period in question.

A similar question exists in the USA. The US Government Accountability Office (GAO) has advised DoD that special procedures should be established to evaluate whether PBL is resulting in cost savings and improved responsiveness [65].

A concern about greater partnering with industry in maintenance/support is the potential loss of in-house or organic expertise. One fear is that the Armed Forces and government will no longer be able to manage industry effectively. This risk is eloquently expressed in a paper by Caruso, a member of the US Navy's Aging Aircraft IPT [66]. Another is that it will not have direct control over key resources in times of heightened tension and combat. Yet another is that the Air Force will no longer be able to field sufficient personnel with in-depth experience and knowledge in times of combat. For these and other reasons, the US Congress has legislated that at least 50% of depot maintenance must be performed organically. The UK's Defence Industrial Strategy of 2005 [67] does not include any such requirement. Instead there is a strong emphasis on through-life partnering with industry on major systems. In view of the UK's limited defence industrial base, competitive tendering for major systems may not always be feasible, cost-effective, or in the national interest. Therefore, the UK also envisages greater transparency on both sides of future requirements, organisation, and costs. To ensure an adequate cadre of trained and experienced military personnel, the RAF places engineering officers and maintenance technicians in industry to work on contracts alongside company staff.

The French Air Force relies on industry for depth maintenance, and hopes that the new organisation SIMMAD will be able to work with industry to reduce escalating costs as well as improve aircraft availability. Their efforts are focussed on providing centralised, expert management of contracts, including a clear definition of priorities and trade-offs, changing from a culture of acquisition to one of maintenance/support, and collaborating with the other services in achieving economies of scale in contracts. The following quotation from General Richard Wolsztynski, Chief of Staff of the French Air Force describes the situation [68]:

> « La SIMMAD, nouvelle structure intégrée, n'a pas encore atteint son régime de croisière, alors que le passif à résorber représente un véritable défi, mais elle a permis d'importants progrès : le taux de disponibilité est, d'ores et déjà, de deux avions sur trois. ……….. Les résultats obtenus dépendent cependant de plusieurs paramètres, notamment celui de la hausse des coûts de MCO pouvant atteindre parfois plus de 50%, coûts difficilement négociables avec les industriels en position de monopole. La situation d'ensemble s'est améliorée, mais il devrait être possible de faire mieux encore grâce à des contrats définissant clairement les priorités, plutôt que de chercher à obtenir à tout prix une disponibilité maximale. ………..… La SIMMAD, tout comme l'armée de l'air dans son ensemble, a un plan de résorption de ses reports de charges, et il faut lui laisser le temps de le mettre en œuvre. Il est positif que le chef d'état-major des armées soit désormais associé à son comité directeur. Le principe d'une organisation traitant les contrats de façon globale est, à l'évidence, la meilleure façon de maintenir une certaine pression sur les industriels chargés du MCO, grâce à une connaissance beaucoup plus fine des prix. L'armée de l'air est bien sûr associée à la mission de l'ingénieur général Louis-Alain Roche, laquelle devrait favoriser le passage d'une logique d'acquisition à une logique de possession. »

The concept of including performance requirements in a contract is plain good sense. However, as explained above, availability-based or performance-based contracting in the context of aircraft design and maintenance/ support implies a shift from the traditional role of the Government as the planner and provider of maintenance/ support. It offers considerable potential advantages for aircraft availability and life-cycle cost, but there are long-term risks to military capability that need to be addressed.

5.5 A CASE STUDY IN SYSTEMS ENGINEERING AND AVAILABILITY-BASED CONTRACTING STRATEGIES

This section is based on part of Paper 3.1 by Béland and Hollick.

5.5.1 Optimized Weapon System Support

A very interesting case study in the application of systems engineering and availability-based contracting to aircraft acquisition and support in a modern context is given by Béland and Hollick in Paper 3.1. The Canadian Department of National Defence (DND), like many of its western military counterparts around the world, has, since the early 1990s, been subject to significant Government-directed downsizing and reductions in both capital and O&M budgets. Whether in response to these initiatives or coincidental to them, some level of coping was enabled by emergent methodologies/concepts such as business process re-engineering, alternative service delivery, and to a lesser degree, the Kaplan and Norton balanced scorecards. Although in recent years the operational demands have increased due to terrorist-propagated conflicts, there has not been a commensurate increase in either staffing or funding. The effect has been most pronounced in the National Defence Headquarters which includes Associate Deputy Minister (Materiel) Group (ADM(Mat)), which is responsible for the acquisition and support of all materiel used by the Canadian Forces, including new fleets of aircraft, ships, and tanks.

It had become increasingly apparent to senior Project and Weapon System managers within ADM(Mat) that there was insufficient qualified and experienced human resources to support continued use of the existing Materiel Acquisition and Support (MA&S) processes. The key features and associated major shortcomings of this “traditional” approach have been characterized in an ADM(Mat) sponsored study as summarized below:

- DND Project Offices over-prescribe the methodologies (e.g. LSA as per Mil-Std-1388) and deliverable data by and with which, respectively, DND will acquire and/or establish the support resources deemed to be needed to assure that an effective level of support will be provided to military operators, but without the benefit of sufficient verification due to cost constraints.
  - DND not only incurs the cost of producing often voluminous contractual documentation, but often pays for data which may not be required while assuming the full cost-risk of OEM estimates that with experience are often proved to be inaccurate (too high or too low).
- During implementation of a new fleet of systems (e.g. aircraft), DND separately competes for a scope of in-service support that is limited to: re-supply of spare parts (e.g. both consumables and repairables); the provision of component R&O and major system; and, the provision of technical investigations and engineering support. The OEM has seldom been awarded a contract to provide in-service technical investigation and engineering support for the aircraft he produced.
  - The practice of tendering many small support contracts squarely places DND in the role of system integrator and has promoted a fragmented industrial base in Canada.
  - Beyond the limitations of acceptance testing, OEMs are not held accountable for system performance shortcomings once the system is fielded.

- Contracts, which are awarded to individual suppliers, are typically structured with a method of payment that is based on cost of time and materials.
  - Use of time and materiel-based contracts leaves little motivation for Contractors to improve component performance, in fact, this would be a major disincentive to the Contactor as the more an item breaks, the more the Contractor is paid.
- DND organically provides all logistics support to end-user operators, with the exception of that indicated above, on the belief that scales of economy are realized by centralization of functions.
  - Centralization of support functions have left DND with a support capability that is not only fractured (i.e. not integrated), but removes the practical possibility of inter-function enhancement trade-offs in consideration of the cost-effective achievement of system level objectives.
  - There is no organization that is centrally accountable for all common organizational factors that affect fleet performance or the overall cost-effectiveness of fleet support.

Being the lead Air Force major capital project during this time period, the Maritime Helicopter Project (MHP) provided ADM(Mat) an opportunity to investigate and be the lead implementer of resolutions to the above noted shortcomings. One of the resolutions adopted was to seek to establish a long-term contractual relationship with an OEM. This resolution was incorporated into the MH procurement strategy which reflected the Government of Canada's intent to award, to the single OEM which emerged as the least cost compliant respondent to an RFP, the following Contracts to begin at the same point in time:

- A Contract for the procurement of 28 Maritime Helicopters with an award fee for on-time delivery of the first MH.
- A 20-year performance-based contract for the set-up and provision of a wide scope of support services.

Other resolutions, now referred to in ADM(Mat) as 'Optimized Weapon System Support' concepts, including those associated with the establishment of an A_O centric performance-based contract, were determined through an extensive consultation with Aerospace Industry in general, and specifically, prospective MHP bidders. This pre-RFP release consultation occurred during the 2000 – 03 time period. Final resolutions were incorporated into the requirement specifications, statements of work and other contractual documentation contained in the RFP that was released to Industry in early 2004. Later that same year, on November 30th, the Government of Canada awarded the above listed contracts to Sikorsky Aircraft Corporation, and so doing marked the beginning of a new era in the in-service support posture for aircraft fleets operated by the Canadian Forces.

5.5.2 The Division of Responsibilities Between the Air Force and Industry

In order to better appreciate the challenge before DND in establishing a performance-based ISS contract that is A_O centric, it is important for the reader to understand that both DND and the Contractor will be required to work in a coordinated manner to achieve the level of fleet A_O specified by DND in the MH Requirement Specification (MHRS). A summary of the CH148 support service responsibilities of each of DND and the Contractor is provided in Table 5-1. It is particularly important for readers to note that the prime mission of the CH148 requires it to be operated from Her Majesty's Canadian (HMC) Ships which are deployed to locations around the globe including climatic environments that range from arctic to tropical. The aircraft may also be deployed to land-based theatres-of-operations. For this reason, DND will be responsible for the conduct and control of all first and second level on-aircraft maintenance of the CH148 Cyclone.

Table 5-1: Division of CH148 Support Service Responsibilities Between DND and the Contractor.

Function	DND	Contractor
Maintenance Support	Conduct and control all first and second level on-aircraft maintenance at each of two main operating bases and while deployed aboard HMC Ships, and second level off-aircraft maintenance of components as determined by the Contractor through the performance of a LORA.	Aircraft third level R&O including periodic painting; Provision of field service representatives at each of two main operating bases, and mobile repair party support as requested by DND.
Supply Support	Management of supply chain and ownership of Government supplied materiel (<1% of aircraft inventory); ownership of contractor supplied items installed on the aircraft and custodianship of uninstalled materiel while deployed.	Management of warehouses on east and west coast main operating bases including timely provision of serviceable spare parts to point-of-maintenance; management of the CH148 supply chain including packaging and transportation/shipping of components between the warehouses and individual suppliers, and to deployed CH148 helicopters; arrangement for depot level R&O of repairables.
Support and Test Equipment (STE) Support	Management of supply chain and ownership of Government supplied materiel; custodianship and care of STE used during deployments aboard HMC ships.	Timely provision of serviceable STE to the point-of-maintenance including maintenance and repair of STE as required to maintain its serviceability.
Training Support	Delivery of CH148 operations and maintenance training including use of operational flight simulators and aircraft maintenance trainers, and training in the use of Integrated Information Environment tools.	Development of all CH148 operations and maintenance training content and courseware, except operational tactical training; provision of serviceable operational tactical simulators and aircraft maintenance trainers to meet training schedule requirements.
Engineering/ Logistics Support Analysis Support	Approval of proposed Class 1 design changes to the CH148; participate in IPT for all ECP development including software change requests; provide full scope of engineering support and management for GSM; facilitate the identification of technical problems against the MHWS inclusive of software.	Provision of configuration and data management, timely investigation and resolution of technical problems raised against the CH148 type design inclusive of the maintenance program, and development of MHWS design change requirements – includes all engineering specialty disciplines including LSA.

Function	DND	Contractor
Engineering/ Logistics Support Analysis Support (cont'd)	Approval of proposed Class 1 design changes to the CH148; participate in IPT for all ECP development including software change requests; provide full scope of engineering support and management for GSM; facilitate the identification of technical problems against the MHWS inclusive of software. (cont'd)	Provision of an MH Avionics Equipment Integration Environment (MHAEIE) provision of a software maintenance and enhancement services within a Software Support Facility (SSF) located at the east coast main operating base.
Integrated Information Environment Support	Provide certification and accreditation of contractor supplied I.S. installed on or accessed from the Defence Wide Area Network (DWAN); maintenance and enhancement of DND supplied I.S.	Provision, maintenance and enhancement of information systems capable of satisfying the requirements of the: integrated electronic technical information service; the Contractor Integrated technical information service; and the training information management service. Provision of timely help desk support to DND.

5.5.3 Seeing Aircraft Availability in Context

Performance-Based Contracting (PBC) is a key component of DND's emerging strategy to partner with Industry for the provision of long-term integrated support services for flight and maintenance operations. Typically, these contracts will specify a wide scope of performance requirements that are associated with quality and timeliness of goods and services provided by a single support Contractor; however, the critical requirement from a strategic perspective is end-system A_O. For a new fleet, the A_O requirement is typically first specified in a document known as the Statement of Operation Requirements (SOR) prepared by strategic level operational planning staffs. The importance of A_O to the Canadian Air Force, and military forces in general, is illustrated in Figure 5-8 below.

Figure 5-8: The Importance of Aircraft Operational Availability A_O to a Military Force.

The successful completion of a mission depends upon many factors as illustrated. First, the aircraft design inclusive of flight and mission systems must be capable of reliably performing specified functions. Both the inherent mission capability and the reliability associated with the use of mission systems in the prescribed environment is a product of the design activity of the OEM team. This is often accomplished as an integrated effort of an aircraft manufacturer and mission system vendors. Another important factor is the efficiency with which flight line maintenance organizations are able to make flight ready and dispatch aircraft that are available for assignment to operations. Lastly, the mission readiness of the fleet is determined by the level of knowledge and skills of aircrew to operate the aircraft to accomplish mission goals, and the availability of mission capable aircraft to be assigned to the flight schedule. Each of the determinants of mission success is of importance. A deficiency in any determinant will adversely affect the outcome. All of the dispatch reliability, aircraft availability and aircrew proficiency in the world cannot make up for an aircraft whose fundamental capability is deficient. Conversely, if the standards set for all determinants are exceeded save A_O, all of this capability is of little use if an aircraft is unavailable to be assigned to meet the mission requirements of the moment.

Logisticians and engineers, and academics have long been aware of factors that contribute to the achievement of A_O for a major weapons system such as an aircraft; however, the focus of design methodologies and associated standards have been on system reliability and maintainability factors. Maintainability analyses have typically excluded delay time factors as uncontrollable by the designer, and as such, definitions and demonstrations always assume that required resources (e.g. qualified and authorized HR, spare parts, support and test equipment, etc.) are readily available. Although advanced techniques have evolved to model the supply chain for a system, no model has been advanced that factors both equipment and ISS design capabilities into consideration to realize a standard for a single measure of effectiveness such as A_O. As such, despite advances in each of these separate areas of focus, the achieved levels of A_O for aircraft fleets operated by military Air Forces in general, and Canada in particular are, on the balance, mediocre, not only for legacy fleets, but for many newly acquired fleets as well.

Other factors that have combined to result in this unsatisfactory outcome include:

- Inadequate investment in R&M testing combined with weak contractual clauses for in-service accountability have resulted in significantly lower equipment R&M performance than predicted by the OEM.
- Inadequate investment in procurement of spare parts.
- Poor responsiveness of procurement/delivery systems to variances in equipment performance relative to that which was predicted.
- Inadequate obsolescence management.
- Insufficient access to OEM design data to enable in-context root cause analysis.
- In-service logistics support information systems failure to collect complete, accurate and standardized data with respect to the performance of the system, as well as that of the support organizations.
- Accountability ambiguity for the performance of unavailability drivers.

5.5.4 Measuring the Causes of Aircraft Unavailability and Attributing Responsibility

The last two items in the above list are of particular relevance. Although it is and has been relatively simple to generate an accurate measurement of A_O for a fleet of equipment, because of the diversity of unavailability drivers which have their effect in overlapping periods of time, on simultaneously occurring on-system maintenance tasks, it has been historically impossible to isolate specific unavailability root causes which would be an essential input to a Pareto of organizational accountability. This practical ambiguity has forced DND in-service Weapon System managers to focus on secondary performance indicators such as system reliability. However, as discussed, due to other issues, this has not resulted in a significant improvement in system A_O performance.

Chapter 4 includes a description of the availability modelling, support system performance measurement, and business rules developed by the Canadian Forces as the core of a new availability-based procurement and support strategy for the Maritime Helicopter Program (MHP). The section in Chapter 5 dealing with availability-based contracting includes a discussion of the contractual incentives to the prime contractor, Sikorsky, to achieve the availability requirements for the Canadian MHP.

5.5.5 Factors Critical to the Success of Availability-Based Contracting

Beland and Hollick identify several factors critical to the success of the availability-based acquisition and support contracts for the MHP:

a) A robust electronic means of capturing maintenance transactional data. Such a capability must capture data in real time, or synchronized real time (i.e. each transaction entry should be date/time stamped), and the data must be irrefutably complete and accurate.

b) Complete automation of the agreed methods of calculation and reporting of current levels of performance, to minimize, if not totally eliminate, any disputes.

c) Business rules for assigning organizational responsibility for every logically separable slice of time must be pre-determined and automated as far as possible. The technician needs to be focused on performing his or her job IAW prescribed standards, not on thinking about the organizational cause of the maintenance. However, the system must identify the need for management intervention when necessary, and such intervention must be subject to Contractor acceptance.

d) The book value of active maintenance tasks performed by Canadian Forces personnel must not be visible to those performing or directly supervising the tasks.

e) Management must educate the workforce and adopt a positive attitude to measured performance. Otherwise, a technically robust performance measurement system may fail to function properly.

In the MHP, maintenance data will be captured by DND in an Interactive Electronic Technical Information System (IETIS). Current levels of performance will be measured and reported in a Performance Measurement System (PMS). These systems will address the critical technical factors mentioned above. The provision of these systems will be subject to the same ISO/IEC 15288 systems engineering processes that are required to be applied to the provision of each of the support services. The critical organisational/human factors will be addressed as an element of the MH Project Implementation Plan.

5.5.6 Implementation Status and Schedule of the Maritime Helicopter Programme (MHP)

As of January 2007, Sikorsky has achieved the critical design review milestone for the aircraft, and the preliminary design review milestone for the integrated support system. Over the next two years, the design of the performance measurement service and its associated integrated information environment enabling system will be finalized and implemented. DND will participate in this process in an advisory capacity only to clarify stakeholder requirements, to witness iterative verification activities, and to conduct final scenario-based validations both of each individual support service, and of the entire integrated support system.

5.6 RELIABILITY AND MAINTAINABILITY (R&M) MANAGEMENT

As mentioned in Chapter 2, it is standard practice in NATO to establish a formal reliability and maintainability (R&M or RAM) management program at the concept design stage. The R&M management program is continued during series production and the life of the aircraft, to ensure that the inherent reliability, or at least the specified reliability, is achieved and sustained in service. While the R&M management program initially focuses on design and manufacture, it provides essential information for the design of the maintenance/support system and for dealing with any later shortfall in reliability. Consequently, when the aircraft enters service, the R&M management program typically evolves to become an integral part of the maintenance/support program.

Structural R&M may be managed under a parallel Aircraft Structural Integrity Program (ASIP), while engine R&M may be managed under a parallel Engine Structural Integrity Program (ENSIP). R&M data from ASIP and ENSIP are captured by the main R&M program.

The management of R&M is as important as the equipment technologies used to improve R&M. The broad principles and practices of R&M management apply to all aircraft components. They have been developed to a high level in NATO countries, and are outlined in this section. ASIP and ENSIP as applied by the US DoD and some other NATO Armed Forces involve ILS work other than R&M management. The main features of ASIP of relevance to aircraft availability are outlined in the next section.

As a discipline, reliability management has developed more recently than the technical aspects of reliability engineering. Dhillon [69] cites the issue in 1959 of Mil-R-27542 as the first evidence of a serious attempt to develop reliability management guidelines for a major military program. He describes in some detail the generally accepted principles of reliability management as they were in 1986. These do not differ greatly from those published in recent military guidelines, such as NATO's ARMP-1 [70], the US DoD's Mil-Hdbk-338 [7] and Mil-Hdbk-470A [71], and MOD UK's Def-Stan 00-40 [56] and 00-41 [57]. ARMP-1 invokes SAE standards JA 1000 [72] for reliability programs and JA 1010 [73] for maintainability programs. The broad principles of R&M program management in all these documents are as follows:

- The Purchaser's R&M requirements shall be determined and demonstrated to be understood by the Purchaser and the Supplier.
- A programme of activities shall be planned and implemented to satisfy the requirements.
- The Purchaser shall be provided with assurance that the R&M requirements have been satisfied.

A typical R&M program contains the activities in Table 5-2.

Table 5-2: Common Reliability Program Elements.

Element	Typical Activities
Planning and Control	• Developing a reliability program plan • Monitoring and controlling sub-contractors
Design	• Design reviews • Developing design criteria • Parts selection • De-rating • Identifying critical items • Robust design (fault tolerance, redundancy, graceful degradation)
Analysis	• Failure modes, effects and criticality analysis • Fault tree analysis • Sneak circuit analysis • Analysis of operating and environmental stresses • Modelling and allocations • Thermal analysis
Testing	• Reliability growth testing • Reliability qualification testing • Environmental stress screening • Verification testing • Functional testing • Failure reporting and corrective action system
Production	• Statistical process control • Inspection • Process failure modes and effects analysis
Other	• In-service reliability

The activities are performed at various times or iteratively throughout the concept, design/development, and production/in-service phases of an aircraft life-cycle. In keeping with the three broad principles of reliability program management listed above, the customer and contractor should work together to plan and execute a program containing these elements and activities. The distribution of activities among the phases of the life-cycle might be as listed below.

Table 5-3: Typical Distribution of Reliability Program Activities Among Life-Cycle Phases.

Activity	Concept Design	Preliminary Design	Design and Manufacturing Development	Production and In-Service
Reliability Program Planning	X	X	X	
Reliability Trade-Off Studies	X		X	
Parts and Materials Programs	X			
Design Reviews	X		X	
Supplier Control	X		X	X
Life-Cycle Planning	X	X		
Critical Item Control	X			X
Reliability Modelling and Preliminary Allocations	X			
Test Strategy	X			
Benchmarking	X	X		
Quality Function Development	X			
Market Survey	X	X		
Analysis of Operational Environment	X			
Environmental Characterization		X		
Fault Tolerance		X	X	
Part and Material Program		X		
Reliability Modelling and Allocations		X		
Durability Assessment		X	X	
Reliability Predictions		X		
Thermal Analysis		X		
User Requirement Translation		X		
Software Reliability		X	X	
Critical Item Identification			X	
De-rating Limits			X	
Part Selection and Application			X	
Thermal Design Limits			X	
Reliability Modelling, Allocation and Simulation			X	
Failure Modes, Effects and Criticality Analysis (FMECA)			X	
Fault Tree Analysis (FTA)			X	

Activity	Concept Design	Preliminary Design	Design and Manufacturing Development	Production and In-Service
Reliability Predictions			X	
Sneak Circuit Analysis (SCA)			X	
Worst Case Circuit Analysis (WCCA)			X	
Design for Storage, Handling, Packaging, Transportation and Maintenance			X	
Reliability Growth Test			X	
Reliability Qualification Test			X	
Accelerated Life Test			X	
Human Reliability			X	
Develop ESS Criteria			X	
Failure Reporting Analysis and Corrective Action System (FRACAS)			X	X
Part Obsolescence				X
Environmental Stress Screening (ESS)				X
Production Reliability Acceptance Test (PRAT)				X
Statistical Process Control (SPC)				X
Inspection				X

Six essential steps, or sub-objectives, are needed to meet the overall objective of a sound maintainability program [71]:

- Understand the Customer's Maintainability Needs – Determine the required level of maintainability as will be measured by the user during actual use of the product.
- Integrate Maintainability with the Systems Engineering Process – Make the maintainability activities conducted during design and manufacturing an integral part of the product and processes design effort.
- Thoroughly Understand the Design – Understand the maintainability of the design and the maintenance required for the product.
- Design for Desired Level of Maintainability – Use proven design approaches to make needed maintenance safe, economical, and easy to perform.
- Validate the Maintainability through Analysis and Development Test – Conduct analyses, simulation, and testing to uncover maintainability problems, revise the design, and validate the effectiveness of the redesign.
- Monitor and Analyze Operational Performance – Assess the operational maintainability of the product in actual use to uncover problems, identify needed improvements, and provide "lessons learned" for incorporation in handbooks and for refining modelling and analysis methods.

As explained in Chapter 2, maintainability is a design parameter that relates to an assumed maintenance/ support system. Consequently, the design of the aircraft and maintenance/support system need to be closely integrated to make best use of advanced maintenance concepts and technologies.

The main activities in a maintainability program and their applicability during the aircraft life cycle are shown in Table 5-4.

Table 5-4: Typical Distribution of Maintainability Program Activities Among Life-Cycle Phases.

Maintainability Activity	Concept Design	Preliminary Design	Design and Manufacturing Development	Production	In-Service
Program Plan	Selective	General (2)	General	General (2)(1)	General (2)(1)
Supplier Control		Selective	General	General	Selective
Program and Design Reviews	Selective	General (2)	General	General	Selective
Design		Selective (2)	General	Modifications	Selective
Analysis	Selective (2)	General (2)	General (1)	Modifications (1)	Selective
Modelling	Selective	Selective (3)	General	Modifications	Selective (3)
Test and Demo		Selective	General	Modifications	Selective (3)
Data Collection, Analysis and Corrective Action		Selective	General	General	Selective

Notes:

(1) Requires considerable interpretation of intent to be cost effective.

(2) Appropriate for those task elements suitable to defining during this phase.

(3) Depends on physical complexity of the product, its packaging, and overall maintenance concept.

These tables are based on the guidelines in Mil-Hdbk-338B, but also reflect the guidelines in the other references given above. The reader is referred to these documents for a full description of all the R&M activities listed, and for guidelines on the R&M engineering methods for performing the activities.

5.7 AIRCRAFT/ENGINE STRUCTURAL INTEGRITY PROGRAM (ASIP AND ENSIP)

The USAF developed a program known as the Aircraft Structural Integrity Program in the 1960s, following a series of serious reliability problems with aircraft structure that resulted in some catastrophic failures and had a long-term impact on aircraft availability. The USAF also introduced a requirement for damage tolerant design and promoted the use of on-condition preventive maintenance, often referred to as “damage tolerance inspections” by structural engineers, to replace or supplement the previous “safe life” failure management policy. Comparable changes started to take place at about the same time in the regulation of civil transport aircraft. The USAF has since developed ASIP into a comprehensive program whose objectives are to:

a) Define the structural integrity requirements associated with meeting operational safety, suitability and effectiveness requirements;

b) Establish, evaluate, substantiate, and certify the structural integrity of aircraft structures;

c) Acquire, evaluate, and apply usage and maintenance data to ensure the continued structural integrity of operational aircraft;

d) Provide quantitative information for decisions on force structure planning, inspection, modification priorities, risk management, expected life-cycle costs and related operational and support issues; and

e) Provide a basis to improve structural criteria and methods of design, evaluation, and substantiation for future aircraft systems and modifications.

As part of major acquisition reforms initiated in 1998, the USAF removed the mandatory status of ASIP. It has since been restored for the USAF, and the requirements have been expanded and refined in Mil-Std-1530C to facilitate its use as a contractual document. The German and Canadian Air Forces and other NATO Air Forces have adopted the ASIP model. While ASIP provides considerable guidance and information for the overall ILS program, or equivalent, it retains a strong focus on reliability and maintainability, and can be viewed as providing the R&M management program for structure. Mil-Std-1530 opens with the following statement, which serves to indicate the importance of ASIP in this context:

> "Every aircraft program must address all sections of this standard (including all tasks and elements within each task) and document this in its ASIP Master Plan. An ASIP Master Plan is required for all programs. Tailoring is only permitted when all of the following conditions exist:
>
> a) The overall aircraft reliability (probability of failure) is established and approved by the appropriate Risk Approval Authority as defined in Mil-Std-882, "Standard Practice for System Safety.
>
> b) The aircraft structure reliability is defined and supports the overall aircraft reliability requirement.
>
> c) The effect of each tailored ASIP task and/or element and its associated impact on aircraft structure is determined.
>
> d) The combined impact of all tailored ASIP tasks and/or elements on aircraft structural reliability is determined and achieves the allocated overall aircraft reliability requirement.
>
> The tailored ASIP tasks and/or elements and the impact of this tailoring on aircraft structural reliability is documented in the ASIP Master Plan and approved in accordance with AFPD 63-10 and AFI 63-1001."

ASIP consists of a set of clearly defined tasks or activities that are to be undertaken as specific times in the aircraft life-cycle. These are summarised in Figure 5-9 and Figure 5-10.

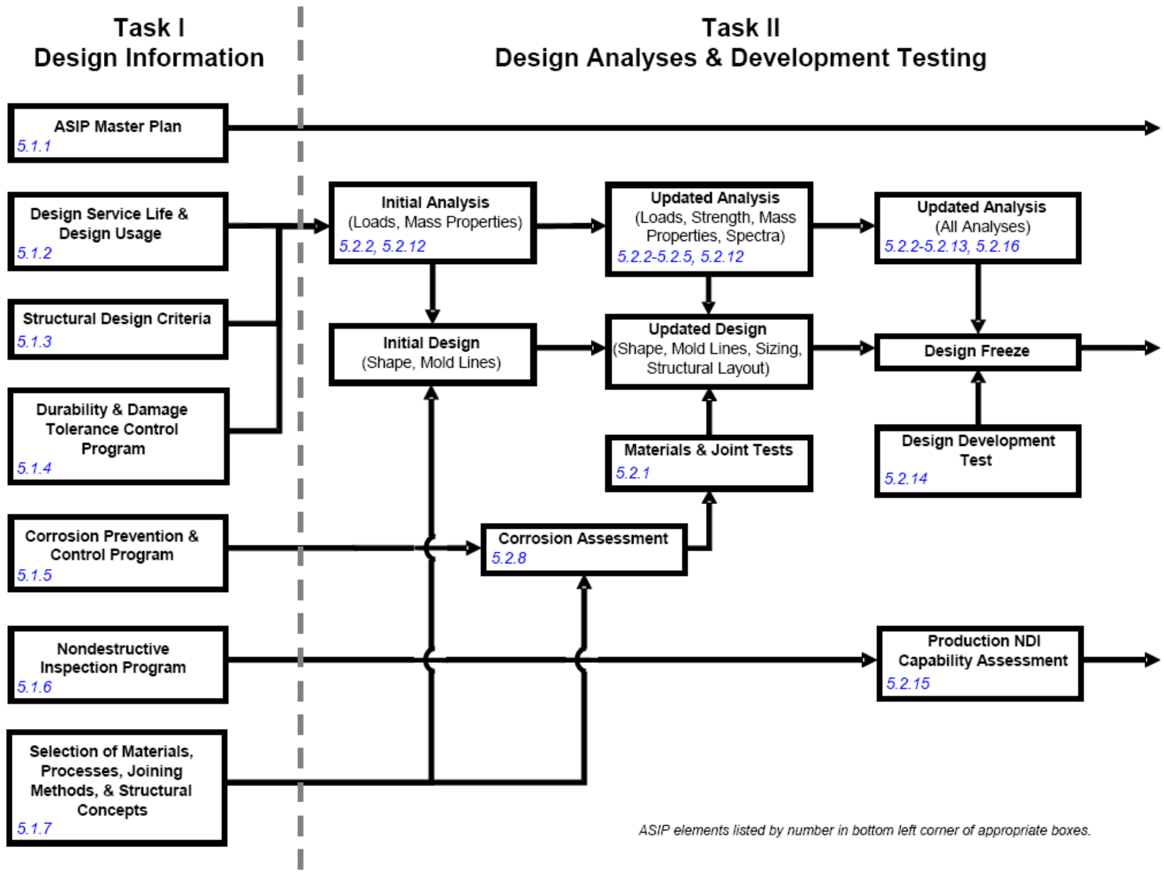


Figure 5-9: Aircraft Structural Integrity Program – Tasks I and II. (Source Mil-Std-1530C [23])

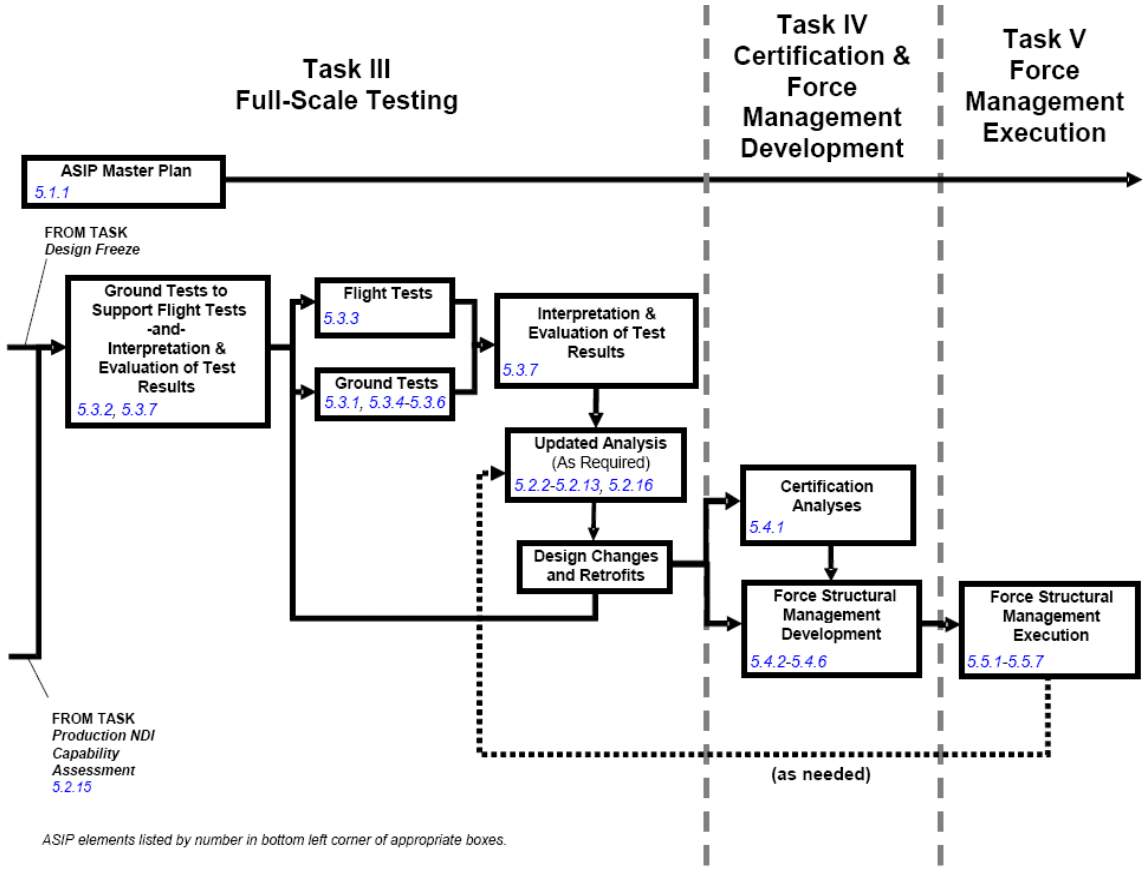


Figure 5-10: Aircraft Structural Integrity Program – Tasks III through V.

The integrated design and maintenance requirements of ASIP have greatly reduced the risks of catastrophic structural failure and major fleet availability problems. These risks are likely to be higher in Air Forces who do not apply an airframe structural integrity program with the same rigour as the main NATO Air Forces.

A comparable management program to ASIP for engines, called ENSIP, is applied by many NATO Air Forces. There are difficulties in applying the on-condition (damage tolerance) maintenance approach used in ASIP to engines, and so engine and airframe maintenance/support strategies differ in some respects. ENSIP as laid out in Mil-Hdbk-1783B [74] is not mandatory in the USAF. Several NATO Air Forces have promoted the development of technologies to allow a greater degree of on-condition maintenance. Civil regulators have recently modified the regulations for engine design and maintenance to make the design for on-condition maintenance (damage tolerance) mandatory where feasible [75]-[76]; however, a safe life maintenance concept must be superimposed on this in the case of critical components.

5.8 TOTAL LIFE-CYCLE SYSTEMS MANAGEMENT (TLCSM) AND THROUGH-LIFE CAPABILITY MANAGEMENT (TLCM)

An important feature of the transformations being made in acquisition and maintenance/support in the USA and the UK is that much greater emphasis is now placed on continuity of program management throughout the life-cycle, and on merging the different cultures of acquisition and maintenance/support. One of the tangible changes in this regard is the appointment of program managers as leaders of Integrated Project Teams (IPT) with the responsibility and authority to manage acquisition and maintenance/support throughout the life-cycle. In the USA, this is referred to in policy documents as Total Life-Cycle Systems Management (TLCSM).

The Defence Logistics Transformation Program (DLTP) in the UK has already been described in Chapter 3. A comparable program is taking place in the US DoD, which emphasises performance-based acquisition and life-cycle management. It started in the late 1990s with the replacement of Military Standard by performance-based contractual requirements. The idea is that these will make the contractor more directly accountable for the design and maintenance/support characteristics and more innovative in meeting them within budget. This change in philosophy is illustrated by the following quotation from a 2002 article [4] by Louis A. Kratz, US Assistant Deputy Under Secretary of Defense for Logistics, Plans, and Programs:

> "Currently, weapon system sustainment is provided by functionally-focused organizations that optimize within their own business structures. Our immediate challenge is that we fight with capabilities and systems, not functions. To maximize our military effectiveness, the DoD is migrating to a performance-based weapon system sustainment model that focuses on weapon system performance, integrated across all functional support organizations.
>
> The foundation of the new sustainment model is the designation of the Program Manager as *Life-Cycle Systems Manager*, responsible for the development, production, and sustainment of the system to meet warfighter requirements.
>
> Program managers will develop and execute sustainment strategies based upon warfighter performance requirements. These strategies will build upon public-private partnerships, combining the best capabilities and inherent efficiencies of the industrial and organic support bases in an integrated support framework. Field results will be collected automatically through prognostics and embedded instrumentation to provide real-time system status. These results will be fed back to guide future system upgrades and block designs.
>
> Clearly, this dramatic shift impacts our entire acquisition and sustainment structure …"

Kratz also states that the Program Manager as life-cycle manager requires financial authority, visibility, and enabling mechanisms with which to execute this responsibility, and that the fundamental shift in business structure must be accompanied by a fundamental shift in financial structures. He points out that *full and effective implementation of TLCSM will require revisions to the weapon system financial funding and DoD financial systems*. Pilot programs in the USA have demonstrated the benefits of program office innovation in improving sustainment; however, they have also indicated the need to ensure that innovative sustainment strategies fit within an overall framework to deliver combat capability.

There is also a new policy in DoD that ensures the orderly development of joint forces capability requirements. However, in the USA, capability management is not continued beyond the point where a new capability has been implemented. In the UK the empowerment of IPT has been accompanied by the establishment of clear processes and a single point of responsibility and accountability for Through-Life Capability Management (TLCM). This change is associated with a general shift in defence acquisition away from the traditional pattern of designing and manufacturing successive generations of platforms – leaps of capability with major new procurements or very significant upgrade packages – towards a new paradigm centred on support, sustainability and the incremental enhancement of existing capabilities from technology insertions [52]. The emphasis will increasingly be on through-life capability management, developing open architectures that facilitate this and maintaining – and possibly enhancing – the systems engineering competencies that underpin it. The attractions for industry should, in general, include longer, more assured revenue streams based on long-term support and ongoing development rather than a series of big 'must win' procurements.

The introduction of total life-cycle systems management by an empowered project team, the focus on clear management performance targets, and the parallel effort to ensure good joint force capability definition and management should ensure that the key elements of capability, such as aircraft platform availability, receive appropriate and sustained attention. There is more discussion of IPT in the next section.

5.9 INTEGRATED PROJECT TEAMS (IPT)

Project teams have traditionally been established for the acquisition of new aircraft, but until recently they did not generally have a continuing role throughout the life of an aircraft. Problems with poor availability and high maintenance/support costs have been traced to inadequate design priority on parameters that affect maintenance/support and on insufficient integration between the design of the aircraft and the maintenance/ support system. As just mentioned, the extension of the mandate of IPT to cover the full life-cycle is one tangible measure taken in the USA and UK to remedy this situation.

IPT in the UK and Canada now have considerable authority with regard to the acquisition phase, the conduct of depot level maintenance, the establishment of public private partnerships, and the negotiation of performance-based contracts. In the USA, the new US DoD policy of 'Total Life-Cycle Systems Management', described in the previous section, includes empowerment of the IPT. This in part arose from a need expressed in a GAO report [77] to develop and implement a process to instil and sustain accountability for successful program outcomes. The GAO stated that at a minimum, this should consider:

- Matching program manager tenure with delivery of a product or for system design and demonstration;
- Tailoring career paths and performance management systems to incentivize longer tenures;
- Empowering program managers to execute their programs, including an examination of whether and how much additional authority can be provided over funding, staffing, and approving requirements proposed after milestone B; and
- Developing and providing automated tools to enhance management and oversight as well as to reduce time required to prepare status information.

It remains to be seen whether the changes to the financial system needed to fully empower the IPT will come about. Full life-cycle IPT have existed for many years in Canada with a mandate to apply well-defined system engineering practices. However, Beland and Hollick pointed out in Paper 3.1 that an adequate level of authority and funding has sometimes been lacking. Elford described a similar problem in the UK, which has in part prompted the recent establishment of an integrated procurement and support organisation by merging the UK MOD's Defence Procurement Agency and the Defence Logistics Organization to be led at 4-star level, or equivalent. It has recently been announced that the new organization is to be known as '*Defence Equipment and Support*' lead by the '*Chief of Defence Materiel*'. While effective IPT have already been in place in the UK for some years, this reorganisation will help to ensure that they continue to receive appropriate support.

In Paper 1.2, Joubert indicated that while the French Air Force organisation SIMMAD does not employ cradle-to-grave IPT it effectively fulfils the same purpose: it has a mandate to ensure that all aircraft achieve and sustain adequate in-service availability; it controls ILS policy and application; and it is involved in all relevant acquisition and support issues.

5.10 TECHNOLOGY INSERTION

The UK's Defence Industrial Strategy Review of 2005 [52] reports that there is a general shift in defence acquisition away from the traditional pattern of designing and manufacturing successive generations of platforms – leaps of capability with major new procurements or very significant upgrade packages – towards a new paradigm centred on support, sustainability and the incremental enhancement of existing capabilities from technology insertions. The emphasis will increasingly be on through-life capability management, developing open architectures that facilitate this and maintaining – and possibly enhancing – the systems engineering competencies that underpin it. The attractions for industry should, in general, include longer, more assured revenue streams based on long-term support and ongoing development rather than a series of big 'must win' procurements.

In a paper in the Journal of Defence Science [78], the UK Defence Scientific Advisory Council (DSAC) point out that Technology Insertion (TI) is not always the answer: upgrades in technology should not be done just because the technology exists and upgrades can be done. However, TI should be properly considered where:

- Increases in military capability are best achieved through introducing new technology; or
- Inserting new technology is likely to reduce the maintenance costs of a system; or
- A specific obsolescence problem is best solved by technology insertion.

Five key recommendations emerge in the DSAC paper as being particularly important. In summary, these are:

- Modularity of system design simplifies TI and needs to be considered up-front by all equipment projects – MOD needs to consider a mechanism to promote this.
- Certification processes can be an obstacle to TI and need to be reviewed to account for modular system design, the appropriate level of certification required and lessons from the civilian sector.
- Technology demonstration, especially in the concept phase of the CADMID cycle, can reduce the risks of TI and needs to be enhanced. (This will typically involve more percentage spend before Initial and Main Gates.)
- Incentives: MOD should undertake a review of the terms of equipment contracts to provide better incentives for industry to make cost-effective use of new and up-to-date technology.
- Organizational: a 'Systems Architect' should be appointed who can draw on a unified budget to take responsibility for the through-life trade-offs involved in TI.

5.11 MANUFACTURING MANAGEMENT

Manufacturing must be considered in the context of maintenance/support, because, as mentioned in Chapter 2, shortcomings in manufacturing can result in a shortfall in aircraft reliability. The maintenance/support system must somehow maintain the required aircraft platform availability despite such shortfalls, while longer-term remedial measures are taken. Manufacturing is also important to maintenance/support, because the supply of spare parts is a maintenance/support function.

Since a full analysis of manufacturing concepts and technologies is outside the scope of this report, it will suffice to highlight that advances in manufacturing management can improve aircraft availability if they:

- Improve the integration of design and manufacturing, sometimes known as concurrent engineering;
- Improve quality control through better inspection and analytical methods;

- Improve the repeatability of manufacturing processes at the nano, micro, and macro levels;
- Reduce the lead time for the manufacture of spare parts; and
- Improve efficiency to free funds for other measures to improve aircraft availability.

There are well-established principles for quality management in industry and organic depots. The advanced enterprise management concepts discussed later in this chapter provide a means of ensuring that quality management is integrated as effectively and as efficiently as possible into the manufacturing processes, to minimise defects and ensure batch repeatability.

5.12 RELIABILITY-CENTRED MAINTENANCE (RCM) TO DETERMINE ESSENTIAL MAINTENANCE AND OPTIMUM FAILURE MANAGEMENT STRATEGIES

5.12.1 Evolution of RCM for the Design of Preventive Maintenance

One of the key processes in the design of the aircraft and its in-service support is the determination of the preventive maintenance needed to achieve the desired availability and mission reliability at optimum cost. Preventive maintenance is defined slightly differently by different organisations (Annex C), but most definitions are close to that in NATO ARMP-7: "The maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item".

In view of its importance, the process used to determine the content of preventive maintenance has received considerable attention from aircraft designers, operators and regulators over the last forty years. The dominant concept that has emerged is Reliability-Centred Maintenance (RCM). RCM has tended to replace other, less rigorous processes because these have been found to result in ineffective and/or inefficient maintenance programs.

In SAE Standard JA1011 "Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes" [79], RCM is described as a specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any physical asset in a given operating context. The SAE Standard states that any RCM process shall ensure that all of the following seven questions are answered satisfactorily and in the sequence shown:

a) What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?

b) In what ways can it fail to fulfil its functions (functional failures)?

c) What causes each functional failure (failure modes)?

d) What happens when each failure occurs (failure effects)?

e) In what way does each failure matter (failure consequences)?

f) What should be done to predict or prevent each failure (proactive tasks and task intervals)?

g) What should be done if a suitable proactive task cannot be found (default actions)?

SAE Standard JA1011 identifies the information to be gathered and the decisions to be made, and requires that all information and decisions shall be documented in a way which makes the information and the decisions fully available to and acceptable to the owner or user of the asset.

Among military forces, the US Navy took the lead with the development and implementation of RCM on aircraft in the late 1960s and early 1970s. It collaborated with American and European aircraft manufacturers and regulatory authorities in a Maintenance Steering Group (MSG), which produced the document MSG-1 “Handbook: Maintenance Evaluation and Program Development” in 1968 [80]. This document included RCM concepts and was used to develop the maintenance program for the Boeing 747. The document has undergone substantial development over the years. It was updated to MSG-2 “Airline/Manufacturer Maintenance Program Planning Document” in 1970. A copy can be found as Appendix 1 to FAA Advisory Circular 120-17A “Maintenance Control by Reliability Methods”, 27 March 1978 [81]. In 1978, the Department of Defense (DoD) sponsored report AD-A066579, “Reliability Centered Maintenance” by Nowlan and Heap [82]. This recommended improvements to MSG-2 with better guidance on process and interval determination. The improved version was issued by the Air Transport Association of America as ATA MSG-3 “Operator/ Manufacturer Scheduled Maintenance Development” [83]. MSG-2 or 3 have been used to develop the maintenance programs for most large civil aircraft since the Boeing 747. As a result of refined RCM concepts, other improvements in logic, and the inclusion of the hitherto separate Corrosion Prevention and Control Program (CPCP) mandated by the FAA, JAA, and other regulatory agencies, MSG-3 has helped to create maintenance programs that are much more efficient than their predecessors. Despite high non-recurring costs, MSG-3 is being applied retrospectively to some earlier fleets. Meanwhile, military as well as civilian organizations have continued the development of the RCM process. It is now widely applied in the aircraft industry and many other industries for the development of preventive maintenance programs.

The term “RCM” may not always be mentioned in maintenance program documents that comply with RCM fundamentals. On the other hand, the widespread use of the term “RCM” has led to the emergence of a number of processes that differ significantly from the original, but that their proponents also call “RCM”. Many of these other processes fail to achieve the goals of Nowlan and Heap, and some are actively counterproductive. SAE Standard JA1011 sets out sets out the criteria that any process must satisfy to be called “RCM”. Definitions for some key RCM terms from SAE JA1011 and other authoritative documents are given later in this section. Additional definitions are in Annex C.

The current US Navy manual is NAVAIR 00-25-403, “Guidelines for the Naval Aviation Reliability-Centered Maintenance Process” [84], which was released in 1996. This manual is perhaps the most readable document available on applying RCM to military aircraft, and is one of the authoritative references on which SAE Standard JA1011 is based. NAVAIR 00-25-403 describes RCM as “an analytical process to determine the appropriate failure management strategies, including preventive maintenance requirements and other actions that are warranted to ensure safe operations and cost-wise readiness”. The manual states that the application of RCM can and should begin with conceptual design and continue until the retirement of the equipment from service. It adds that using RCM as a part of the design process allows early identification of failure modes that may result in expensive or difficult preventive maintenance action, require design mitigation or elimination, or benefit from the introduction of design features such as easy access, Prognostics and Health Management (PHM) technology, easy inspection, interchangeability, or technological advances.

The US Navy issued NAVAIR 00-25-403 after the general suspension of Mil-Standards for new acquisition, and required that RCM be superimposed on any other acquisition processes. RCM has since been retrospectively applied to many US Navy aircraft types. The NAVAIR RCM process is summarised in Figure 5-11. The core of the process is the Failure Modes, Effects, and Criticality Analysis (FMECA).

During the FMECA, the functions of a given component and the failure modes that could cause the failure of each function are identified. The effects and consequences (criticality) of each functional failure are analysed and significant functions are identified. Significant functions are those whose failure could affect safety, the environment, operations, and cost. These significant functions and their failure modes are further analysed to determine appropriate failure management strategies.

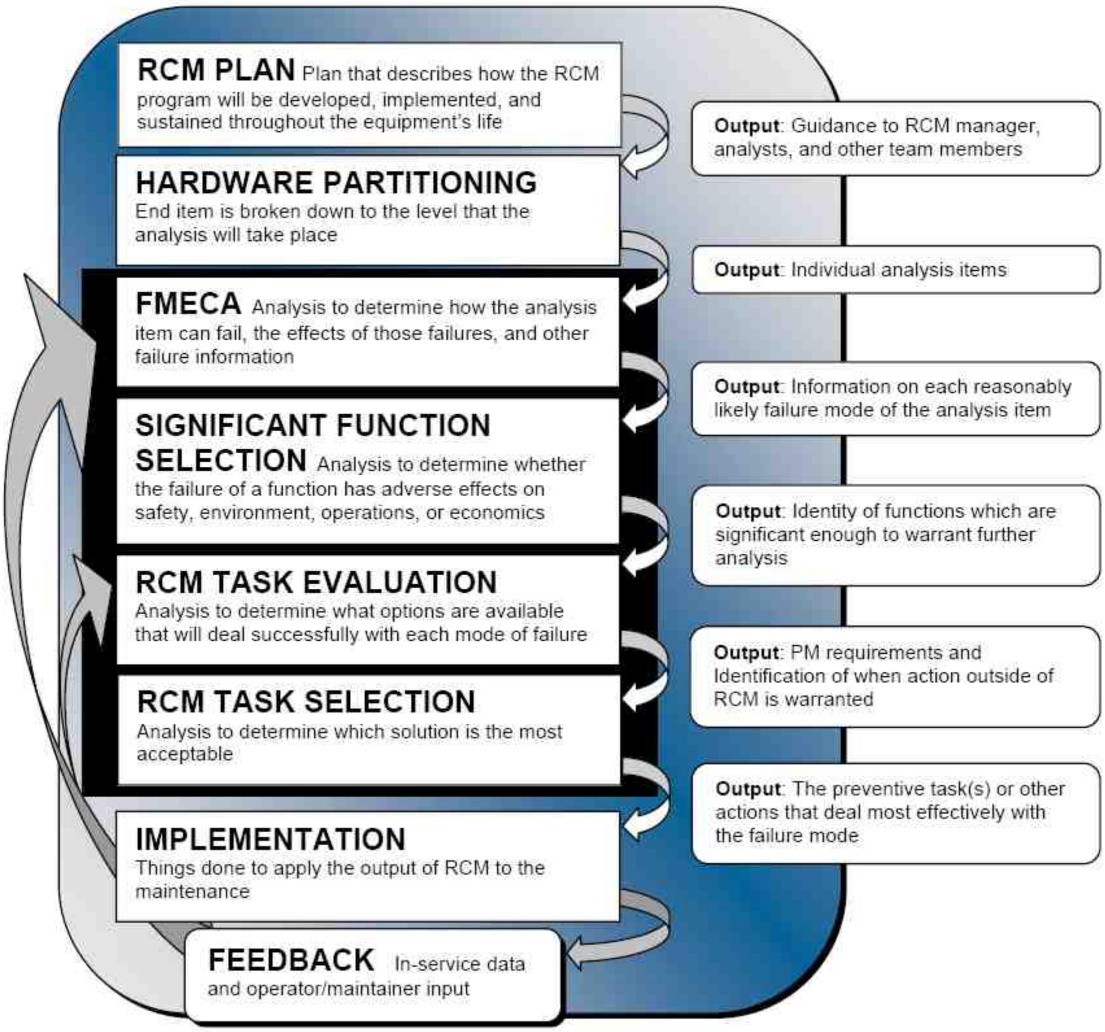


Figure 5-11: Outline of US Navy RCM Process. (Source: NAVAIR 00-25-403 [84])

The US Navy RCM process includes an ongoing evaluation of technological advances, to reduce reliance on physical inspections and calendar-based maintenance, and to facilitate opportunistic maintenance. The guidelines state that trade-off processes should be used to ensure such technologies are evaluated for life-cycle cost effectiveness.

MSG-3 specifies a process of maintenance development that is comparable to the US Navy's process. Its states that the objectives are as follows:

a) Ensure realization of the inherent safety and reliability levels of the aircraft.

b) Restore safety and reliability to their inherent levels when deterioration has occurred.

c) Obtain the information necessary for design improvement of those items whose inherent reliability proves inadequate.

d) Accomplish these goals at a minimum total cost, including maintenance costs and the costs of resulting failures.

The MSG-3 process is summarised as follows:

a) The manufacturer partitions the aircraft into major functional areas until all on-aircraft replaceable components have been identified.

b) Using a top down approach, the manufacturer determines which system components should be considered as Maintenance Significant Items (MSI) and which structural components should be considered as Structural Significant Items (SSI). Although their definitions differ in detail, MSI and SSI are components in which failure could significantly affect safety, operations, or cost.

c) For each MSI and SSI a detailed analysis is performed to identify the functions, functional failures, failure effects, and failure causes. This analysis also identifies devices whose functions are either to indicate failure or to relieve or avoid the abnormal conditions which follow a failure.

d) Using the results of this analysis and strict decision logic laid out in MSG-3, a decision is made on the tasks to be included in the scheduled maintenance program, together with the threshold and intervals at which they will be performed.

e) A parallel schedule of zonal inspections is also developed and integrated into the overall maintenance program. These are visual inspections and visual checks of each zone of the aircraft, which are defined by access and area. The purpose of zonal inspections is to check system and power plant installations and structure for security and general condition. The inspections are intended to complement the more specific system and structural maintenance tasks and to reduce the risk of combustion due to the degradation or contamination of wiring and lightning protection systems.

For civil aircraft the development of the initial maintenance program for an aircraft type is managed by an Industry Steering Committee consisting of airframe and major systems manufacturers and a representative group of operators. It is subject to the oversight and approval of the regulatory authorities. The ongoing development of the initial maintenance program developed using the MSG-3 process is the responsibility of the individual operators under the supervision of the relevant regulatory authorities.

Some military operators, e.g. the Canadian Forces, also use the MSG-3 process for both transport and combat aircraft.

5.12.2 RCM Failure Management Strategies

The application of the RCM process to a given item results in one or a combination of the following failure management strategies, which are defined in SAE Standard JA1011, and/or NAVAIR 00-25-403, and/or MSG-3:

a) *Servicing Task* – The replenishment of consumable materials that are depleted during normal operations.

b) *Lubrication Task* – The periodic application of a lubricant to items that require lubrication for proper operation or to prevent premature functional failures. (Sometimes regarded as a Servicing Task.)

c) *Discard Task* – A scheduled task that entails discarding an item at or before a specified age limit regardless of its condition at the time.

d) *Restoration Task* – A scheduled task that restores the capability of an item at or before a specified interval (age limit), regardless of its condition at the time, to a level that provides a tolerable probability of survival to the end of another specified interval.

e) *On-Condition Task* – A scheduled task used to detect a potential failure.

f) *Failure-Finding Task* – A scheduled task used to determine whether a specific hidden failure has occurred.

g) *One-Time Change* – Any action taken to change the physical configuration of an asset or system (re-design or modification), to change the method used by an operator or maintainer to perform a specific task, to change the operating context of the system, or to change the capability of an operator or maintainer (training).

h) *Run-to-Failure* – A failure management policy that permits a specific *failure mode* to occur without any attempt to anticipate or prevent it.

The following additional RCM terminology is important to a proper understanding and communication of RCM failure management strategies:

- *Functional Failure* – A state in which a physical asset or system is unable to perform a specific function to a desired level of performance.
- *Failure Mode* – A single event, which causes a functional failure.
- *Evident Failure* – A failure mode whose effects become apparent to the operating crew under normal circumstances if the failure mode occurs on its own.
- *Hidden Failure* – A failure mode whose effects do not become apparent to the operating crew under normal circumstances if the failure mode occurs on its own.
- *Multiple Failure* – An event that occurs if a protected function fails while its protective device or protective system is in a failed state.
- *Protective Device or System* – A device or system which is intended to avoid, eliminate, or minimize the consequences of failure of some other system.
- *Potential Failure* – An identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring.
- *Scheduled* Task – A task performed at fixed, predetermined intervals, including “continuous monitoring” (where the interval is effectively zero).
- *Hard Time Task* – The scheduled removal of an item, or a restorative action at some specified maximum operating limit to prevent functional failure. (This is a collective term for failure management strategies c) and d) above.)
- *Conditional Probability of Failure* – The probability that a failure will occur in a specific period provided that the item concerned has survived to the beginning of that period.

- *Safe Life* – A safe life item must survive to an age below which no failures are expected to occur. Safe life limits are imposed in RCM on only those items whose failure modes have safety/environmental consequences.
- *Age Exploration* – A process used to collect specific data to replace estimated or assumed values that were used during a previous RCM analysis.

Some additional explanation of failure management strategies will be helpful at this point. In general, a *functional failure* must be prevented if it will jeopardise safety or environmental compliance. In many cases it is also operationally or economically desirable to prevent a *functional failure*. S*ervicing tasks* and/or *lubrication tasks* may be required for a given component even if other maintenance tasks have been scheduled. *Discard tasks* and *restoration tasks* (collectively known as *hard time tasks*) are only useful for *failure modes* which display an increase in the *conditional probability of failure* with time. In such cases, the component may be replaced or restored to a specific reliability after a *safe life*, which is set to be much shorter than the demonstrated mean life of the component. On the other hand, o*n-condition tasks* can be useful for any *failure mode*, but only if it possible to detect a condition that gives prior warning of the *failure mode*. This condition is known as *potential failure*. When it is impractical to employ a *hard time* or *on-condition* strategy to prevent a failure, the designer may employ a *protective device or system* – i.e. redundancy or fault tolerance – to avoid or mitigate the effects of a component failure. In such cases, a *multiple failure* of two or more components would be required to cause a *functional failure* in a higher level component or the aircraft. To guard against *hidden* isolated failures of *protected* components, *failure-finding tasks* are employed. The interval of the *failure-finding task* would be set so as to keep the risk of *multiple failure* at an acceptably low level. Finally, if safety and environmental compliance are not involved and the economic and operational impacts of a *functional failure* are small, the most cost-effective failure management strategy might be to allow a component to *run to failure*.

In general, *on-condition tasks* must be designed and scheduled so as to maintain a sufficiently low probability of failure until *potential failure* is detected. For this to be the case, the interval of time or usage between *potential failure* and *functional failure* – known as the *Potential Failure (PF) interval* – must be predictable with sufficient accuracy. To meet this requirement, sophisticated analytical modelling, experimental work, usage monitoring, and detection methods may be needed.

An *on-condition task* contains only the inspection phase of the maintenance evolution. Corrective maintenance tasks that follow the detection of a *potential failure* during an *on-condition task* are considered separate tasks. Usually, corrective maintenance following the detection of a *potential failure* is performed before the next flight. However, full corrective action is sometimes deferred for a limited period to cope with unusual operational demands. In such cases, special maintenance requirements, such as additional inspections, are usually imposed to manage the increased risk until corrective maintenance has been performed. The approval of the relevant airworthiness authority may be needed.

The tasks intended to detect failures or potential failures may be performed by any appropriate means. Regardless of the means chosen, the above RCM terminology would remain valid. For example, an *on-condition task* performed automatically and continuously by an on-board system is still referred to as an *on-condition task*. When an inspection is performed continuously, the inspection interval is effectively zero.

5.12.3 Choosing the Best Failure Management Strategy

Since many mechanical components exhibit an increase in the conditional probability of failure with time, it can be viewed as more efficient to adopt a hard time failure management strategy rather than an on-condition strategy – in other words, to discard or restore components at safe lives rather than institute a program of scheduled inspections to pre-empt failures. However, it is difficult to design for a long enough safe life without incurring an unacceptable weight and/or performance penalty. This is because there are several uncertainties. Firstly, there is often large variability in the laboratory test lives of the systems and their components. Secondly, there are uncertainties in the past and future usage of the aircraft and its various systems. Finally, analytical and experimental capabilities are generally limited for technical and cost reasons in their ability to simulate real aircraft operating environments, particularly those that involve random combinations of loading and/or environmental conditions, including random discrete source damage. Consequently, analysis and testing may not reveal all the potential failure modes, and may underestimate the rate of degradation in the failure modes studied.

Despite these uncertainties a hard time / safe life strategy has generally been adopted in the case of engines, landing gear, and helicopter transmissions, because access for inspections is difficult and the combinations of materials and stress levels needed to achieve adequate aircraft performance result in small critical crack sizes. In some cases, a hard time / safe life strategy has also been adopted for the structure of combat aircraft that must operate for long periods in locations where maintenance resources are limited, such as aircraft carriers.

However, in most other cases, there has been a preference for using on-condition failure management for mechanical components. On-condition failure management has been used for the past thirty years in most of the airframe structure of military and civil transport aircraft and many combat aircraft. It is implicit in the damage tolerance design and inspection requirements for airframe structure in procurement, maintenance, and airworthiness regulations/guidelines, e.g. [23], [85], [86], [87], and [88]. An on-condition/damage tolerance maintenance strategy has been preferred, because it has offered economic advantages and a greater degree of flexibility in risk management. In particular, it provides a means of managing the risk of failure due to accidental damage and unforeseen design, manufacturing, and maintenance anomalies, while also reducing weight and/or increasing durability. These advantages have even made it worthwhile to introduce the strategy retrospectively on in-service aircraft designed to safe life criteria. In many cases, the strategy has allowed the lives of components and aircraft to be extended.

While a hard time / safe life failure management strategy is still required for engines, some military operators have been attempting to introduce on-condition failure management to the extent possible. In the civil world, “damage tolerance assessments” were mandated for engine life-limited parts in 2007 in FAR 33.70 [75]. In this new FAR, the stated intent of the damage tolerance assessments is to address the potential for failure from material, manufacturing, and service-induced anomalies within the approved life of the part. Engine life-limited parts, are rotor and major static structural parts whose failure is likely to result in a hazardous engine effect. The associated Advisory Circular AC 33.70-Y [76] adds that the damage tolerance assessments are intended to supplement the existing safe life methodology, and that in-service inspections based on the assessments are an option available for reducing the risk of fracture from inherent and induced anomalies. Thus, while the FAR does not make inspections for potential failure mandatory in future engines, it provides considerable encouragement in this direction.

Many Air Forces have set up Aircraft Structural Integrity Programs (ASIP) and Engine Structural Integrity Programs (ENSIP), to ensure structural integrity and reliability. Even though terminology may vary, ASIP and ENSIP effectively ensure that the RCM process is applied with appropriate rigour throughout the life-cycle. The ASIP and ENSIP concepts are comparable. The ASIP concept is described in more detail later in this chapter.

Since most electronic equipment has a constant failure rate, a “run to failure” strategy has typically been employed. However, for mission-critical equipment it may be appropriate to design for redundancy, fault tolerance, and graceful degradation (a gradual reduction in functionality). Built-In Test (BIT) would also have to be included to perform failure finding inspections. Such features would improve mission reliability and enable an on-condition failure management strategy. However, there would be a penalty in weight, complexity, cost, and (general) reliability.

To enhance the mission reliability of electrical and electronic systems, a more appropriate strategy than preventive maintenance can be to provide the system with redundancy or fault tolerance, and to use failure-finding tasks. The failure-finding task can easily be automated by adding a failure warning system to alert the aircrew and/or groundcrew.

Redundancy is defined in European Standard EN 13306 Terminologie de la maintenance [89] as the existence of more than one means at a given instant of time for performing a required function. Fault tolerance is defined in ARMP-7 [2] as the attribute of an item that makes it able to perform a required function in the presence of certain given sub-item faults. There are degrees of fault tolerance. A partial fault is characterized by the fact that an item can only perform some but not all of the required functions (EN 13306). In some cases it may be possible to use the item with reduced performance. If so, the item may be specifically designed to incorporate "graceful degradation".

There has recently been heightened concern over the risk of combustion due to failures in electrical wiring. This has led to the development of innovative methods of inspecting existing wiring for degradation that represents a potential failure. While it is difficult to define accurate PF intervals for wiring, this development of an on-condition approach to wiring maintenance is an important achievement.

5.12.4 RCM and "Condition-Based Maintenance (CBM)"

As mentioned in Chapter 2, Condition-Based Maintenance (CBM) is not yet well defined in military and international standards. There are no international standards describing CBM in any detail, but the following are two short international standard definitions of the term:

- Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. The performance and parameter monitoring may be scheduled, on request, or continuous. European Standard NF EN 13306 [8].
- Maintenance performed as governed by condition monitoring programmes. ISO 13372 [27].

ISO 13372 is one of a series of ISO standards dealing with the condition monitoring and diagnostics of machines. Condition monitoring is defined in the same standard as the detection and collection of information and data that indicate the state of a machine – the machine state deteriorates if faults or failures occur.

A new DoD policy on maintenance/support [22] defines CBM as follows:

> "A maintenance strategy based on equipment operational experience derived from analysis. CBM includes maintenance processes and capabilities derived from real-time or approximate real-time assessments obtained from embedded sensors and/or external tests and measurements using either portable equipment or actual inspection. The objective of CBM is to perform maintenance based on the evidence of need while ensuring safety, reliability, availability, and reduced total ownership cost."

This DoD definition includes traditional, ground-based inspection methods as well as embedded sensor systems. The policy refers the reader to a new "DoD Guide for Achieving Reliability, Availability and Maintainability (RAM)" [28] for more information. This guide confirms that DoD regards CBM as embracing all forms of inspection, including ground-based NDE. It clouds the issue by stating elsewhere: "Continuous monitoring or continuous inspection is the basis of CBM". However, this statement may refer primarily to land and sea vehicles, where sensor systems would present lesser problems of weight, integration, and cost.

A new text book by Vachtsevanos, Lewis, Roemer, Hess, and Wu [90], who have been associated with the F-35 JSF program, define CBM as the use of machinery run time data to determine the machinery condition and hence its current fault/failure condition, which can be used to schedule required repair and maintenance prior to breakdown.

A standard Open System Architecture (OSA) for implementing condition-based maintenance systems, named OSA-CBM, was developed in 2001 by an industry led team partially funded by the US Navy [91]. The team consisted of Boeing, Caterpillar, Rockwell Automation, Rockwell Science Center, Newport News Shipbuilding, and Oceana Sensor Technologies. Other team contributors included the Penn State University / Applied Research Laboratory and MIMOSA (Machinery Information Management Open Standards Alliance). OSA-CBM is an implementation of the ISO-13374 functional specification "Condition Monitoring and Diagnostics of Machines" [92], which defines the six blocks of functionality in a condition monitoring system, as well as the general inputs and outputs of those six blocks. These are shown in Figure 5-12, and provide some insight into what US industry considers to be the elements of a CBM system.

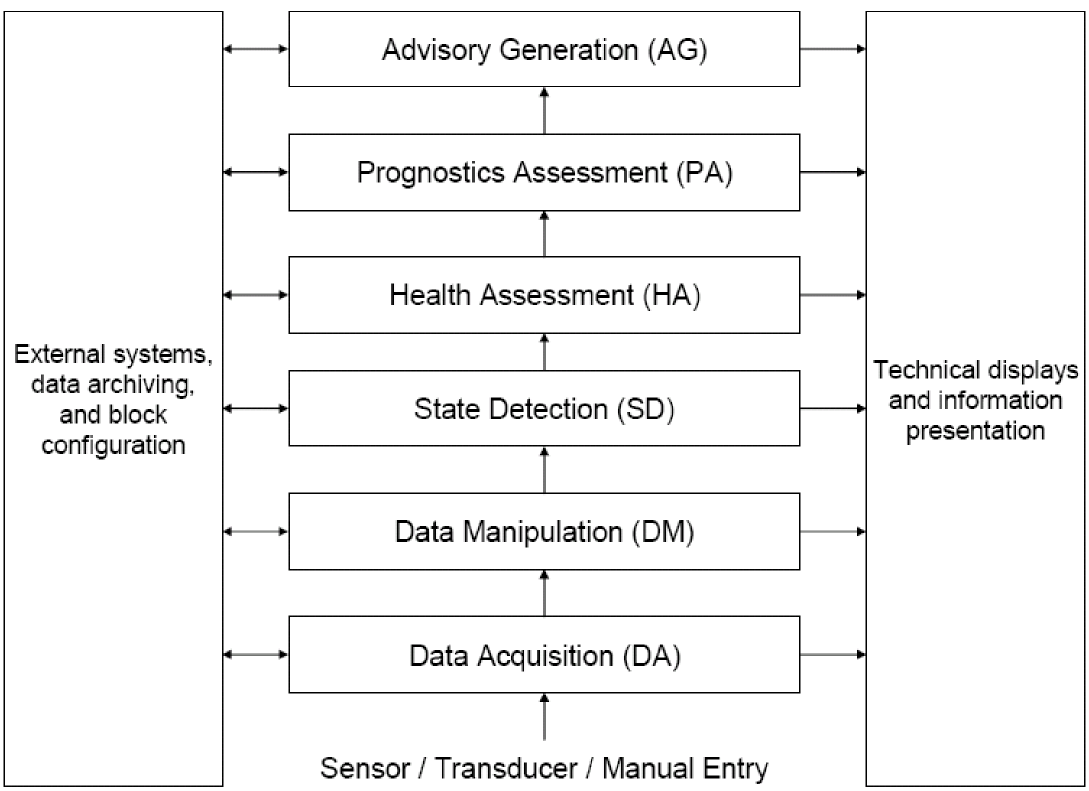


Figure 5-12: ISO-13374 Data Processing and Information Flows.

All the functions shown correspond with functions that have traditionally been performed by an aircraft maintenance/support system using a combination of manual methods, ground-based systems, and on-board systems.

The greater degree of automation of on-condition tasks implied by this architecture offers the possibility of improved aircraft availability and lower net life-cycle cost, but there will be a need for careful trade-offs with increased weight, reduced general reliability, and increased equipment costs. This OSA-CBM architecture includes the functions also associated with SHM, HUMS, PHM, and IVHM.

The first three blocks are typically technology specific (e.g. vibration monitoring, temperature monitoring, electrochemical monitoring) and provide these functions:

- Data Acquisition (DA) – Converts an output from the transducer to a digital parameter representing a physical quantity and related information (such as the time, calibration, data quality, and data collector utilized, sensor configuration).
- Data Manipulation (DM) – Performs signal analysis, computes meaningful descriptors, and derives virtual sensor readings from the raw measurements.
- State Detection (SD) – Facilitates the creation and maintenance of normal baseline “profiles”, searches for abnormalities whenever new data are acquired, and determines in which abnormality zone, if any, the data belong (e.g. alert or alarm).

The second three blocks combine human concepts with monitoring technologies in order to assess the current health of the machine, predict future failures and provide recommended action steps to operations and maintenance personnel:

- Health Assessment (HA) – Diagnoses any faults and rates the current health of the equipment or process, considering all state information.
- Prognostics Assessment (PA) – Determines future health states and failure modes based on the current health assessment and projected usage loads on the equipment and/or process, as well as remaining useful life.
- Advisory Generation (AG) – Provides actionable information regarding maintenance or operational changes required to optimize the life of the process and/or equipment.

The definitions and perceptions of CBM illustrated above differ mainly in where and how CBM tasks should be performed. The common factor in most usage of the term is that CBM is consistent with the RCM concept of “on-condition” maintenance.

5.13 LEAN AND OTHER ENTERPRISE MANAGEMENT CONCEPTS

The Armed Forces and industry at large continue to make improvements in general enterprise management concepts. These can be applied within the systems engineering and project management approach described earlier to reduce risk, and improve efficiency, schedule, and quality (compliance with specifications). In a large enterprise like a maintenance/support system there are, not surprisingly, many opportunities for refining the details of the overall management process. Some of the advanced business management concepts relevant to aircraft maintenance/support that have been developed and applied widely over the past 40 years include:

- Theory of Constraints (TOC) – Originated by business consultant Dr. Eliyahu M. Goldratt and described in a series of books, starting with [93].
- Lean Enterprise Management (Lean) – Originated by Toyota under a different name and publicised by authors from the Massachusetts Institute of Technology in [94].

- Reliability-Centred Maintenance (RCM) – Development sponsored by the US Navy and the civil airline industry (described earlier in this chapter).
- Six-Sigma – Originated by Motorola Inc. and described by Motorola authors in [95].

Some of these have displaced earlier concepts such as Total Quality Management (TQM). There is a body of literature and text books describing all of them.

RCM is particularly important for developing and sustaining cost-effective aircraft maintenance programs, and has already been discussed at some length. Of the others, Lean is the concept currently most favoured in NATO forces as a means of improving efficiency and providing an objective approach to Continuous Process Improvement (CPI). TOC is also used to identify process bottlenecks and other process deficiencies, and Six-Sigma is used on specific problems that warrant detailed quality analysis. Lean, TOC, and Six-Sigma are also used by the defence industry. For example, Lockheed Martin has adapted Lean and Six-Sigma as part of a corporate culture of excellence [96].

The key principles of Lean as applied by the US DoD are:

a) Perfect first-time quality through quest for zero defects, revealing and solving problems at their ultimate source, achieving higher quality and productivity simultaneously, teamwork, worker empowerment.

b) Waste minimization by removing all non-value added activities making the most efficient use of scarce resources (capital, people, space), just-in-time inventory, eliminating any safety nets.

c) Continuous improvement (reducing costs, improving quality, increasing productivity) through dynamic process of change, simultaneous and integrated product/process development, rapid cycle time and time-to-market, openness and information sharing.

d) Flexibility in producing different mixes or greater diversity of products quickly, without sacrificing efficiency at lower volumes of production, through rapid set-up and manufacturing at small lot sizes.

e) Long-term relationships between suppliers and primary producers (assemblers, system integrators) through collaborative risk-sharing, cost-sharing and information-sharing arrangements.

In the management of maintenance/support, principles b) and c) tend to receive the most attention. There is understandable interest in improving the speed and efficiency of aircraft maintenance work and the supply of parts as soon as possible, by using “value stream mapping” to identify and eliminate “waste”. Considerable success has been achieved in reducing costs and improving aircraft average availability.

In presentation 3.4 Heilhecker described the success achieved by the USAF and Boeing at Tinker Air Force Base, Oklahoma, in improving the availability of KC-135 tanker aircraft and reducing depot maintenance costs. The approach involved the following steps:

- Identify the main constraints to process flow using a TOC analysis.
- Radically re-engineer processes to create aircraft flow.
- Apply Lean principles to minimise wasted time and resources.
- Utilize 6 Sigma to reduce or eliminate process shortcomings.
- Change the culture to sustain success and continuous improvement.

Visible evidence of improved processes and working conditions after the Lean transformation can be seen in comparing Figure 5-13 with Figure 5-14 and Figure 5-15.

Figure 5-13: Depot Maintenance Production Line *Before* Lean Transformation.

Figure 5-14: Depot Maintenance Production Line *After* Lean Transformation.

Figure 5-15: Streamlined Access to Maintenance Tools and Resources *After* Lean Transformation.

The achievements to the end of 2005 were as follows:

- Steadily improved on-time deliveries of aircraft to near 100% (Figure 5-16).
- Cut flow days in half – FY00 427 days to FY05 195 days.
- Increased capacity.
- Liberated 60,000 sq ft of floor space (3 docks).
- New fly-in modification and maintenance workload.
- Cut Work In Progress (WIP) from 53 Aircraft in FY00 to 22 in FY05.
- Resulted in 31 aircraft returned to the warfighter.
- Saved the Air Force US$38.4 million.

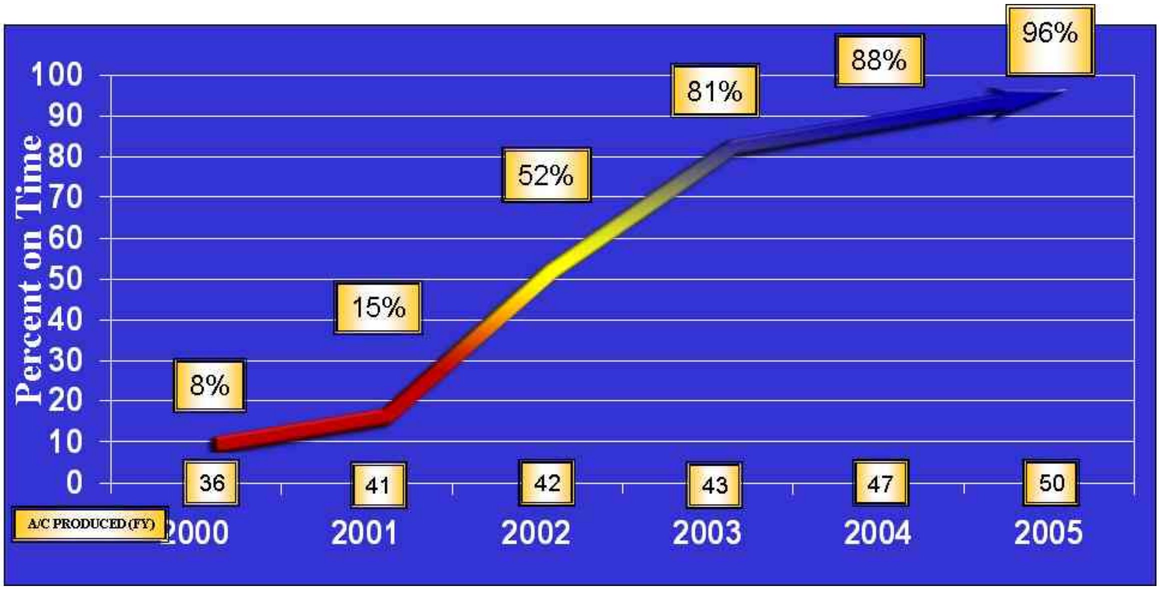


Figure 5-16: KC-135 Depot Maintenance Delivery Performance – Percentage of Aircraft on Time.

Lean methodologies can also be applied at 1st and 2nd Lines to improve aircraft availability. The UK National Audit Office (NAO) has given the following illustrations [64]:

- *Hot refuelling* – Previously Tornado GR4 aircraft returning from a sortie were shut down in order to prepare for the next flight. The cycle of powering up and shutting down an aircraft tends to introduce a number of minor faults, for example leaks and minor electrical problems. Keeping the systems powered while refuelling has reduced the number of faults reported and increased the number of sorties achieved per aircraft. In addition allocating planned parking bays to each aircraft reduces the amount of time to refuel as fuel bowsers are waiting when the aircraft arrives.
- *Changes in the way the Tornado GR4 is flown* – For example the use of wheel brakes instead of air brakes on landing or limiting the use of afterburners in transit to an exercise. Both can impact on the wear rate of the engine.
- *Single man reception and despatch* – Reception and dispatch of aircraft entails pre- and post-flight checks and replenishment of consumables, such as fuel. Using lean techniques, the tasks have been simplified and manpower reduced from two personnel to one for each aircraft.
- *Flying programme* – Using lean techniques forward squadrons identified and removed wasted time in between sorties. For example by crews sharing aircraft more sorties are achieved.
- *Forward repair scheduling* – Harrier – ‘primary’ and ‘primary star’ services were traditionally performed after a certain number of flying hours. This work has been organised into equalised work packages that are undertaken more regularly when aircraft are already on the ground for fault rectification.
- *Tornado 2nd Line scheduled maintenance* – Use of lean techniques has reduced Tornado 2nd Line scheduled maintenance from 15 days down to 2.5 days (Primary) and from 20 to 15 days (Primary Star).
- *Harrier – smarter acceptance procedures from Depth Maintenance* – Due to the large number of GR7 and GR9 aircraft transferring from depth repair hubs to forward squadrons as part of the upgrade programme a more efficient acceptance procedure has been developed.

- *Reorganising work areas in hangars* – Through using lean techniques, squadrons have reorganised work areas so that the right tools are in close proximity to areas of specific repair, reducing the need to search for equipment and walking time.
- *Project Eurystheus* – Twelve areas of Tornado GR4 forward activity were identified as having the most potential to improve the operational availability of aircraft. Work is ongoing to establish any benefits to changes in practice, for example training and induction, more efficient recording of repair activity and extension of intervals between maintenance for components.

5.14 MAINTENANCE MANAGEMENT DECISION SUPPORT – EUROFIGHTER EXAMPLE

5.14.1 General

In Paper 4.1, Buderath describes how Eurofighter air and ground systems provide strategic and tactical decision support. The efficiency of maintenance planning and execution can be greatly enhanced by providing essential maintenance data in a form that will assist managers and technicians. The Eurofighter Typhoon aircraft incorporates one of the most advanced maintenance decision support systems currently available. It is known as the Integrated Monitoring and Recording System (IMRS), and is outlined in Figure 5-17. The IMRS forms an integral part of the avionics suite on Eurofighter. Its main functions are:

- Structural Health Monitoring (SHM) facility;
- Mission data loading facility;
- Video and voice recording facility;
- Mission data recording facility;
- Crash recording facility;
- Maintenance data loading facility;
- Limited configuration checking facility;
- Special study recording facility;
- Warnings handling facility;
- (Externally) Initiated Built-In Test (IBIT) handling facility;
- Recording of consumables information facility; and
- Erasure of secure data facility.

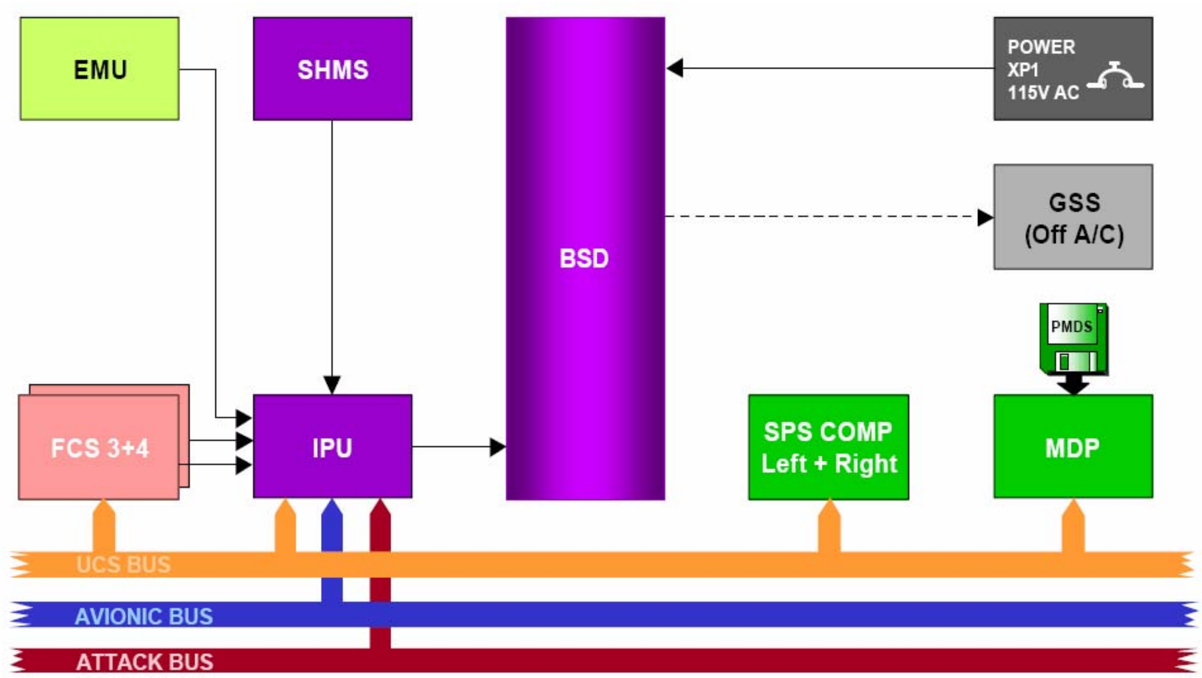


Figure 5-17: Integrated Monitoring and Recording System (IMRS) on the Eurofighter.

Two features of the system are particularly important for maintenance management and decision support:

- Maintenance Data Panel – The Maintenance Data Panel (MDP) is a fixed on-aircraft piece of equipment that displays information to the support personnel allowing them to query on-aircraft systems data. SHM details available on the MDP show the total life consumed by each SHM monitored location and information on SHM event messages that may have occurred on the previous sortie.
- Portable Maintenance Data Store – The Portable Maintenance Data Store (PMDS) is a solid state memory device, approximately the same size as a cigarette packet (100 x 60 x 25 mm). The PMDS is used to transfer SHM, engine and maintenance data to and from the aircraft.

Since there is considerable integration of ground-based and on-board equipment through networking, the ground-based segment of the IMRS is included in the aircraft's integrity certification process. This integration has driven the development of new concepts for data handling and logistics. Further development is under way to integrate information from several currently independent on-board systems to improve the efficiency and effectiveness of aircraft health management:

- Aircraft System Health (ASH);
- Structural Health Monitoring (SHM);
- Engine Health Monitoring (EHM);
- Secondary Power System health monitoring (SPS);
- Logistic software package (EFLog);
- Non-Destructive Inspections (NDI);

- Experience Capturing Systems (ExCS); and
- Aircraft Integrated Systems (AIS).

It is important to understand how and where the data and information are used in the supportability process. There are two main decision support levels: the "Tactical Level" and the "Strategic Level". Each requires information at a different level of detail. Figure 5-18 details the two levels of decision support, and provides a rough indication what type of information is needed.

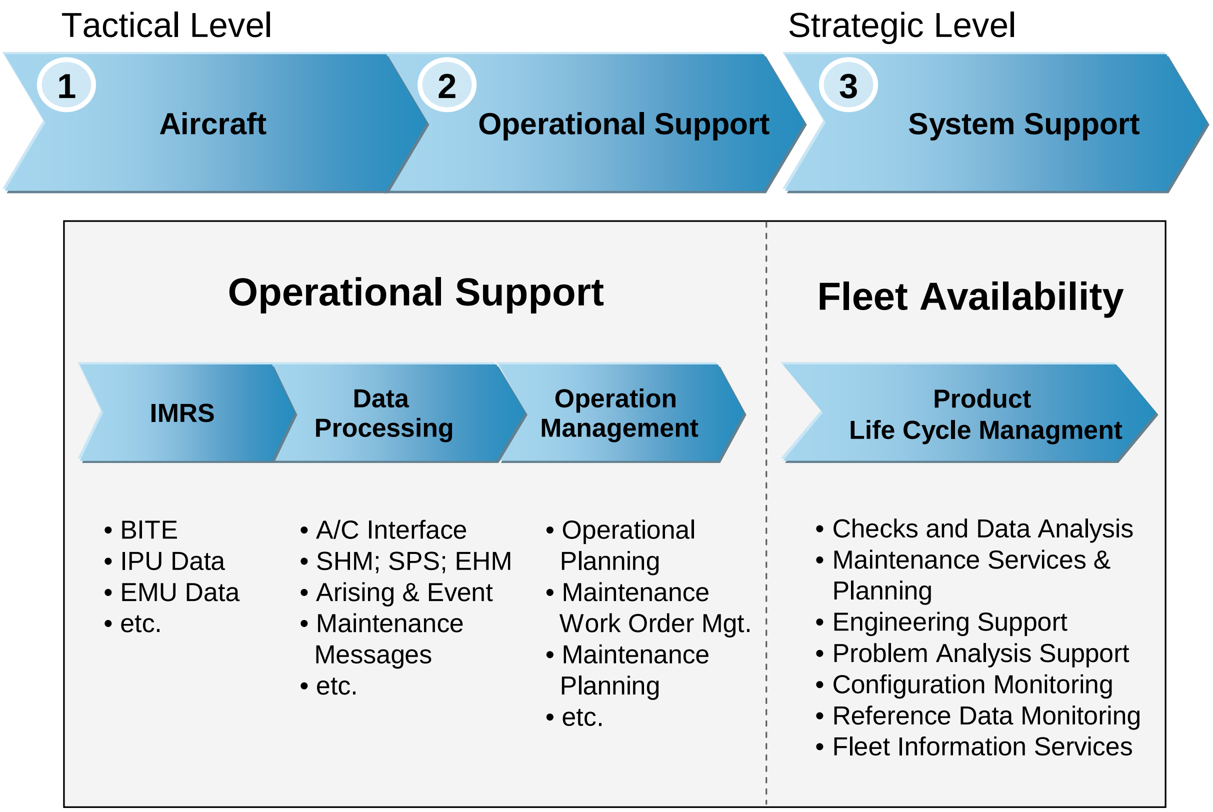


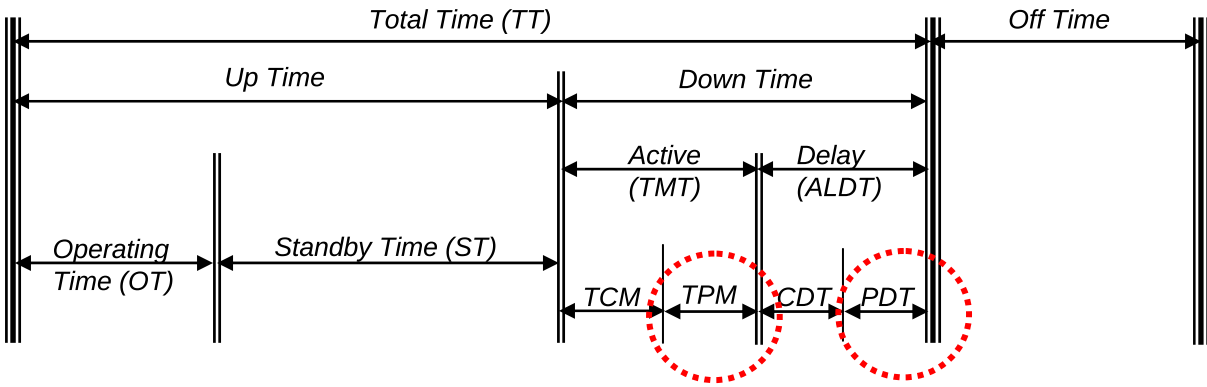
Figure 5-18: Information Provided by the Integrated Monitoring and Recording System (IMRS) on the Eurofighter for Decision Support at the Tactical and Strategic Levels.

5.14.2 Decision Support at the Tactical Level

The objective at the tactical level is to support operational planning, troubleshooting, maintenance planning at base level, etc. The following main features are required:

- Decision support technologies;
- Information to be provided to the point of operations; and
- Data management services from operational to strategic level.

The efficiency of the decision support can be measured by through the operational availability equation, as shown in Figure 5-19 where mainly the time of corrective maintenance is optimized.



$$Operational \quad Availibility, A_o = \frac{OT + ST}{OT + ST + TPM + TCM + ALDT}$$

TCM = Total Corrective Maintenance Time
TPM = Total Preventive Maintenance Time
CDT = Corrective Maintenance ***Delay*** *Period*
PDT = Predictive Maintenance ***Delay*** *Period*

Figure 5-19: Measuring the Effectiveness of Tactical Decision Support by the Effect on Eurofighter Operational Availability.

5.14.3 Decision Support at the Strategic Level

At the strategic level there are other stakeholders in the process who require a different set of information. The main objectives at the strategic level are as follows:

- To maintain readiness and safety performance of the fielded equipment;
- For diagnosis, to fix the problems we have;
- For prognosis, to indicate incipient conditions before the failure occurs, to separate real problems from anomalous conditions;
- For verification of corrective action implementation;
- To focus maintenance efforts;
- To optimize operational utilisation; and
- To optimize aircraft availability and operational and support costs.

At the strategic level the optimization of operational availability is related to the total preventive maintenance time and the predicted maintenance delay time.

The optimization of operational availability and the reduction of operation and support costs are strongly dependent on the efficiency of the maintenance information management system and the usage of information resulting from the analysis of the health data. The key success factor in the management of aircraft and fleet availability is the capability to:

- Link the results of the in service data analysis with system knowledge;

- Perform a cross-functional system health assessment;
- Perform health assessment at aircraft and fleet level; and
- Distribute the right information to right person in the supportability process.

EADS Military Air System has developed a life-cycle management platform for Eurofighter, which offers the following main functionalities (Figure 5-20):

- Status and condition monitoring from serial to system level.
- Status and condition monitoring at aircraft and fleet level.
- Cross functional health assessment at system and aircraft level.
- Decision support:
  - Remaining life based on aircraft usage at aircraft, system and sub-system level;
  - Inputs for predictive maintenance planning based on aircraft usage, trend and prognostic;
  - Verification for system modifications and upgrades;
  - Verification of corrective maintenance; and
  - Maintenance free operating time.

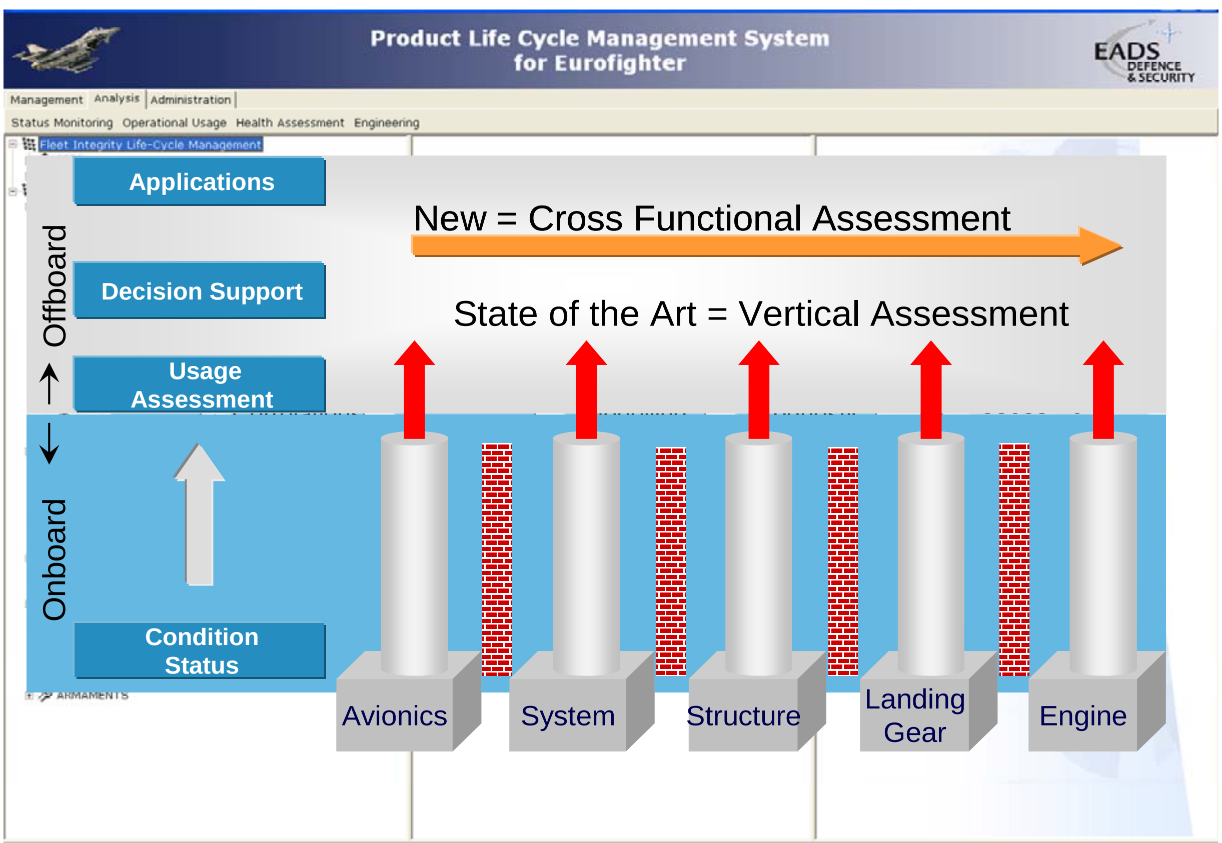


Figure 5-20: Product Life-Cycle Management SW for Eurofighter Typhoon.

5.15 INTEGRATING THE MAINTENANCE/SUPPORT SYSTEM FOR A MAJOR INTERNATIONAL PROGRAM – THE A400M TRANSPORT

5.15.1 Introduction

So far in Chapter 5 we have described advanced maintenance/support management concepts and technologies in a segregated fashion. We conclude the chapter with an account of how various important concepts have been assembled into a successful major international program, the A400M tactical transport aircraft. This account is based on Paper 3.5 by Heuninckx. It explains the maintenance and support concepts used to improve availability and reduce costs, such as a commercial approach, optimisation of the scheduled maintenance programme, extensive use of on-condition maintenance, a Maintenance-Free Operation Period (MFOP), common support solutions, and innovative support concepts. It also explains the technological measures applied during the design of the aircraft to improve availability, such as computer-aided design, damage-tolerant design, on-board systems integration, and increased components reliability. It also shows that availability cannot be dissociated from costs, and that a higher operational availability and lower costs can have organisational, but also industrial effects that could lead to increased efficiency of the Forces, but also of the European defence industry.

The A400M programme is a cooperative European programme between seven European Nations and managed by the Joint Organisation for Armaments Cooperation (OCCAR) for the acquisition from Airbus Military of a military transport aircraft system in response to common military requirements. As a new programme built on a commercial approach, it is bringing together many improvements in aircraft availability. This section, after introducing the reader to OCCAR and the A400M programme, will present the maintenance and support concepts, as well as the technological measures applied in the programme to improve aircraft availability as compared to current platforms.

However, despite the fact that effective operations and national security drive requirements for increased availability, the latter cannot be considered in isolation from Whole Life Cost (WLC), especially in these times of reduced defence budgets. A balance therefore has to be sought between increased availability and optimised costs, and this paper highlights how this is envisioned to be achieved for the A400M.

5.15.2 The Joint Organisation for Armaments Cooperation (OCCAR)

OCCAR, which is the French acronym for *Organisation Conjointe de Coopération en matière d'Armements*, is an international organisation created by a treaty (the OCCAR Convention) signed in 1998 by France, Germany, Italy and the United Kingdom. OCCAR gained its legal status in January 2001 at the end of the ratification process of the OCCAR Convention, and has since then welcomed Belgium (in 2003) and Spain (in 2005) as Member States. In addition, OCCAR includes an Executive Administration (OCCAR-EA) made-up of staff members recruited within its Member States.

The mission of OCCAR is to facilitate and manage collaborative European armament programmes and technology demonstrator programmes. For that purpose, OCCAR aims to be a centre of excellence and the partner of choice in Europe in the acquisition of defence equipment. The activities of OCCAR are based on five principles defined in the OCCAR Convention, as follows:

- The achievement of cost-effectiveness over the whole life of the system procured.
- The harmonisation of requirements, methods and technology across the Participating States and industries in each programme.

- Contributing to the building of a competitive Defence Technological and Industrial Base (DTIB) in Europe.
- The renunciation of the *juste retour* principle of fair industrial return that led in the past to many less than cost-effective work allocation decisions among countries in favour of a global balance across programmes and over the years.
- Openness to other European countries, under which States that are not members of OCCAR may participate in programmes managed by OCCAR.

These principles indicate that, unlike some other international organisations, OCCAR is far from being a "closed club".

OCCAR currently manages seven programmes of various sizes covering a wide array of system types. Each programme is managed by a Programme Division that, together with a Central Office located in the OCCAR headquarters in Bonn, form OCCAR-EA. The graphical representation on Figure 5-21 represents the programmes managed by OCCAR, their size and costs, and the location of their Programme Division.

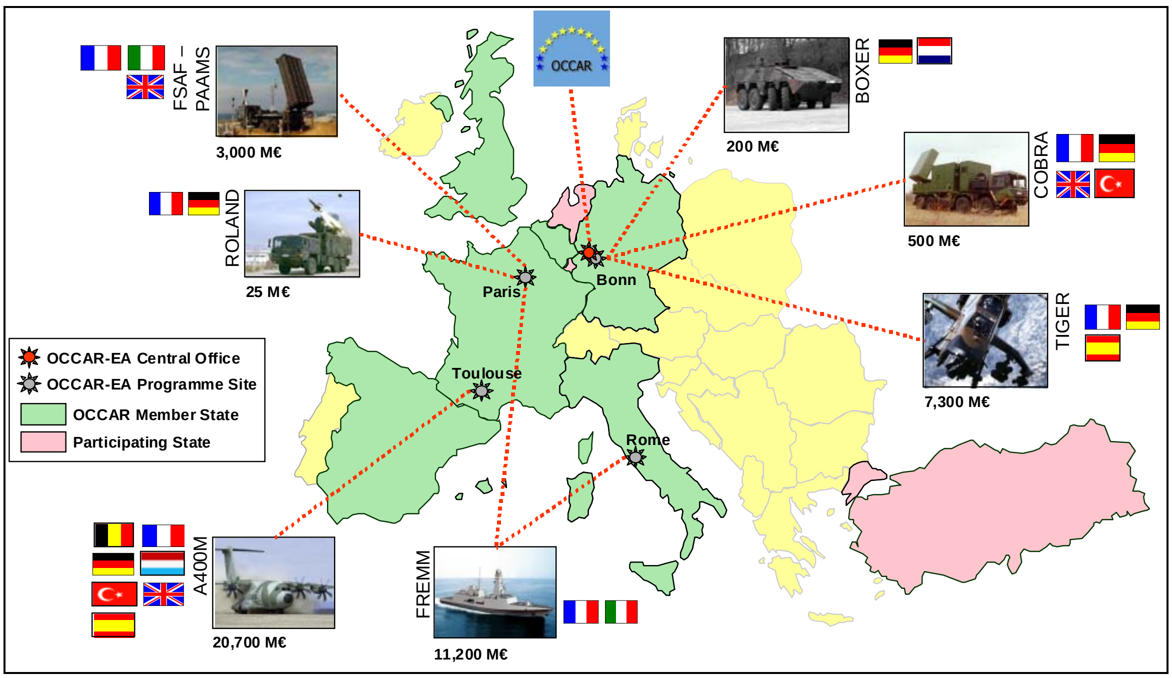


Figure 5-21: OCCAR Programmes, Estimated Total Costs, and Participating States.

It is interesting to note that the global overhead of OCCAR-EA compared with the costs of the programmes it manages is only about 1.1%, while its yearly turnover for each of its 200 full-time employees is about 15.1 million euro. OCCAR-EA has been certified to ISO 9001:2000 by the German accreditation authority TÜV since 2005.

OCCAR maintains close links with other international organisations in the field of defence in Europe, such as the European Defence Agency (EDA) and the NATO Maintenance and Supply Agency (NAMSA), which supports OCCAR-EA in spares management on a number of programmes.

5.15.3 The A400M Programme

5.15.3.1 The Programme and the Aircraft

The A400M programme (formerly known as the Future Large Aircraft or FLA) is a cooperative European programme between Belgium (representing also Luxembourg), France, Germany, Spain, Turkey and the UK for the acquisition of a military transport aircraft system in response to common military requirements. The programme uses a commercial approach. Its aim is to produce and deliver the aircraft and the appropriate support at fixed price conditions through a single-phase contract, which includes development, production and initial support. The contract targets minimum life-cycle costs. The Participating States have contracted to procure a total of 180 aircraft: Germany 60, France 50, Spain 27, the United Kingdom 25, Turkey 10, Belgium 7 and Luxembourg 1. Development and production was launched in May 2003, and the first flight is scheduled for early 2008. The aircraft will be delivered between 2009 and 2021. Following the launch of the programme, South Africa ordered 8 aircraft and Malaysia ordered 4.

The Airbus Military consortium, comprising Airbus, EADS, TAI of Turkey and Belgium's FLABEL, is the programme prime contractor and is located in Toulouse and in Madrid. It has sub-contracted the management of development activities of the A400M to Airbus, and uses the existing Airbus production centres plus the facilities of its industrial partners, most notably the single final assembly line located in Seville (Spain). Airbus Military is also responsible under the prime contract for the delivery of the necessary support products and services, such as technical documentation, spare parts, Ground Support Equipment (GSE), training and training aids and maintenance and support services.

The A400M itself is a four engine strategic and tactical military transport aircraft capable of carrying troops and/or cargo loads, performing airdrop, and acting as a tactical air-to-air refuelling tanker. It is propelled by four 10,000 shp TP400-D6 engines manufactured by Europrop International (EPI) and FH386 propellers manufactured by Ratier Figeac (RFHS). The aircraft performances will include a high cruise speed of Mach 0.68 to 0.72, a cruise ceiling in normal operation of 37,000 ft, a range from 1,700 NM (at maximum payload) to 4,100 NM (for ferry flights), a MTOW of about 136.5 tonnes and a guaranteed maximum payload of about 32 tonnes.

Figure 5-22 shows a graphical representation of the A400M.

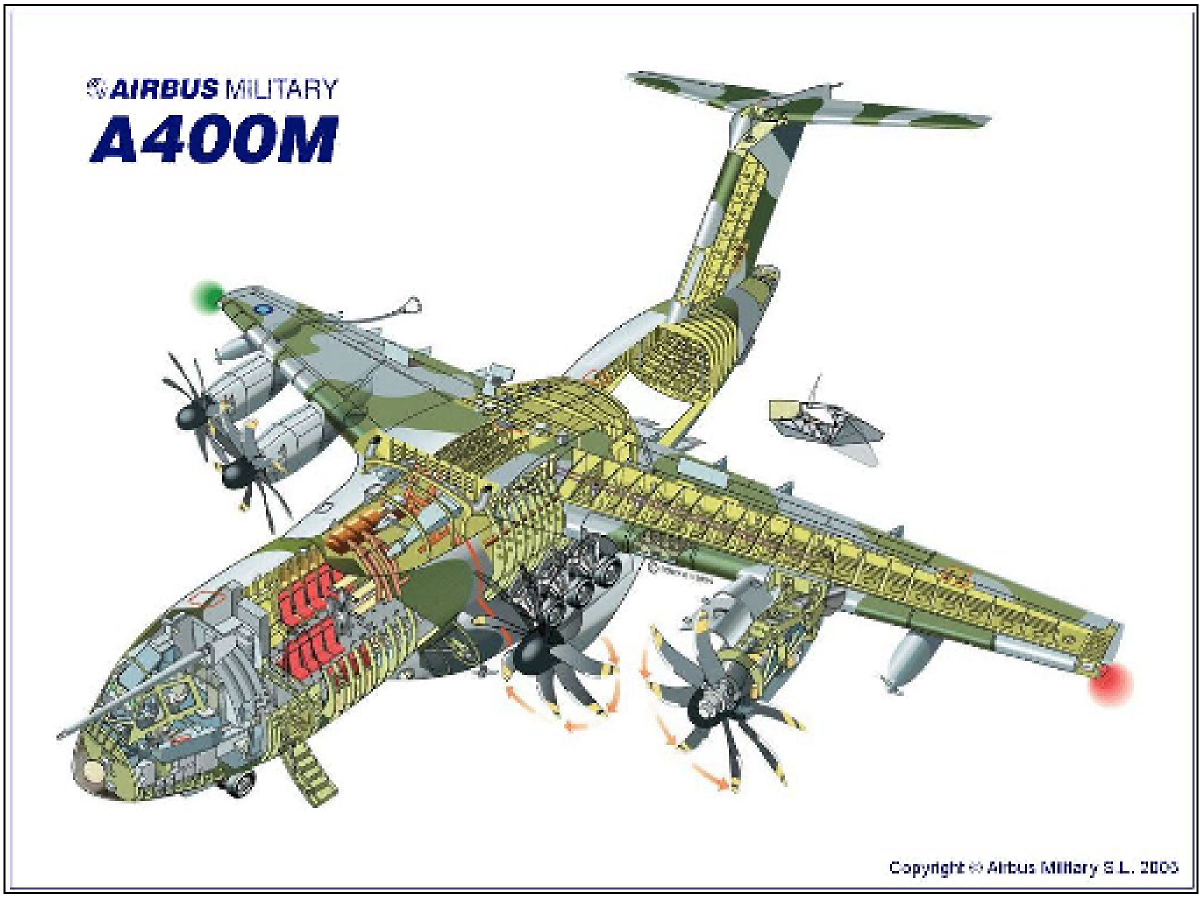


Figure 5-22: A View of the A400M Military Transport Aircraft.

The aircraft in its basic configuration is referred to as the Common Standard Aircraft (CSA), but the delivered A400M will include the installation of, or provisions for, additional optional systems that will be different for each Participating State and depend on the specific role of the aircraft. However, the aircraft configurations are about 90% common.

The aspects of the aircraft relevant to civilian certification will be certified by the European Aviation Safety Agency (EASA), while the whole aircraft, including the military systems, will be certified by a multi-national military body set-up specifically for the programme, the Certification and Qualification Organisation (CQO) and comprising representatives of the Military National Airworthiness Authorities (MNAA) of the Participating States.

Management of the A400M programme has been entrusted to OCCAR by the Participating States. It is the first programme to be incorporated in OCCAR from the start of its development phase. As such, it constitutes a pilot programme to demonstrate in a practical way the validity of the OCCAR principles. The A400M Programme Division is composed of about 30 staff members supported by experts from the Participating States, and is located in Toulouse, France.

The A400M programme is intended to remedy one of the currently identified European Armed Forces capability gaps, namely the ability to project quickly and effectively Armed Forces into overseas theatres of operation. As such, it will replace the existing fleet of C-130 and C-160 of the Participating States. It should also strengthen the European DTIB.

5.15.3.2 Key Performance Indicators and Modelling for A400M

The management of OCCAR programmes is based on a set of High-Level Objectives (HLO), which enable OCCAR to develop and implement a programme management aligned with the principal aims of the Participating States. These HLO include Key Performance Indicators (KPI) that define system performance, schedule objectives (defined for each national fleet as the date of initial capability and that of full capability), and financial objectives covering both the development and production phase costs as well as the Whole Life Cost (WLC) of the fleet.

Availability has been especially considered in the modelling of the programme cost objectives. The A400M WLC has been projected in a MS Excel-based model called A400M LCC Toolsheet (the resulting file is about 25 Mb in size, which gives an idea of the dimensions of the features included). The development of this model was based on an Airbus Military tool, but was further performed in cooperation with experts from the Participating States and OCCAR, and validated and verified independently by the Pricing and Forecasting Group (PFG) of the UK Defence Procurement Agency (DPA), thereby providing the users with a guarantee that the working of the model is not biased. This model is now widely used in the Participating States to predict WLC, calculate budgets, and perform simulations on the impact on WLC of differing operating assumptions.

The A400M LCC Toolsheet uses the target operational availability of the fleet (input by the user) to calculate the necessary human resources to support it in-service, as well as the required spares availability. On that basis, it optimises the pack of spare parts that would be required to achieve that target. Despite the fact that operational availability is not a guarantee under the DPP Contract, each Air Force has defined a target operational availability for its A400M fleet that it can enter in the A400M LCC Toolsheet as an input. The user can then immediately know the cost impact of his or her requirements related to availability. Figure 5-23 show an extract of the spares availability sheet of the A400M LCC Toolsheet. In that example, the target operational availability was set at 90%, leading to a required spares availability of 93.96%, which is then allocated among the aircraft systems.

A400M Life Cycle Cost - Target Spares Availability.

Target Spares Availability (As) **93.96%** *(See below for derivation)*

ATA	DESCRIPTION	URR/1000FH	URR		As Target
21	Air Conditioning	4.253	0.00425276		0.9957495
22	Auto Flight	0.135	0.00013519		0.9998646
23	Communications	1.043	0.00104317		0.9989557
24	Electrical Power	5.707	0.00570742		0.9942997
25	Equip & Furnishings	1.055	0.00105515		0.9989437
26	Fire Protection	0.525	0.00052474		0.9994746
27	Flight Controls	1.838	0.00183774		0.998161
28	Fuel	3.453	0.00345316		0.9965473
29	Hydraulic Power	1.099	0.00109948		0.9988994
30	Ice & Rain Prot	0.482	0.00048238		0.999517
31	Instrum/Record	1.534	0.00153441		0.9984643
32	Landing Gear	8.400	0.00840043		0.9916214
33	Lights	3.249	0.00324917		0.9967509
34	Navigation	2.845	0.00284486		0.9971546
35	Oxygen	1.268	0.00126825		0.9987305
36	Pneumatic	3.057	0.00305674		0.996943
38	Water/Waste	1.266	0.0012661		0.9987327
49	APU	1.625	0.00162488		0.9983738
52	Doors	1.252	0.00125214		0.9987466
53	Fuselage	0.011	1.1463E-05		0.9999885
54	Nacelles	0.015	1.4791E-05		0.9999852
55	Stabilisers	0.571	0.00057145		0.9994278
56	Windows	0.038	3.8495E-05		0.9999614
57	Wings	3.793	0.00379303		0.9962081
			0.04851742	77.96%	
61	Propellers & G'box	3.057	0.00305739		0.9969424
71	Propellers & G'box	3.057	0.00305739		0.9969424
72	Engine Core	1.459	0.00145927		0.9985394
73	Engine Fuel/Cont	2.713	0.00271302		0.9972863
74	Engine Ignition	0.325	0.00032451		0.999675
75	Engine Air/Deice	0.398	0.00039807		0.9996014
76	Engine Controls	0.172	0.00017178		0.999828
77	Engine Indicating	0.851	0.00085127		0.9991477
78	Engine Exhausts	0.222	0.00022211		0.9997776
79	Engine Oil	1.256	0.00125629		0.9987425
80	Engine Starting	0.208	0.00020823		0.9997915
			0.01371933	22.04%	
99	0	0.000	0	0.00%	1
		TOTAL	**0.06223675**	**100.00%**	**93.96%**

DERIVATION OF TARGET SPARES AVAILABILITY
(based on projected scheduled maintenance programme)

	Scheduled Interval				
A Check / A Multiple	**5**	*months*	*Annual utilization*	**660**	*FH/ac/year*
Light C Check / C Multiple	**15**	*months*	*Average mission length*	**3.01**	*FH/cycle*
Intermediate heavy C Check	**6**	*years*	*Unscheduled removals*	**66.45**	*/1000FH of which 70% = AOG*
Full heavy C Check	**12**	*years*	*Average time to rectify*	**3**	*MMH/removal*

	Down-time		Annual down-time			
A Check / A Multiple	**1**	*days*	2.40	*days*		
Light C Check / C Multiple	**5**	*days*	4.00	*days*		**Operational Availability (Ao)**
Intermediate heavy C Check	**18**	*days*	3.00	*days*		
Full heavy C Check	**32**	*days*	2.13	*days*		
					Target Ao	**90.00%**
Scheduled maintenance down-time TOTAL			**11.53**	***days =***	3.16% of 365 days	**96.84%**
Unscheduled maintenance down-time TOTAL			**3.84**	***days =***	1.09% of remaining	**98.91%**
					Target Spares Availability (As)	**93.96%**

Figure 5-23: A400M Life-Cycle Cost Toolsheet Spares Availability Calculation (Example).

In addition, spares optimisation is also performed by the subject matter experts of the OCCAR Central Office using the commercial off-the-shelf OPUS 10 tool (from the company Systecon in UK). That tool, based on a different routine than the A400M LCC Toolsheet, specifically performs spare parts package optimisation based on the required operational availability. This allows the comparison of the results of both models for a detailed analysis of the initial provisioning recommendations of the company, thereby providing the Nations with an alternative source of information to support their decisions.

It is common knowledge that, whilst the In-Service Support (ISS) phase of a programme amounts to more than 50% of its WLC, decisions made during feasibility, definition and specification phases define about 80% of the platform's WLC. Therefore, support has to be considered as early as possible in the life of a programme, and this is the case for the A400M. Support considerations are an integral part of the concurrent engineering design of Airbus through a process called Supportability Engineering (SE), similar in objectives to the Logistic Support Analysis (LSA) process. This process is explained in more detail in § 5.1 below.

For that purpose, Airbus is using a dedicated Excel-based model called Operational Reliability Analyser (ORA) to support system design by analysing the operational availability consequences of both system architecture and components Reliability, Maintainability and Testability (RM&T) characteristics. Based on that analysis, supportability engineers can influence system design if the current solution would not lead to a satisfactory availability result that cannot be otherwise compensated. We will come back later in this article on the practical impact and use of this tool.

5.15.3.3 Operational Availability and/or Operational Reliability?

Because of the reference of the ORA tool to "operational reliability", now is probably the time to highlight a fundamental difference between the way civilian and military people approach aircraft availability.

Military aircraft are generally underused. The expected usage of the A400M varies from Nation to Nation, but averages 650 Flying Hours (FH) per year per aircraft. In contrast, a civilian airliner is used for more that 2,000 FH per year per aircraft, or about 6 FH per day. These aircraft are designed to carry on their missions (up to four or six per day) despite the occurrence of faults, which are only repaired by mechanics during the night. In contrast, military aircraft are generally waiting to be used, but when that need arises, a maximum availability is expected because the vital interest of the State, and indeed human lives, are at stake.

This explains why civilian and military operators place emphasis on different metrics in assessing the availability of their aircraft. Civilian companies such as Airbus use the concept of Operational Reliability (OR), defined as *the percentage of flights without mission loss.* It is close to the military term 'Mission Reliability'. A mission loss will be declared if there is a delay of more than 15 minutes in the mission departure time for technical reasons, or if the mission has to be interrupted (on ground or in flight). The contractual operational reliability requirement for the A400M is set at 98.7%.

As discussed in Chapter 2, military forces are concerned with availability for missions as well as mission reliability. Each Participating States has defined a non-contractual target for the operational availability of its A400M fleet. Most require an operational availability of 90%, which is higher than has been achieved with existing military transport aircraft.

The personnel working on the A400M programme, both military and civilian, understand the importance of both operational availability and operational (mission) reliability.

5.15.4 Maintenance/Support Concepts to Improve A400M Availability

5.15.4.1 Commercial Approach

The Statements of Principles of the Future Large Aircraft (FLA) defined as early as 1997 that the programme (now the A400M) was to be managed in accordance with a "commercial approach". This is one of the key characteristics of the A400M programme.

Under this commercial approach, the prime contractor has the freedom to decide on design and manufacturing sources for airframe, engine and equipment, choosing those that provide best value for money together with acceptable capability and quality. The prime contractor is to use best commercial practice in the management of the programme to ensure that design and manufacturing are properly and efficiently integrated. Government participation is then limited to ensuring that the work is being conducted in accordance with these principles.

The commercial approach is intended to ensure that the A400M can be purchased, operated and supported at minimum WLC. Under these principles, the prime contractor is free to design and manufacture a product that meets the contractual requirements of the Participating States and satisfies the widest possible market at costs that are internationally competitive. This requires best international practice in management, design, development, production and support and the competitive allocation of sub-contract work. Participation in the programme is to provide the Nations' industries with work opportunities (under the Global Balance principle mentioned above), as long as they do not create significant adverse impact on the economy of the programme and if they are competitive in quality, price and delivery.

Despite not being explicitly mentioned in the original definition of the commercial approach, aircraft availability is one of its key elements. This approach intends to build on the record of Airbus that, for its fleet of commercial airliners, is able to achieve an operational availability of more than 98%, as shown on Figure 5-24 for the A320 family.

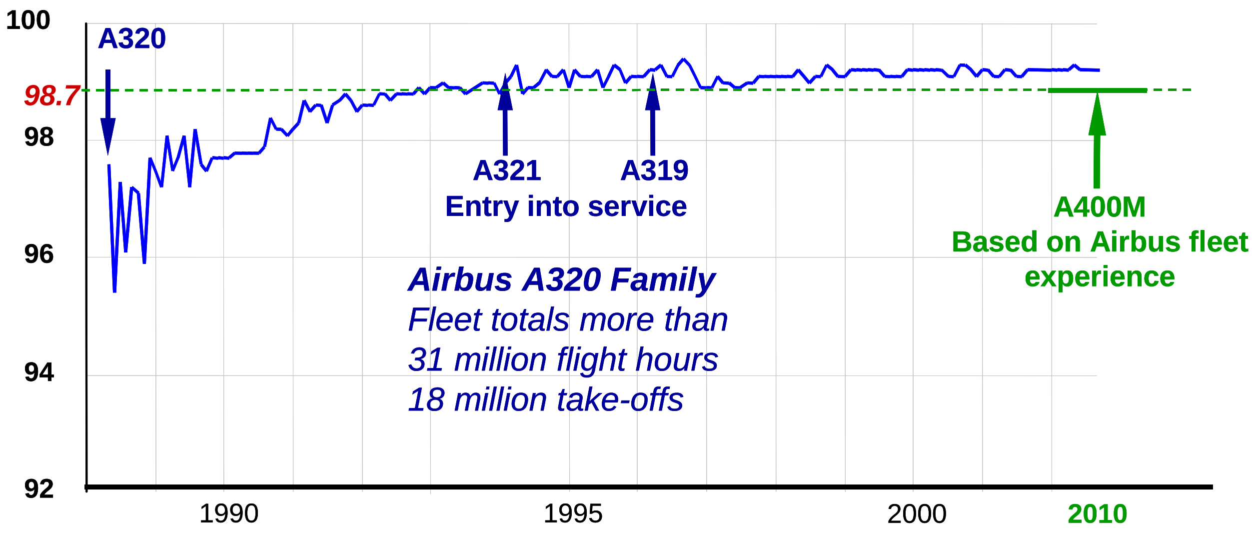


Figure 5-24: Airbus Fleet Operational Reliability (Percentage of Flights Without Delay Greater Than 15 min or Interruption for Technical Reasons).

5.15.4.2 Optimised Scheduled Maintenance Programme

It has been showed extensively that an optimised scheduled maintenance programme is one of the keys to cost reduction and availability increase. Studies performed by the US Air Force have shown extensive differences between the workload of scheduled inspections of the traditional aircraft of the ‘60 and ‘70 such as the DC-8, and that of more modern aircraft, such as the Boeing 747 or the DC-10, for which the scheduled maintenance programme had been defined using the Maintenance Steering Group 3 (MSG-3) process. For the A400M, these gains are expected to be even bigger, as shown on Table 5-5.

Table 5-5: Scheduled Maintenance Gains Through the MSG-3 Process.

Type of Preventive Maintenance	*Traditional*	*Modern*	*A400M Expected*
Structural inspection	4,000,000 MMH	66,000 MMH	9,000-20,000 MMH
Hard-time overhauls	339 items	7 items	None
Turbine shop maintenance	-	50% DMC reduction	-

MMH: Maintenance Man-Hours DMC: Direct Maintenance Costs

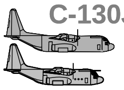
The scheduled maintenance programme of the A400M is therefore defined in close collaboration between Airbus Military, Airbus, OCCAR, the airworthiness authorities and the Participating States based on the MSG-3 process. Under this process, each Maintenance Significant Item (MSI) and Structure Significant Item (SSI) is analysed based on its criticality, architecture and RM&T characteristics in order to perform only the scheduled maintenance activities that are absolutely necessary for the safety and economics of operations.

As many as 10 Maintenance Working Groups (MWG) have been set-up to perform that analysis for all of the systems and the structure of the aircraft. These MWG are provided with detailed architecture and design information by industry, including the results of the Maintenance Task Analysis (MTA) and Failure Modes and Effects Analysis (FMEA) – which, under the Airbus procedures, also covers criticality – as well as recommendations for the scope and schedule of maintenance tasks. As the MWG are manned jointly by experts from industry and from the Air Forces, the latter have the opportunity to feed into the process their experience of military aircraft maintenance and operations.

This process will lead to the approval of a common A400M maintenance programme by the civilian EASA and the MNAA of the Participating States working together within the CQO. This maintenance programme will then be customised to meet the specific needs and operations to each Participating State.

The expected scheduled maintenance gains from that activity and from the other improvements that we will detail below can be seen on Table 5-6, the source of which is Airbus Military based on publicly available data. These gains translate directly into an increased operational availability. However, it is clear that the A400M MSG-3 process is still ongoing and that its results will affect these figures.

Table 5-6: Expected Scheduled Maintenance Downtime.

	Maintenance Intervals			Effect	Maintenance Downtime in 5 years
	Line (A-Check)	Light C-check	Heavy C-Check		
 C-17	60 Days	18 Months	36 Months (sampling)		**~ 150 Days**
	**150 Days**	**15 to 24 Months**	**72 Months**		**~ 50 Days**
 C-130J / C-130J Str.	120 Days	12 Months	60 Months		**~ 120 Days**

During the in-service phase, the operation and maintenance data will be collected by the Participating States and passed on to AMSL to allow for the revision and evolution of the initial maintenance programme. These evolutions will also take into account the evolutions in the configuration of the aircraft. The Participating States have agreed to manage these further evolutions of the maintenance programme in common, which should increase interoperability. This feedback loop will allow for the optimisation of the maintenance programme over time. In that sense, the MSG-3 process for the A400M will continue during the whole aircraft life.

5.15.4.3 Extensive Use of On-Condition Maintenance and Automated Condition Monitoring

Monitoring systems onboard the aircraft may supplement or even replace periodic inspections that are part of the scheduled maintenance programme. Automatic condition monitoring of the aircraft allows certain on-condition preventive maintenance inspections to be performed continuously or near-continuously. This approach allows more of the service life of some items to be used. An assessment of aircraft status and the need for maintenance action in such cases will be determined by monitoring dedicated parameters to identify the need for maintenance action before an anticipated failure occurs, and monitoring performance or systems configuration degradation to enable maintenance to be undertaken before a critical loss of function occurs.

Degradation of a mission-critical system, otherwise transparent to the crew, is detected by the monitoring system, which predicts a *schedule interval* (referred to in Chapter 4 as a ‘Predictive Maintenance Window’) during which a maintenance action will be required. For the duration of this interval, maintenance action may be deferred to the most convenient time, and aircraft operation may continue with a high degree of confidence that a mission loss or further degradation will be avoided. Despite the fact that this might lead to the removal of a component that still has some potential, it allows the corrective maintenance activity to be performed when the aircraft is on standby or (preferably) during a scheduled inspection, thereby avoiding any net impact on operational reliability. The schedule interval can be defined based on parameter or configuration requirements, as illustrated in the examples in Figure 5-25.

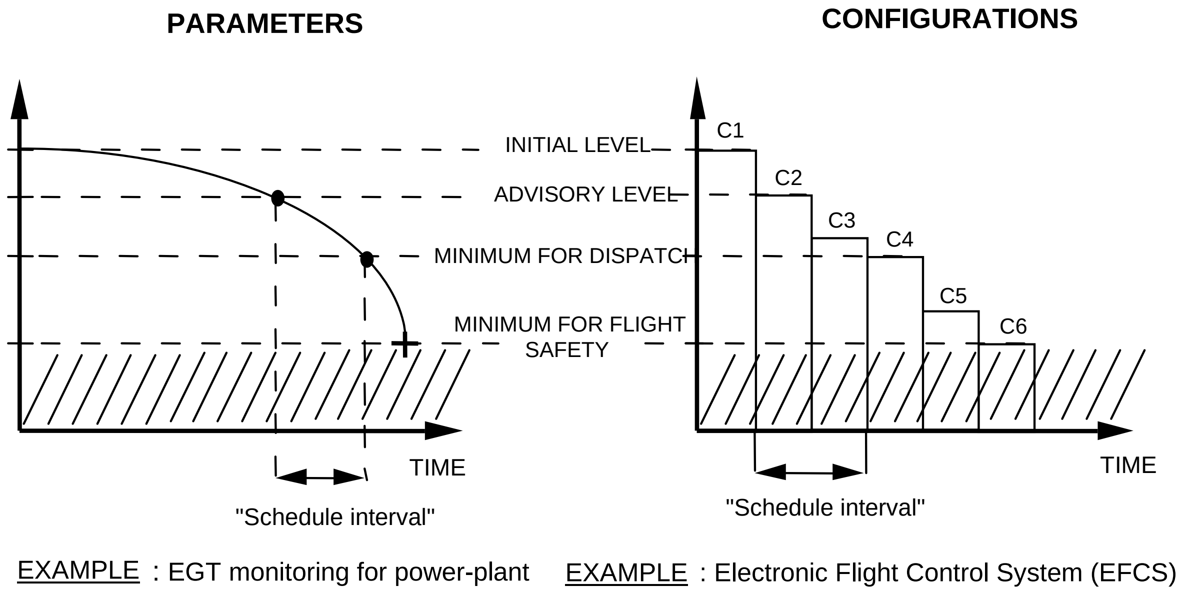


Figure 5-25: On-Condition Maintenance – Examples of Schedule Interval Definition.

Automated condition monitoring, used for a long time on Airbus aircraft, is being systematically applied to as many systems and structural components of the A400M as possible. For that purpose, the integrated avionics of the A400M is equipped with an Aircraft Integrated Monitoring and Diagnostic System (AIMDS) that centralises the control of Built-In Test Equipment (BITE) of all systems on each aircraft, detects system faults and provides failure messages in plain English, and also collects and records engine, APU and critical systems data. This data can then be analysed using the Maintenance Data System (MDS), which is explained in more detail below, to enable prognostics, trend analysis, maintenance planning and health and usage monitoring.

In addition, the extensive use of Integrated Modular Avionics (IMA) and redundant architecture makes easier the continuation of operations with degraded configurations. This feature is also explained in more detail in a further section of this paper.

In summary, automated condition monitoring (inspection) increases the potential applications of on-condition preventive maintenance and decreases the intervals between inspections. The dramatic reduction of hard-time overhauls resulting from the use of on-condition maintenance, with and without automated condition monitoring, on modern aircraft and the additional improvements that will be realised on the A400M were highlighted in Table 5-5. The potential benefits of on-condition maintenance with automated condition monitoring for operational availability and operational reliability are also significant: advance warning of mission-critical and safety-critical failures can be obtained; systems can be reconfigured in flight to mitigate the effects of failures; and repairs can be deferred to a convenient time (either during scheduled maintenance or at a time when the aircraft is not being operated).

5.15.4.4 Maintenance-Free Operating Period (MFOP)

One of the key requirements of the A400M is its deployment reliability, defined as the probability that one aircraft operated and maintained in accordance with standard conditions will complete a planned deployment period, using only spare parts contained in a transportable deployment kit. The deployment reliability of the A400M is guaranteed as 90% for a deployment of 15 days.

In order to satisfy this requirement with limited deployment kits and personnel, Airbus Military has the objective to provide the users with a Maintenance-Free Operating Period (MFOP) of 15 days. The MFOP is defined as a period of operation during which an aircraft is able to carry out its assigned missions without the need for any maintenance except pre-defined flight servicing (e.g. generic visual inspection, replenishment) and role change activities. During an MFOP, faults may occur in the aircraft but they must not require corrective maintenance action until the aircraft returns to the base. Once the MFOP is complete, an aircraft may have to be restored to its fully serviceable state at a suitable location (maintenance recovery period). Because of redundant architecture and of the application of on-condition maintenance techniques, any faults occurring during the MFOP (but not affecting the mission) may be deferred to the maintenance recovery period.

The current design activities performed by Airbus Military show that it will not be possible to achieve a 15 days MFOP with 90% certainty, although an MFOP of 15 days if still possible (with a lower probability) and the guaranteed deployment reliability mentioned above can still be achieved using the spare parts of the deployment kit. This shows the difficulty of an MFOP, even with a modern aircraft.

Another requirement of the A400M is that no preventive maintenance is required during deployments of up to 90 days, with 150 days being the objective. This requirement is taken into account both in the design of the aircraft, but also of course in the maintenance programme definition process.

In addition, a number of supportability guarantees are provided by Airbus Military: a mean time between critical faults of 225 flying hours, an average of 10 Maintenance Man-Hours (MMH) per flying hour for all levels of maintenance over the aircraft life (assuming a typical maintenance labour efficiency of 75%), a maximum elapsed time for servicing and maintenance activities of 40 minutes active maintenance time on the flight line, as well as other guarantees such as maximum parts costs per flying hour and no fault found rate. These guarantees aim to support the objective of improved availability.

The successful achievement of those guarantees will be verified during an In-service Reliability, Maintainability and Testability Evaluation (ISRMTE), whereby in-service data will be collected by the Forces during a period of about two years and transmitted to Airbus Military for the calculation of the actual in-service parameters. These calculations will be reviewed by the Participating States and OCCAR, and any negative deviation from the guaranteed values will lead to remedial actions such as retrofits. The management of this ISRMTE still has to be defined, but this process has been started by OCCAR-EA.

5.15.4.5 Common Support Solutions

Some ways to improve availability and reduce costs do not necessarily involve an impact on the aircraft design or operation and maintenance procedures. One of these is the search for an agreement amongst the Participating States to perform support in common, thereby sharing resources and achieving increased efficiencies as well as economies of scale.

A detailed analysis of the impact of common support on A400M WLC, with the operational availability considered as a constant, have led to the conclusion that substantial gains could be made from common support solutions such as common maintenance leading to economies of scales, pooling of spare parts, spare parts lateral support between the Participating States, common configuration management to share the non-recurring costs of modifications, and performing training mostly in common centres. Based on an A400M WLC comparator for non-common solutions for the whole fleet of 180 A400M (no variation of price and no discounting), the gains from common support and optimised support concepts are shown on Table 5-7.

Table 5-7: Potential Whole Life Cost (WLC) Gains of A400M Common Support.

Expected Gain from Common Support	*Of WLC*	*Of Support Costs*
Total Maximum WLC Gain (least expensive solutions)	7.15%	14.30%
Total Expected WLC Gain (most cost-effective solutions taking into account operational and policy criteria)	3.98%	7.96%

Although these results may seem limited, one should remember that – as a general rule – 80% of the WLC of a platform is defined by the feasibility, definition and specification phases. Only about 10% of the WLC can be affected by support concept decisions. Additionally, it should be noted that in some cases the benefits of common support are already realised in the A400M development and production contract, such as through common design authority services, common training device development and common central services for technical support and material support.

In addition, certain common support decisions can increase operational availability at times when it is needed the most. For instance, cross-maintenance, in which the mechanics of a Participating State would be allowed to maintain an aircraft of another Participating State, could be an extremely useful tool during deployments. In addition, spare parts lateral support between Participating States can be used in order to restore an aircraft to operation more rapidly than if the part had to be flown from the home base. In that sense, the participation of countries such as South Africa to these common schemes can be beneficial, as a number of operations of European States are conducted in Central Africa. In addition, these common processes are not especially difficult to implement.

However, common support in general (especially common contracting) often requires the Participating States to review some of their internal procedures and practices, and the agreements that will in fact be reached among the Participating States remain to be seen.

5.15.4.6 Pragmatic Support Concepts and Innovative Contracting

Another way of optimising the availability of the A400M at lower costs is an adequate choice of support concept by the Participating States. Within the scope of the A400M programme, support concepts are defined as the *allocation of work between the military services and industry*. A generic terminology has been agreed to identify support concepts within the programme, as shown on Table 5-8. ML1 (meaning Maintenance Level 1) covers line maintenance and servicing. ML2 on aircraft covers light scheduled inspections, while ML2 off aircraft includes the replacement of Line Replaceable Units (LRU) modules and parts in specialised workshops. ML3 on aircraft covers the heavy structural and corrosion inspections and ML3 off aircraft includes the repair of modules and parts in workshops.

Table 5-8: A400M Support Concepts.

Support Concept	Maintenance Level Performed By	
	Nation	**Industry**
Total Support	Some ML1 and all support to deployments	ML1 to ML3 on aircraft and off aircraft
Baseline Plus	All ML1	ML2 and ML3 on aircraft and off aircraft
Baseline	ML1 and ML2 on aircraft	ML2 off aircraft, ML3 on aircraft and off aircraft
Baseline Minus	ML1 and ML2 on aircraft and off aircraft	ML3 on aircraft and off aircraft
National Depot	ML1 to ML3 on aircraft and/or off aircraft	Support as required

In addition, some Participating States are moving away from the ownership of spare parts, instead choosing to rely on a spares lease option whereby spare parts would be owned, and even managed, by industry. Technicians from the forces would provide industry with a failed part and receive a functional one through a ‘hole in the wall’ located on the air base. The management of the whole supply chain behind the ‘wall’ would then be the responsibility of industry.

Because of the optimisation of the A400M maintenance, studies have shown that the most cost-effective support concept for the Participating States is either the *Baseline* (for larger fleet) or the *Baseline Plus* (for smaller fleet), meaning that most of the LRU repairs (including the engine) should be contracted to industry. This on the one hand moves away from the old support concepts applied by the military, where military depots were responsible for most of the maintenance, and on the other hand places more dependency on industry to ensure aircraft availability. This is rendered possible by the changes in the threat and in the multi-national security environment since the beginning of the ‘90s, but security of supply remains a potential issue.

Most Participating States are likely to follow the conclusions of these studies and to reduce drastically the maintenance activities performed in-house and, as a consequence, the needed resources. However, in order to ensure aircraft availability under these concepts, innovative contracts have to be put in place. This process is ongoing, but most Participating States are currently looking to contract for availability, pooling and leasing spare parts, and even in some cases (notably in the UK), partnering contracts with industry. These contracts, obviously, can be negotiated and concluded by OCCAR, thereby providing the expected gains of common support. The most complex issues being discussed for these contracts are the responsibility allocation between industry and the Participating States for any unavailability, the management of the deployment kits to be used in operations, and the coverage of changing environmental conditions in the contract prices.

This process will have a significant impact on the European industry and on national depots. An analysis of the industry workload in terms of dock occupation for on-aircraft maintenance (in the case of the Baseline support concept) performed by the Participating States and OCCAR based on the available data shows the results of Figure 5-26. It confirmed the results of a similar study performed earlier by Airbus Military. These figures cover the industrial workload for heavy systems, structural and corrosion inspections, as well as the resulting corrective maintenance and routine service bulletins implementation.

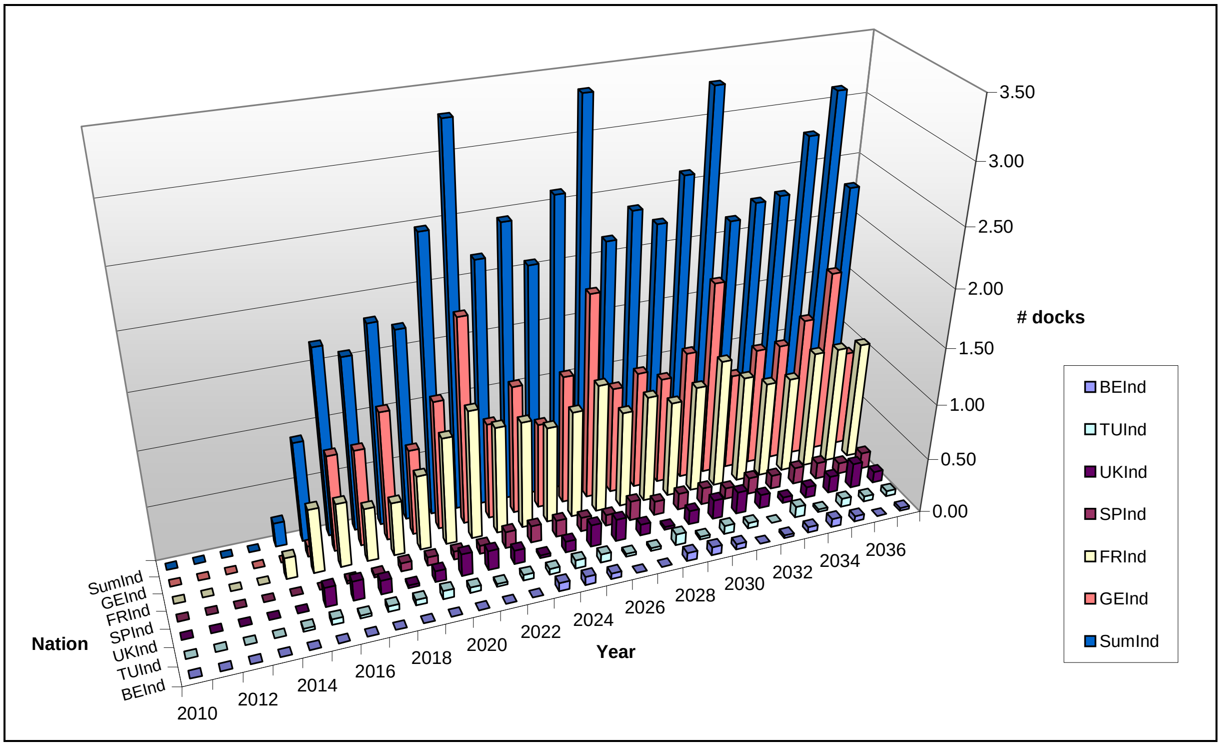


Figure 5-26: Estimated Occupation of Industry Maintenance Docks (Baseline Support Concept).

One can see that, should each Nation contract nationally, only France and Germany would be able to provide their national industry or national depot with a reasonably constant on-aircraft maintenance workload, but that workload would be much lower than for the current fleet (maximum two aircraft in maintenance at any one time). All the other Nations would only require partial use of one maintenance dock over time in their industry or national depot, the most extreme case being Belgium, which would likely only need the use of a maintenance dock for about one month per year.

Moreover, would industrial on-aircraft maintenance be contracted in common (thereby allowing for efficiencies in maintenance dock occupation), only three maintenance docks would be required in industry for the whole A400M fleet. To that figure must obviously be added the requirements deriving from incidents, operations and major modifications, but even this would keep the figure much lower than the current maintenance docks requirements of the existing aging fleet of C-130 and C-160.

In order to achieve these efficiencies, mandated by reduced defence budget, not only will the military have to modify their fundamental views of aircraft maintenance (a process that is well underway in most Participating

States), but also the European defence industry will have to produce the required synergies. Even though this could lead to mergers and more focus on core business, this can only lead to a more competitive European DTIB, which is one of the principles and aims of OCCAR.

5.15.5 Technological Measures to Improve A400M Availability

5.15.5.1 Computer-Aided Design

In addition to maintenance and support concepts, technological measures can be used to improve aircraft availability, or maintain the same availability at lower costs. Based on the Airbus experience, a range of these measures has been used on the A400M.

The concurrent engineering process of Airbus includes a process called Supportability Engineering (SE) that aims to include supportability considerations into the design of an aircraft. All design information is stored in a Digital Mock-Up (DMU) that allows not only a visual representation of the aircraft and its systems, but also to perform analyses of supportability. An example of DMU picture is shown on Figure 5-27.

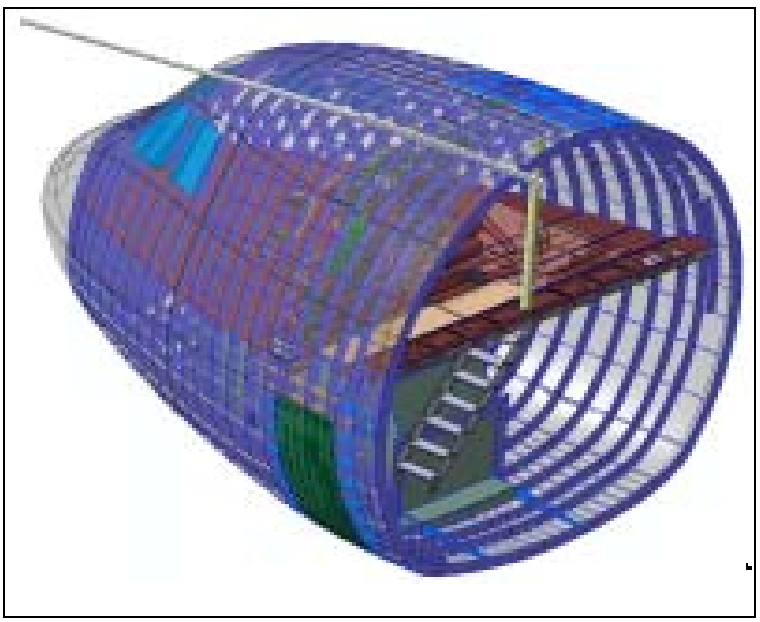


Figure 5-27: Portion of A400M Digital Mock-Up (DMU) – Forward Fuselage and Cockpit.

A graphical representation of the SE process is shown on Figure 5-28. Based on the supportability needs of the customers (in this case, the Participating States), a support specification is agreed which, together with in-service experience from other military and Airbus aircraft, leads to the systematic identification of supportability requirements. For the A400M, the support specification is an integral part of the procurement contract. The supportability requirements are reviewed by the experts of the Participating States and OCCAR-EA within the scope of the supportability assurance process. They form the basis upon which the aircraft will be designed for supportability through a supportability analysis.

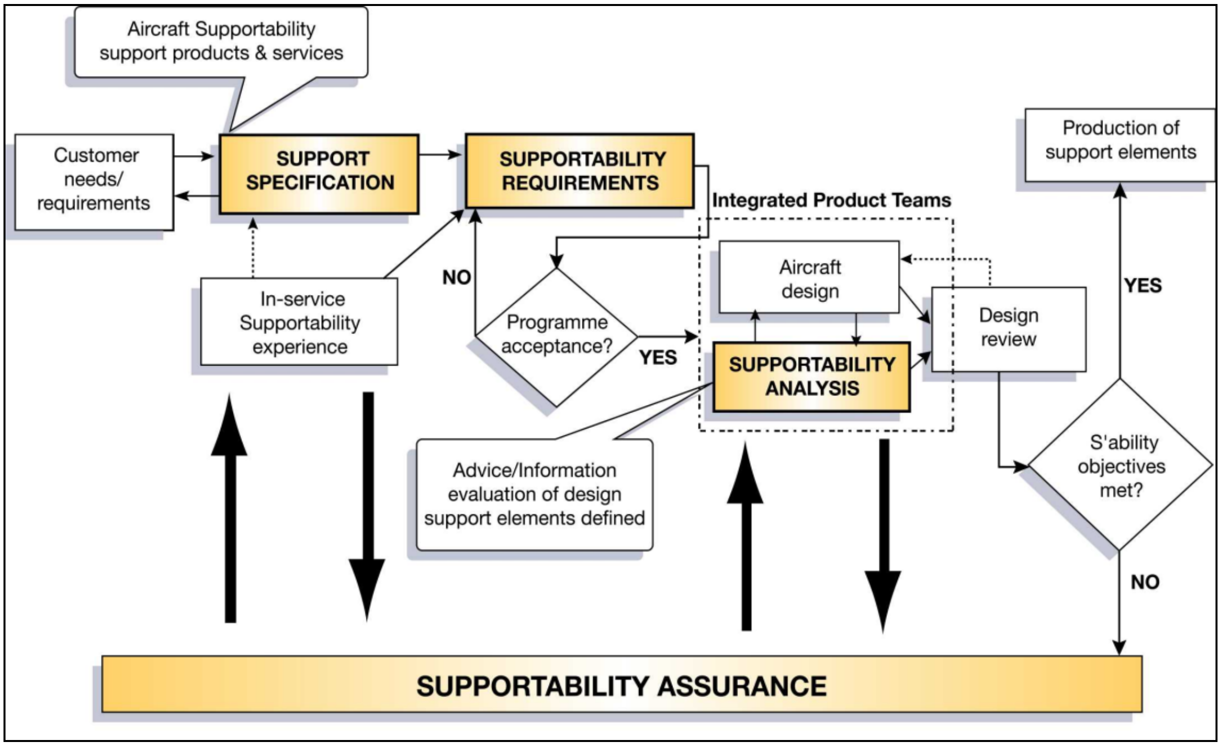


Figure 5-28: The Airbus Supportability Engineering Process.

The supportability analysis is divided into two main phases. In the first phase, during the Qualitative Maintainability Analysis (QMA), all parts are checked for accessibility and ease of removal. When the removal of a part would be too complex or require the removal of too many other parts, the supportability engineers request a change in the installation design. In a second step, the Maintenance Task Analysis (MTA) finalises the list of maintenance tasks and their Ground Support Equipment (GSE), tooling, procedure and manpower/ duration requirements, all the time verifying that these are within the supportability requirements and related contractual guarantees, and would lead to an optimised availability. These two phases can be performed concurrently for various systems.

During the whole supportability analysis phase, any supportability issue that would influence the design is reported to the design teams and discussed. The design is modified whenever necessary to improve supportability (an example of such design modification is shown below). The Participating States and OCCAR are involved in the supportability analysis through a supportability assurance process where customer involvement allows advising the Airbus engineers on the specifics of military operations (e.g. the consequences of landing on rough strips), as well as providing assurance to the customers that the design is progressing as planned.

The results of the SE process are compiled in computer databases in a similar way as the LSA Report (LSAR), which are accessible to the customer and constitute the basis for the authoring of the Interactive Electronic Technical Publications (IETP), which will replace paper documentation for the A400M.

Of particular importance is the use of the DMU to perform verifications of adequate maintainability. Human beings (male and female, with and without NBC clothing) are therefore modelled in the DMU in order to verify accessibility and maintainability during the QMA. An example of this is shown on Figure 5-29, which identifies an accessibility issue for the removal of the aircraft right battery. This led to the relocation of the banister that was blocking the access. If this action had not taken place, the replacement of the right battery would have required additional maintenance, and would have negatively affected operational availability. During the MTA, tooling is modelled into the DMU to verify the adequacy of the installation and removal procedures of each maintenance task.

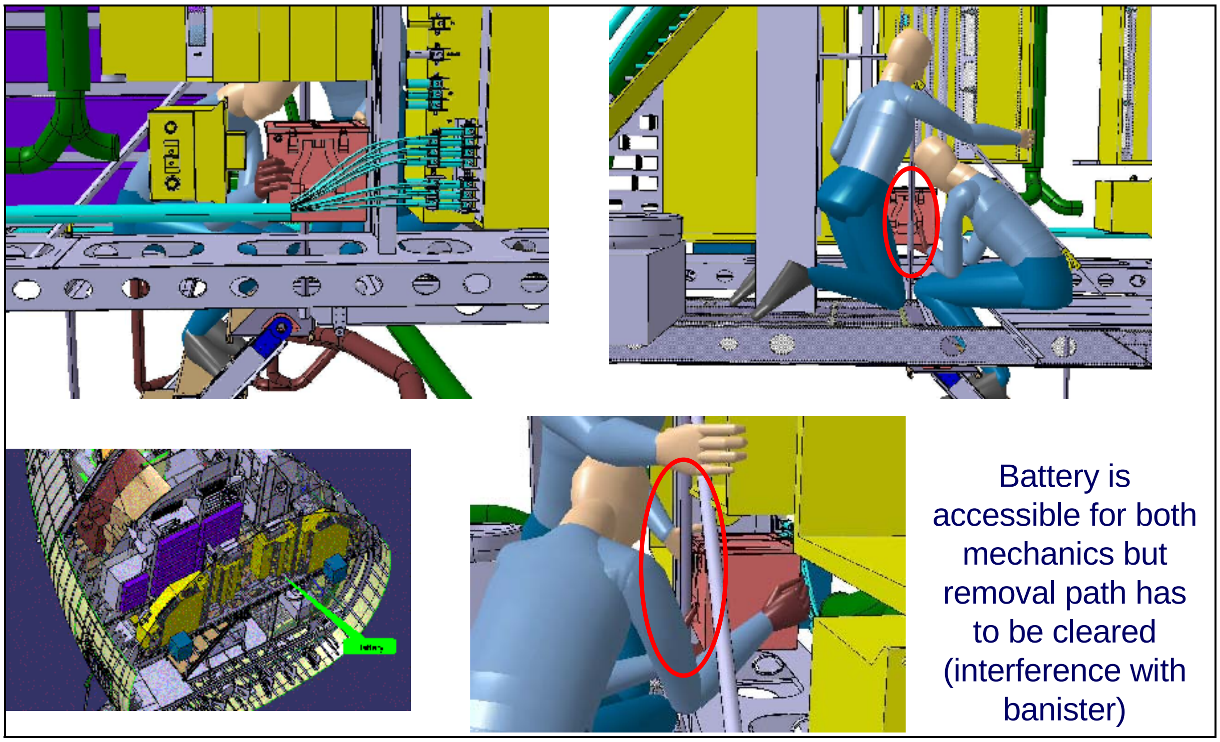


Figure 5-29: Example of Qualitative Maintainability Analysis (QMA) Using the A400M Digital Mock-Up.

The maintainability of the A400M will be verified jointly by personnel from AMSL and the Participating States during maintainability demonstrations that will be performed first on digital mock-ups and then on the flight test aircraft. A number of maintenance tasks will be selected for verification by OCCAR and the Participating States, and the performance of these tasks will be verified in terms of interchangeability, elapsed time, required resources, and adequacy of the technical documentation.

The DMU allows optimising the equipment installation. In addition, during the SE process, the architecture of the systems is also defined in order to guarantee aircraft availability. This is done within Airbus by using an Excel- and Cab Tree-based tool called Operational Reliability Analyser (ORA), as we mentioned above. The main interface sheet of the ORA tool for a specific system of the A400M is showed on Figure 5-30.

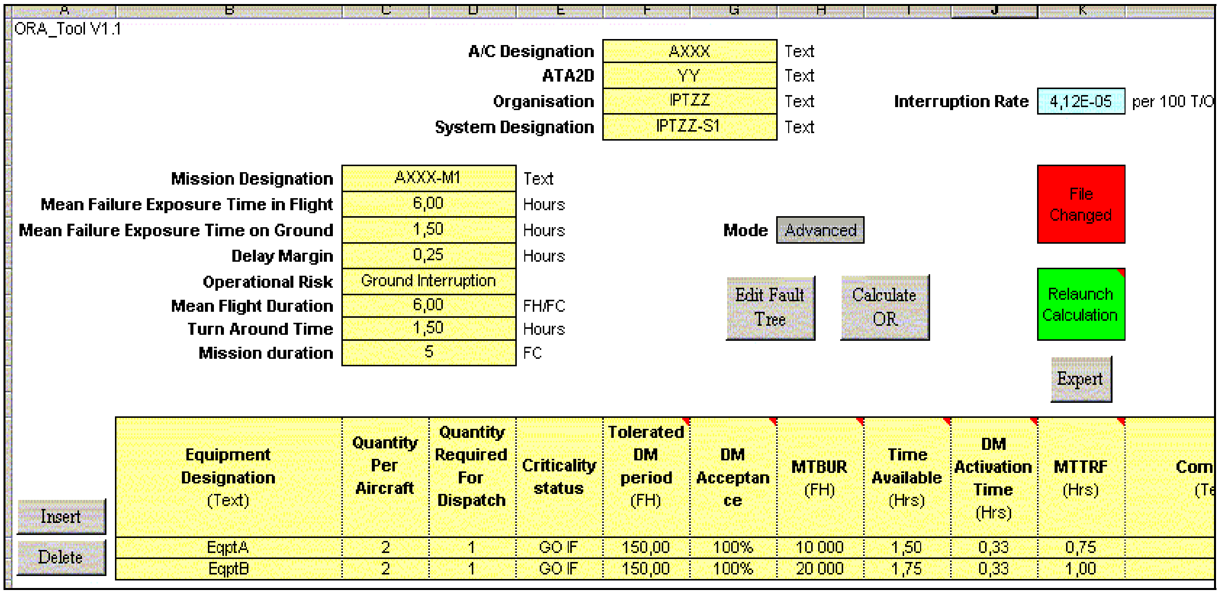


Figure 5-30: Example of Operational Reliability Analyser (ORA) Main Interface Sheet.

The operational reliability guarantees at the aircraft level are allocated as reliability targets at the system level based on the experience of the design teams. By modelling the systems architecture and the RM&T data of its components within ORA, the supportability engineers of Airbus can calculate reliability projections and assess if the system as a whole could meet the target. If this is not the case, the architecture of the system and/or the requirements for its individual equipment would be reviewed, potentially leading to modifications of the specifications used for the selection of the equipment suppliers. If this cannot solve the discrepancy, the target allocation may be reviewed at the system level, and a target reallocation between systems can then be agreed.

On that basis, the supportability engineers can support the definition of the most efficient system architecture, define the components reliability requirements and make simulations to verify compliance with the contractual requirements. In that sense, supportability is a key part of the concurrent engineering design process of Airbus.

5.15.5.2 Damage Tolerant Design

Scheduled maintenance programmes are defined and applied to protect an aircraft from environmental damage (corrosion), accidental damages, and fatigue damage. For the latter, the *damage tolerance* concept has been introduced in the late ‘70s. Based on the improvement of inspection techniques and increased knowledge of the propagation rates of cracks in metallic structure, it has been possible to ensure continued airworthiness through more focussed inspections.

Fatigue and damage tolerance stress analysis and tests are performed as part of the design, certification, and during the in-service life of any new aircraft model. The resistance of structures to cracking, and the behaviour of the structure in presence of cracks are investigated during these processes. This is done using computer models but also full-scale fatigue tests, where actual aircraft parts mounted in a test rig are subjected to stress similar to that experienced during more than their whole life. For the A400M, discussions are ongoing to define if these full-scale tests should simulate up to three times the expected aircraft life of thirty years. Figure 5-31 shows a digital mock-up image of the full-scale fatigue test of the new Airbus A340-600.

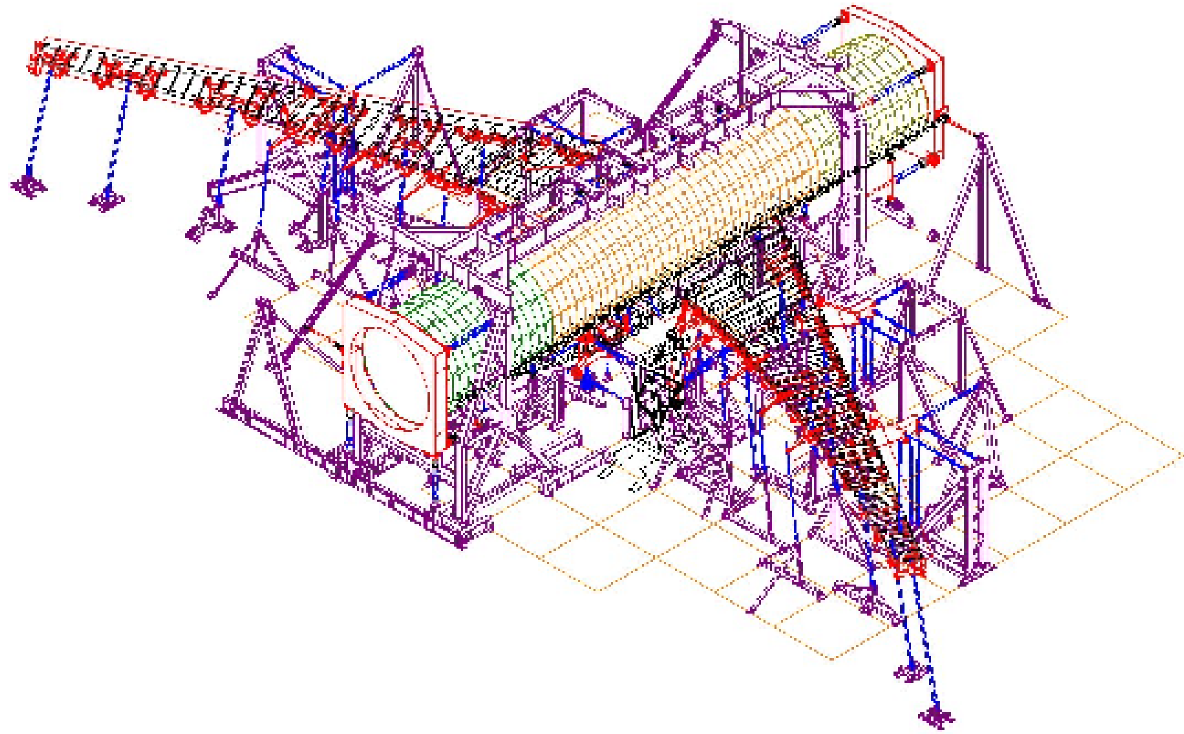


Figure 5-31: Airbus A340-600 Full-Scale Fatigue Test.

The scheduled maintenance tasks for fatigue damage are generally provided with an inspection threshold, and repeat interval. This is based on the fact that it will take a certain time before a crack initiates and starts to grow. Inspections will be repeated so that a crack exceeding the detectable crack size will be discovered before it may reach its critical size under limit load.

Inspection tasks are defined based on assumptions regarding aircraft usage. These cover average mission profiles, including phases between take-off and landing; average aircraft weights, speeds, altitudes, distances per flight stage, etc., and their variation. Therefore, a mix of missions with different parameters has to be considered, and this is especially true for military aircraft, for which the mission mix is much wider than for airliners. The results of the fatigue tests will be used to calibrate the A400M Life-Time Monitoring System (LTMS), discussed below, that will be used to predict the needs for structural inspections based on the actual aircraft use.

This concept is being applied for the design of the A400M structure, based on various operating assumptions provided by the experts of the Participating States, and the 'fatigue consumption' for the Structure Significant Items (SSI) can then be calculated during the aircraft design phase, allowing to define the best structure to meet the mix of missions. Figure 5-32 shows an example of this analysis based on C-160 data. The A400M full-scale fatigue tests, which are part if its certification process, are scheduled to be completed in January 2011.

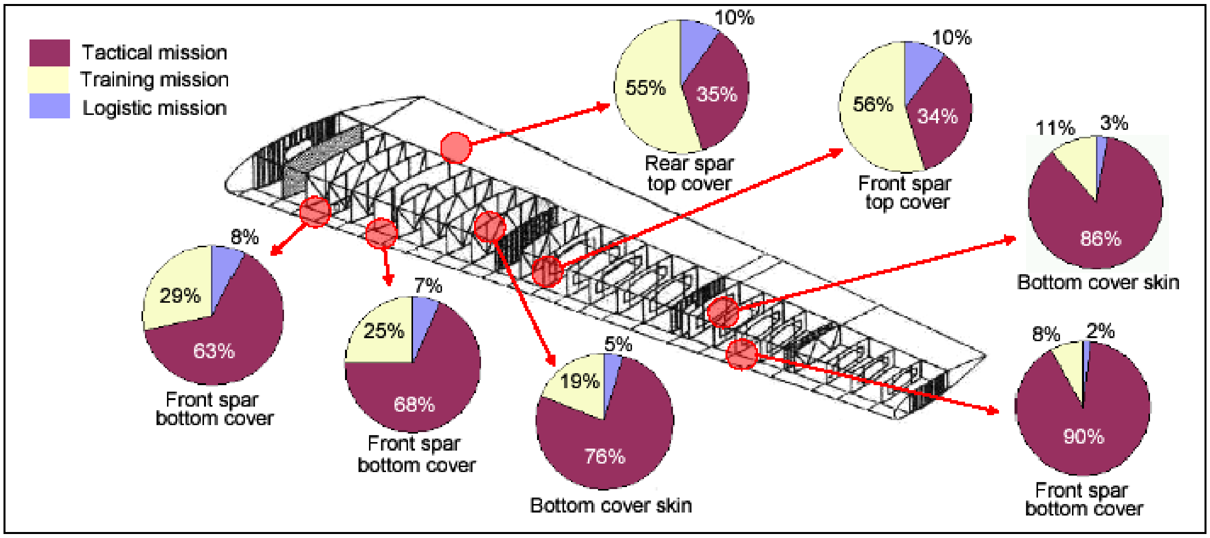


Figure 5-32: Comparison of Fatigue Consumption in Wing Structure Significant Items (SSI).

During the in-service phase, actual operational and maintenance data will be collected in order to fine-tune the scheduled maintenance programme. This data collection will partly be based on on-board data collection and diagnostic systems that are described in the next section of this article.

5.15.5.3 On-Board Systems Diagnostic Integration

Another way to improve operational availability is to reduce the time required for corrective maintenance. In addition to an efficient system installation, which reduces the duration of component replacements, maintenance time can be reduced by improving the diagnostic capabilities of the aircraft. As we have seen before, the Aircraft Integrated Monitoring and Diagnostic System (AIMDS) of the A400M centralises the control of BITE, detects system faults, and provides failure messages in plain English. It also collects and records engine, APU, and critical systems data, thereby enabling trend analysis and maintenance planning. This data can be analysed onboard the aircraft, or it can be analysed more deeply on the flight line by using a Portable Multi-purpose Access Terminals (PMAT). The PMAT allows groundcrew to interrogate the AIMDS via plug-in points inside and outside the aircraft, and facilitates a more in-depth analysis of failures. The PMAT includes access to Interactive Electronic Technical Publication (IETP) for troubleshooting and corrective actions.

The PMAT can download the AIMDS data and upload it into a Ground Support System (GSS) that includes both a Mission Planning and Restitution System (MPRS) and a Maintenance Data System (MDS). These systems, developed by Airbus Military for the A400M from existing systems – in the case of the MDS, from the AirNav system developed by Airbus for its commercial customers. The GSS provides database facilities, manages the performance of corrective actions on the aircraft, and schedules the preventive maintenance tasks. It will present the aircraft status in real time and perform other functions such as engine health monitoring. In addition, studies are being conducted to allow the transmission of maintenance data from the aircraft in flight to the ground via a data link, which would allow a more efficient management of maintenance activities on the flight line and increase operational availability. Such methods are already in use by some civil airlines. A schematic representation of the functionalities of the A400M MDS, showing its external interfaces and main functions can be found on Figure 5-33.

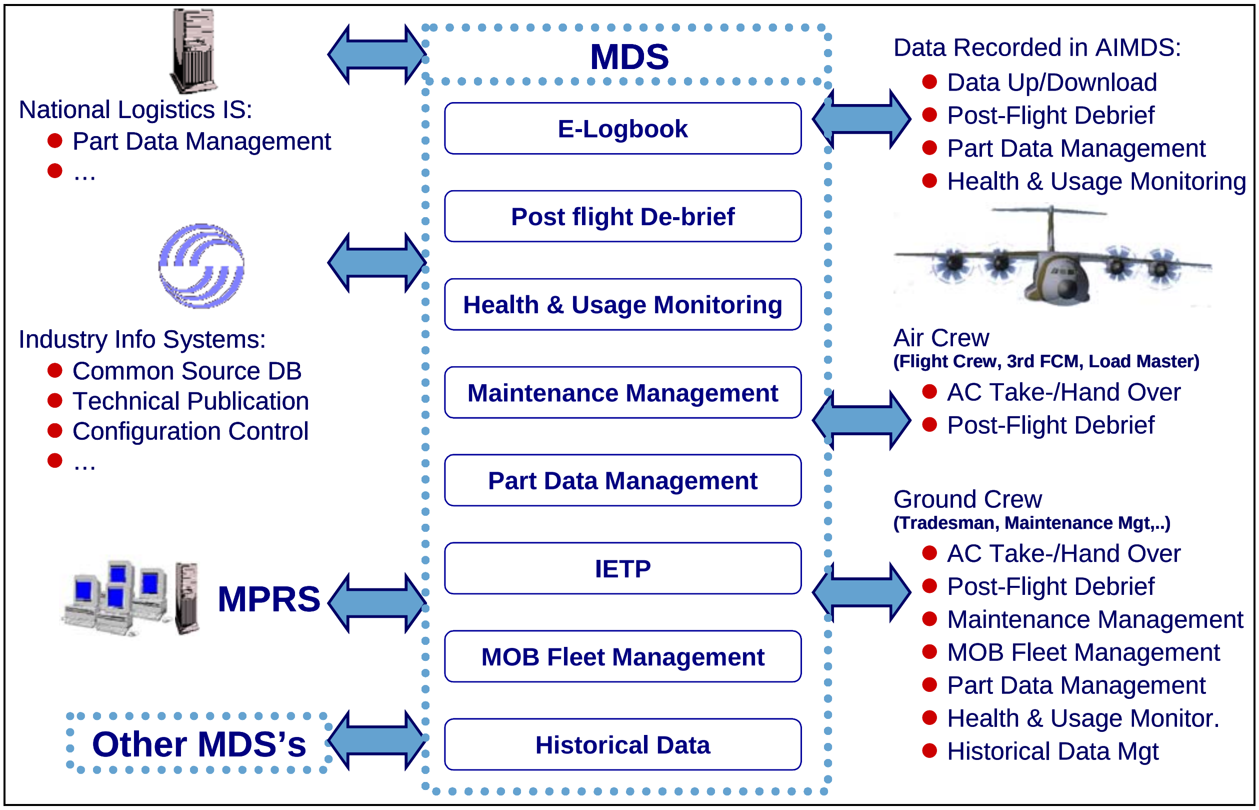


Figure 5-33: A400M Maintenance Data System (MDS) External Interfaces and Main Functions.

In addition, the aircraft may be equipped with an optional Life-Time Monitoring System (LTMS), for which an added option exists to perform direct measurements via strain gages. This system will record aircraft structural loads, including overloads, hard landings and total cycles accumulated, enabling operators to track aircraft utilization and associated fatigue. This will allow the operators on the one hand to plan their on-condition maintenance more efficiently, but also to review the scheduled maintenance programme if required.

5.15.5.4 Increased Components Reliability and Systems Redundancy

The RM&T characteristics of aeronautical parts, especially electronic components, have dramatically increased over the last decennia. The A400M design is based on these highly reliable components, which will reduce maintenance downtime and thereby increase availability while reducing WLC. In addition, a number of systems will benefit not only from the Airbus design methods and tools, but also from the experience of other recent Airbus programmes, such as the A340-600 and the A380. A number of A400M systems will be based on the design of similar systems in these aircraft. Whenever possible, Commercial Off-The-Shelf (COTS) or Military Off-The-Shelf (MOTS) components are used.

Moreover, the redundancy and possibilities of reconfiguration of the aircraft systems will provide increased operational availability by allowing the A400M to be operated normally with a number of failures. As an example, the aircraft will be equipped with four V/UHF voice radios, while only two are required by international civil aviation regulations for a normal logistic flight in civilian controlled airspace. Moreover, the critical systems can reconfigure automatically in case of failures, thereby easing the burden to the aircrew.

In addition, the aircraft structure will make intensive use of composite materials, which is expected to reduce the requirements for inspections for corrosion and fatigue.

5.15.6 Conclusions

The A400M is one of the key multi-national aeronautical projects in Europe, compensating the air transport capability gap of the European Air Forces and enhancing the competitiveness of the European DTIB. To that end, it provides an opportunity to implement many improvements in the operational availability of the European air transport fleet, as well as optimising their WLC. This section has highlighted these improvements, both in the area of maintenance and support concepts and of technological measures.

We can see that many of these improvements complement each other, and have both a managerial and technological components, so that none of these two should be considered separately. In addition, we have seen that operational availability cannot be dissociated from the related costs, and that the A400M attempts to strike a balance between these two critical factors. Moreover, the experience gained with civilian aircraft can certainly be used for the benefit of military aircraft.

By using the military experience of the European Air Forces and the aircraft design experience of Airbus, the A400M should be able to reach the optimum of operational availability and costs for the benefit of the European military, thereby helping to bridge its air transport capability gap and helping to optimise the competitiveness of the European defence industry.

Chapter 6 – AIRCRAFT AND SUPPORT EQUIPMENT CONCEPTS AND TECHNOLOGIES FOR IMPROVING AIRCRAFT AVAILABILITY

6.1 INTRODUCTION

Goals for aircraft design and maintenance/support for optimising aircraft platform availability were developed in Chapter 2. Also, some strategies were outlined for moving towards these goals. The central objective in all these goals and strategies is to reduce the need for maintenance and the associated downtime. Any strategy that has this objective is likely to benefit aircraft platform availability. Later, Chapter 5 described some advanced management concepts and technologies that could serve the strategies in Chapter 2. The current chapter describes some advanced on-board and ground-based equipment concepts and technologies that could also be useful. Since the design of the maintenance program was dealt with in Chapter 5, the Chapter 2 goals that are addressed by the concepts and technologies in the current chapter all involve the minimisation of downtime. They are as follows:

a) Design the aircraft for maintainability (ease of maintenance).

b) Reduce the downtime for servicing (replenishments).

c) Reduce the downtime for replacement/restoration of lifed components by:
   1) Designing for aircraft maintainability with particular attention to the components in question;
   2) Extending remaining useful life;
   3) Improving the scope and accuracy of usage monitoring; and
   4) Using on-condition inspection instead of component replacement/restoration.

d) Reduce the downtime for inspections, i.e. on-condition and failure-finding tasks.

e) Reduce the downtime for "age exploration".

f) Reduce the downtime for diagnostics.

g) Reduce the downtime for failures that cannot be duplicated (CND).

h) Reduce the downtime for repair.

The chapter is organised into groups of maintenance/support concepts and technologies that currently form sectors or areas of specialisation within the industry, as follows:

a) Usage monitoring.

b) Failure modelling for prognostics (life estimation).

c) Inspection using Non-Destructive Evaluation (NDE).

d) Sensors for on-board usage monitoring and inspection systems.

e) Diagnostics for electrical and electronic systems.

f) Automated inspection and diagnostics for mechanical systems, structure, and engines.

g) Information analysis.

h) Integrated maintenance systems for usage monitoring, inspection, diagnostics, and prognostics (health management).

i) Maintenance concepts and technologies to achieve a Maintenance-Free Operating Period (MFOP).

j) Rapid repair of aircraft damaged in action.

k) Corrosion prevention and repair.

The implementation of the aircraft and equipment concepts and technologies described in the current chapter generally involves adjustments both to the design of the aircraft and to the design and management of the maintenance/support system. In some cases, implementation may require significant changes in managerial and regulatory policy. As emphasised in Chapter 5, a systems engineering approach to both the managerial and technical aspects of aircraft design and maintenance/support is needed to ensure relevance, affordability, and an adequate return on investment.

The ability of the supply chain to provide reliable spares when needed is central to aircraft platform availability. Budget constraints place a limit on supply chain performance, and so the current chapter includes concepts and technologies that will help to reduce downtime and costs associated with the off-aircraft maintenance of LRU and SRU as well as aircraft. In this regard, particular attention is paid to engines, because engine maintenance is a major factor in aircraft availability, safety, and life-cycle cost, and because 1st Line engine maintenance concepts need to be integrated with 2nd to 4th Line engine maintenance concepts to minimise aircraft downtime, including supply delays.

The current chapter is based mainly on the papers and discussions at the Workshop and on a few supplementary papers invited by the AVT-144 Technical Team. The chapter provides overviews of concepts and technologies, but attempts to add detailed explanations and examples of applications where this would be of use to engineers and managers in NATO and PfP countries. Additional detail on some technologies is available in other RTO reports and symposia [97]. The chapter does not cover all aircraft and equipment concepts and technologies that could benefit aircraft platform availability. There are other relevant maintenance/support concepts and technologies that could not be covered in the time available to the AVT-144 Technical Team. In particular, we would like to have provided additional information in the following broad technology areas:

- *Information and Communications Technologies (ICT) to assist technicians in the rapid execution of maintenance tasks*, including: Interactive Electronic Technical Manuals (IETM); Personal Information Devices (PID); local wireless communication systems; and global network systems (for linking to central databases).

- *Aircraft and equipment technologies relevant to the storage and movement of materiel in the Supply Chain*, including: ICT as above to assist maintenance technicians in the rapid identification and ordering of parts; Radio Frequency Identification (RFID); Packing, Handling, Storage, and Transportation (PHS&T) technologies, particularly those relevant to deployments/expeditions; and technologies to reverse engineer and manufacture discontinued components. PHS&T technologies of particular interest include environmental monitoring of packaged items to detect potentially catastrophic mishandling, special in-theatre and forward storage concepts, and packaging concepts for spares, repair parts, and whole aircraft.

- *Concepts and technologies for repair (in addition to those covered)* that will reduce the downtime for on-aircraft repairs at any maintenance organisational level, but particularly 1st Line. Of particular importance are efficient and robust concepts and technologies for the repair of composite structure. Also of importance are advanced concepts and technologies for the repair of metallic components, including the use of cold working of holes and surfaces to restore fatigue life, bonded repairs, laser beam welding, friction stir processing, and thermal spray of surface protection. Finally, robotics is becoming increasing important in many on-aircraft maintenance processes.

- *Aircraft and equipment technologies associated with the Human Factors Integration (HFI)* in maintenance/support, in particular those associated with the list of maintainability strategies in Chapter 2.

6.2 USAGE MONITORING

6.2.1 Introduction

Usage monitoring systems have been in use for decades. An example is the mechanical accelerometer used in monitoring gross airframe load exceedences. Also, systems of several strain gauges have been used for many years in monitoring the usage of airframe and other mechanical components. As the costs of aircraft and their components have increased, there has been a growing interest in monitoring the usage of more components with greater accuracy. Accuracy can be increased by monitoring the usage parameters more directly during flight. This data can be fully or partially processed on-board to reduce storage requirements. It must eventually be downloaded into ground-based computer systems for full analysis and reporting. The growth of data available on the aircraft databus for other reasons has provided a means of improving the accuracy of usage monitoring at minimal recurring cost. The use of existing data is sometimes referred to the use of "virtual sensors".

6.2.2 An Improved Approach to Usage Monitoring – The Fleet Usage Management System (FUMS)

6.2.2.1 The Need to Improve Usage Monitoring

In Paper 4.5.1, Cook (G) describes a R&D program in the UK to improve the efficiency and effectiveness of usage monitoring for helicopters. The long term aims of this program are to automate preventive maintenance in a cost-effective manner, to improve safety by expanding the use of on-condition tasks, and to retain expensive components in service as long as possible. It is illustrative of work that is going on in several other NATO Nations with the same aims, and so is covered in detail below.

Cook explains that under a duty of care and in-line with the UK Civil Aviation Authority requirements for large helicopters, in 2000 MOD UK introduced a Health and Usage Monitoring System (HUMS) for one of its helicopter fleets. Subsequently, the MOD fitted HUMS to several other helicopter fleets, and has an intention for future fits too.

To date the emphasis has been on the Health Monitoring aspects of HUMS, in particular with respect to automated rotor track and balance, and the analysis of drive-train vibration. This has led to some significant successes with the detection of failing gearboxes.

The need to maximise the exploitation of the HUMS data in terms of cost/benefit, improved availability and improved airworthiness, however, has led to a growing emphasis in developing prognostic capability. The vast amount of data available, together with the rapid improvements in computer processing speed and storage capacity has made on-board prognostics feasible.

For prognostics, an accurate estimate of past and future usage is needed. Currently, usage is measured by the pilot's watch. A better approach would be to estimate the usage of specific components from data available to the Flight Data Recorder (FDR), which on the helicopters mentioned above is an integral part of the HUMS. Over 132 engineering parameters are monitored.

Cook points out that an objective view of individual aircraft usage could allow the lives of some components to be extended. It would also improve airworthiness by identifying unusually adverse usage that might lead to premature component failure. It would also facilitate a move from a safe-life approach to a damage tolerance (on-condition) approach on some helicopter components.

The development of a more accurate estimate of past and future usage by the analysis of data already available on the databuses of UK helicopters is described below. The development is part of a system known as the Fleet Usage Management System (FUMS), which was developed by MOD UK in collaboration with MJA Dynamics (now named GE Aviation – Southampton). FUMS development has focused on three main areas:

a) Usage monitoring.

b) Data Fusion (DF).

d) Intelligent Health Monitoring (IHM).

Only those aspects of FUMS related to usage monitoring are described here.

6.2.2.2 Methods of Usage Monitoring Used in FUMS

FUMS measures aircraft usage through a comparison of actual and design usage spectra, and also by analysis of the cyclic nature of certain key parameters to provide a usage index.

6.2.2.2.1 Comparison of Actual and Design Usage Spectra

The comparison of the actual usage spectrum with the design usage spectrum is based on flight regime recognition analysis of the aircraft's FDR data (Figure 6-1). From a comparison of the actual and design usage spectra shown in the figure, it can be seen that for the 156 flights monitored the aircraft spent more time on the ground than was anticipated, significantly less time in straight and level flight and more time low level flying. The significance of this, particularly with respect to lifing issues, can only be fully assessed by taking into account the design authority's assessment of the flight loads associated with the flight regimes.

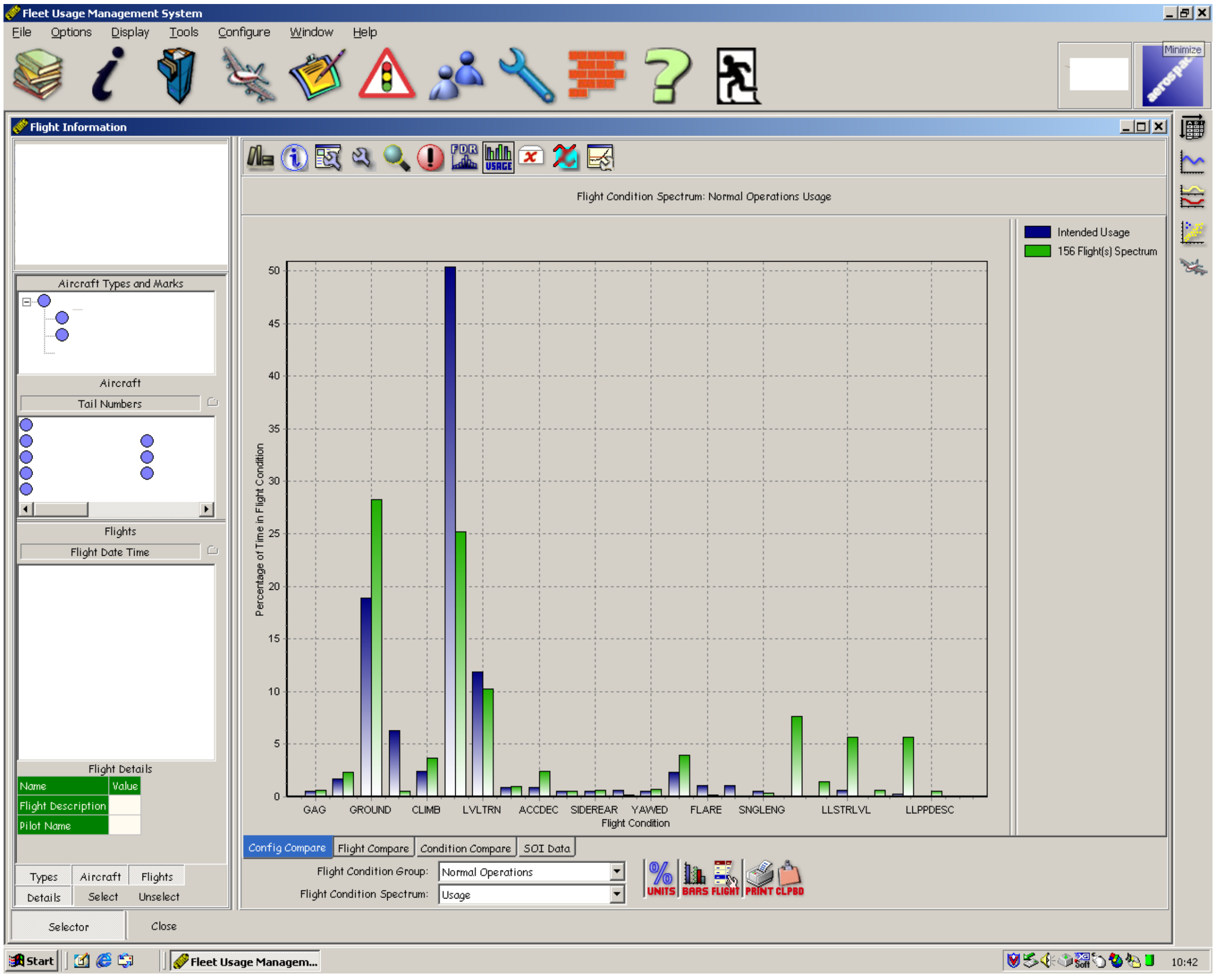


Figure 6-1: Comparison of Actual Usage Spectrum (Green) and the Design Usage Spectrum (Blue).

6.2.2.2.2 Usage Index

Usage Indices (UI) based on a rainflow analysis technique are used to quantify the cyclic nature of certain key parameters, such as indicated airspeed, control movements, engine temperatures and pressures, and pressure altitude. The results are summarised as a single figure for each parameter for each flight, the higher the figure the higher the “severity” of use (Figure 6-2). Each bar in the chart shows the usage index for a flight based on indicated airspeed. Initial investigation of the high severity value shown by the yellow bar can be carried out by viewing the actual indicated airspeed record for that flight shown by the blue line graph. In this case the reason for the high severity score is the large number of take-offs and landings, GAG cycles.

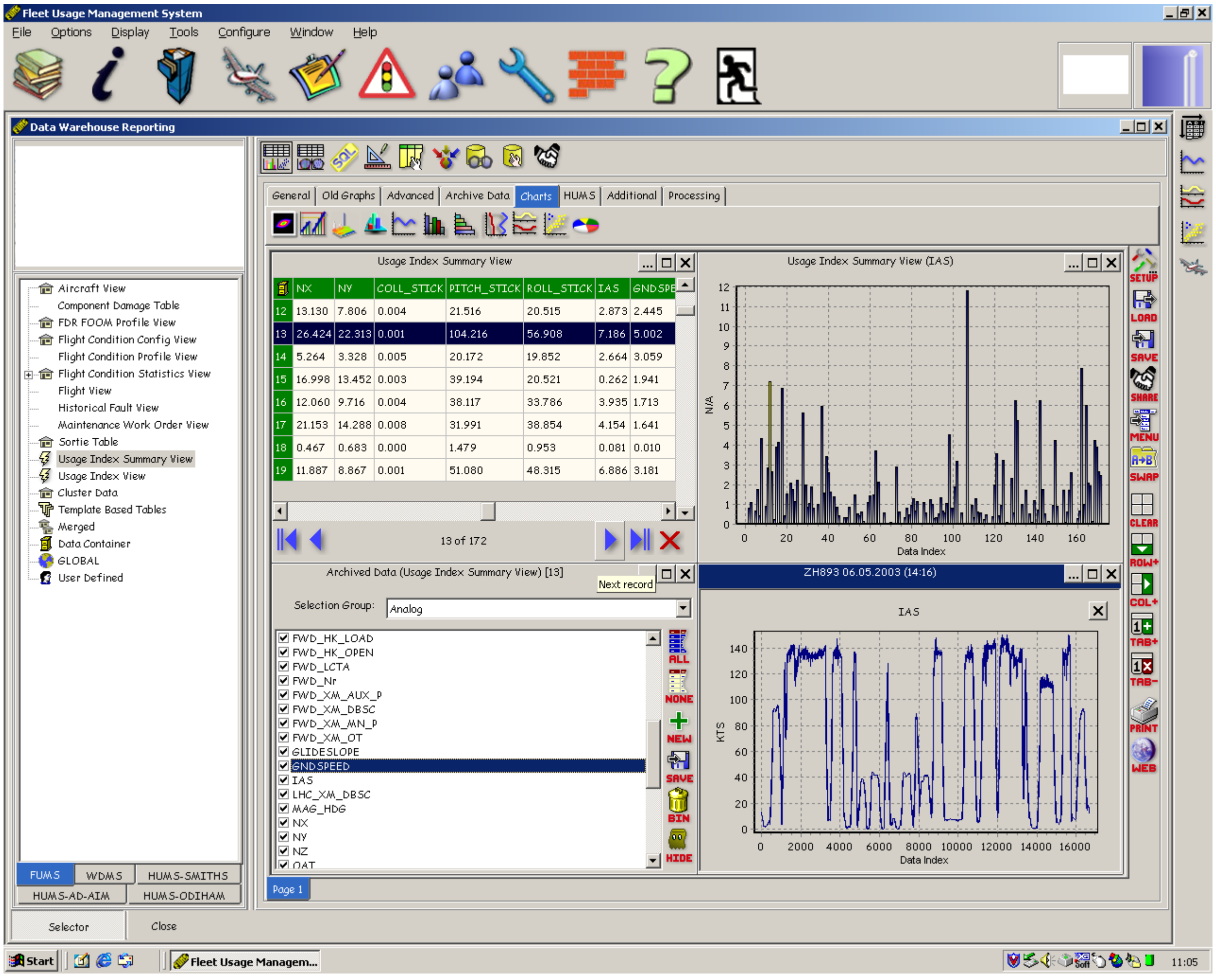


Figure 6-2: Usage Index Summary View.

6.2.2.3 Usage Spectrum

Currently the Royal Air Force is required to carry out a manual data recording exercise every three years in order to assess the actual usage spectrum, and then supply the results for comment to the appropriate design authority. FUMS provides the potential to carry out that assessment at anytime, and also for specific theatres of operation, specific squadrons, or specific operating bases.

The actual usage spectrum is a simplified summary of flight regimes to facilitate manual recording. Typically, when carrying out a flight loads survey for a prototype aircraft, the design authority would look at well over a hundred flight regimes. FUMS can be set up to monitor this refined spectrum for individual flights, and, by linking this data directly with the flight loads, the fatigue damage for individual lifed components can be measured.

Conceivably, the weighted amalgamation of the fatigue increments could be used as a single parameter indication of “severity”. This single parameter could then be used to investigate correlation of component failures with “severity” of use, and thereby facilitate the use of a damage tolerance (on-condition) approach instead of a safe life approach to failure management.

6.2.2.4 Fatigue Synthesis

FUMS usage indices can provide a very good basis for the synthesis of fatigue, and hence a virtual fatigue meter for lifed components or critical aircraft structure. Figure 6-3 and Figure 6-4 show the results of a collaborative work between MOD, GE Aviation, BAE Systems and Rolls Royce.

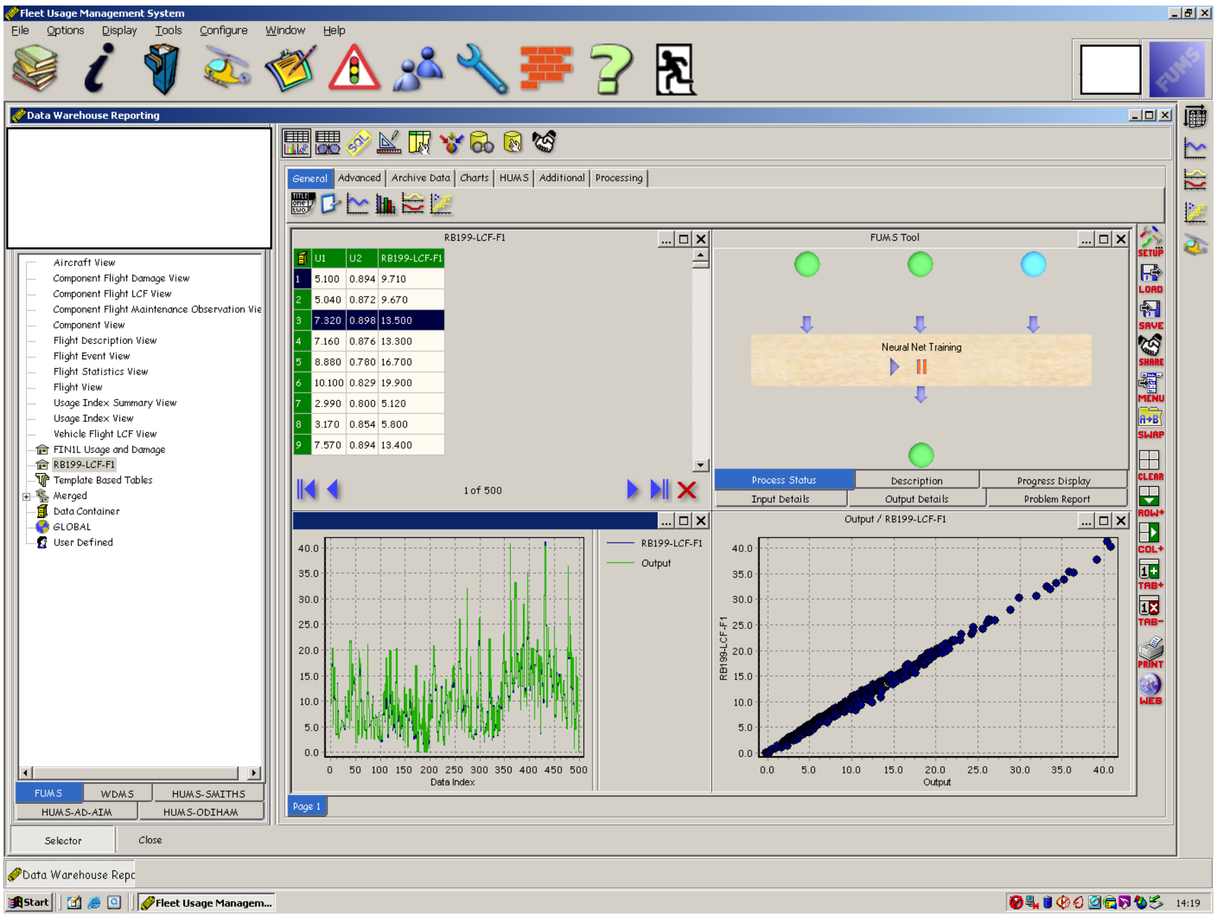


Figure 6-3: Synthesis of Fatigue for an Engine Component Using a Neural Network and UIs.

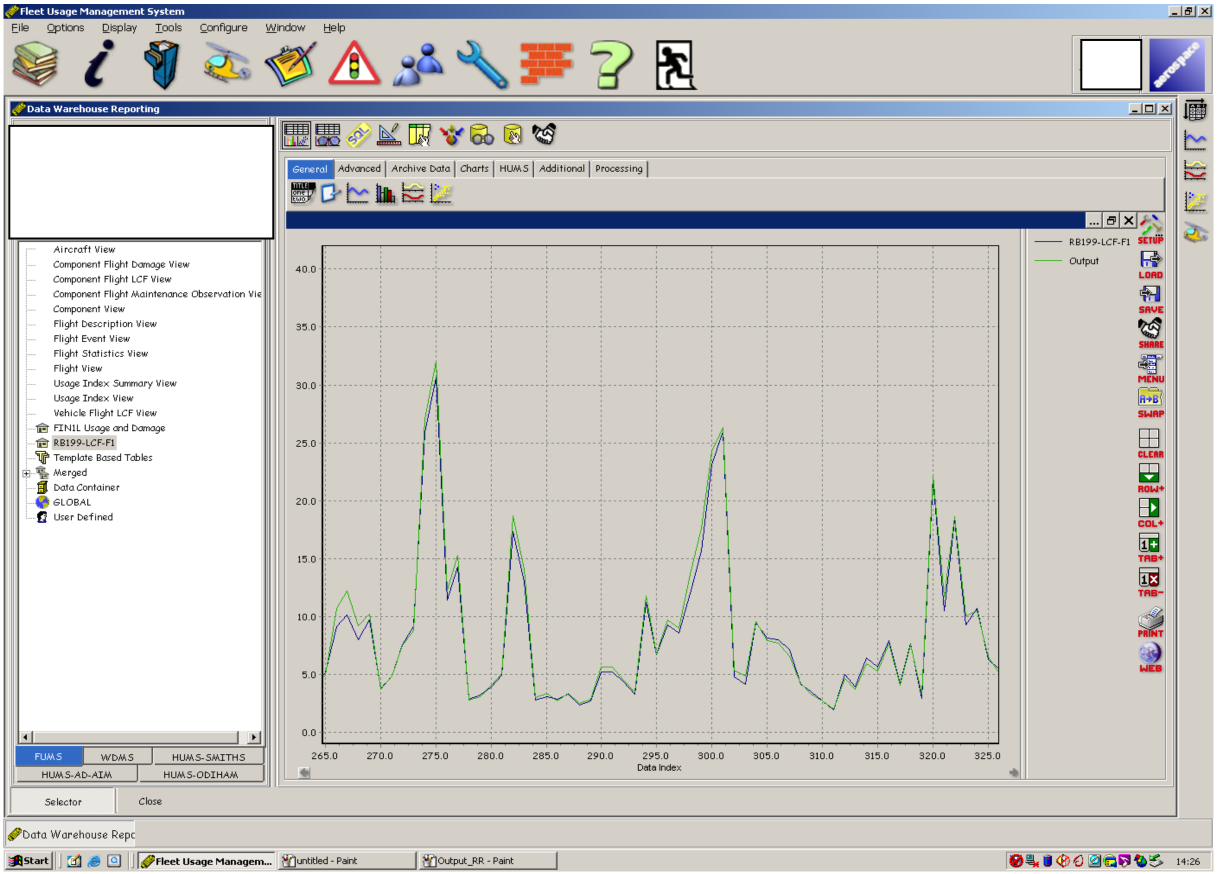


Figure 6-4: Results of Synthesised Fatigue.

Two usage indices, U1 and U2 based on two compressor shaft speeds, were calculated for each of 500 flights. The two usage indices were input to a neural network. The target training data for the neural network consisted of the low cycle fatigue increment for a specific engine component for each flight, which was calculated by Rolls Royce. The output of the neural network, when plotted against the RR LCF data, showed a very good straight-line relationship with a correlation of 0.997 after only two thousand iterations.

6.2.2.5 Other Usage Factors

There are a number of factors that can impact on failure rates that cannot be identified from the FDR data, such as All Up Mass (AUM), the Centre of Gravity (C of G), operational factors, environmental factors, corrosion, and pilot skills. Development is already under way to include in HUMS the estimation of AUM and C of G from FDR data.

6.3 FAILURE MODELLING FOR PROGNOSTICS (LIFE ESTIMATION)

6.3.1 Introduction

A key process in the design of an aircraft and its maintenance/support system is the determination and analysis of likely failure modes. The information from such an analysis allows the reliability of the aircraft to be improved, preventive maintenance tasks to be designed when the inherent reliability is insufficient, and maintainability to be improved to facilitate the preventive maintenance. As discussed in Chapter 5, Failure Mode and Effects Analysis (FMEA) is a fundamental element of both R&M management program and the design of the maintenance program using RCM. To ensure that safety-critical and mission-critical failure modes are given due attention, a criticality analysis is included. Thus the analysis process is usually known as Failure Mode, Effects, and Criticality Analysis (FMECA).

There are several international standards providing guidelines on FMECA, including SAE J1739, AIAG FMEA-3 and Mil-Std-1629A. Mil-Std-1629 was cancelled in 1998, since adequate international standards had become available.

Having determined the likely failure modes and their relative importance, it is necessary to predict the life to failure under the expected usage and the likely variation in this life. If preventive maintenance is required on a given component, a decision must be made on whether to replace/restore the component at a safe life or to perform on-condition inspections. For on-condition inspections to be feasible, it must be possible to detect degradation well before functional failure occurs and to predict the Remaining Useful Life (RUL) under varying conditions of usage. This prediction is sometimes referred to as “prognostics”. Depending on the application, it may be necessary to model the rate of degradation as well as the RUL.

Mathematical failure models for life assessment may be data-based, physics-based, or a combination of these. Data-based models rely on previous measurements from the system to assess the current damage state, typically by means of some sort of pattern recognition method such as neural networks [98]. Although data-based assessment techniques may be able to indicate a change in the presence of new loading conditions or system configurations, they will perform poorly when trying to classify the nature of the change. Thus, it is not uncommon to use the results from a physics-based model to “train” a data-based assessment technique to recognize damage cases for which no experimental data exists.

A physics-based model uses mathematical equations that theoretically predict the system behaviour by simulating the actual physical processes that govern the system response [98]. These assessments/models are especially useful for predicting system response to new loading conditions and/or new system configurations (damage states). However, physics-based assessment techniques are typically computationally intensive. Equations with in which parameters must be determined experimentally, such as the Paris equation for fatigue crack growth rate, are strictly speaking data-based failure models, but might be regarded as physics-based models with limited applicability.

As mentioned in Chapter 2, a discussion of established reliability engineering methods is outside the scope of the AVT-144 study. However, physics-based modelling is not yet in this category, and is receiving considerable attention, because it facilitates the following failure management strategies:

a) The use of an on-condition rather than a safe-life maintenance strategy, to extend component life, and thereby reduce maintenance, without increasing risk;

b) The use of an on-condition as well as a safe-life maintenance strategy, to improve mission reliability and safety – as in recent civil regulations for engines; and

c) The use of a Predictive Maintenance Window (PMW), as discussed in Chapter 4, to allow corrective maintenance to be planned instead of unscheduled, i.e. to be deferred instead of performed before the next flight.

There has been strong interest in physics-based failure modelling for mechanical/structural components. There may be several reasons for this: mechanical/structural components tend to consist of only one or a few monolithic, non-standard piece-parts; their failure rate is not constant; there is usually a need to investigate all the failure modes of each piece-part through analysis and testing; and there is limited flexibility to lower stresses and add redundancy.

Physics-based modelling is also of interest for electronic equipment, but the general situation is different. Electronic hardware typically contains many discrete, standard piece-parts. The equipment failure rate is approximately constant with time, and so a "run to failure" maintenance strategy has often been employed. Hardware reliability has generally been predicted using standard circuit analysis and statistical procedures together with empirical handbook data on piece-part reliability. The associated reliability engineering methods have developed to an advanced stage over several decades, and circuit design can be used to build redundancy and fault tolerance into the equipment.

The remainder of this section is drawn from Supplementary Paper #3 by Koul et al. of Life Prediction Technologies Inc., and illustrates the state of the art in physics-based modelling at the microstructural level in mechanical components. It describes a probabilistic case study carried out in collaboration with Standard Aero Limited, on the Rolls Royce Allison (RRA) 501KB first stage gas turbine blades. The value proposition of using prognosis in conjunction with physics-based microstructural damage analysis for reliability assessment is clearly demonstrated. In maintenance applications, the modelling techniques could be used in conjunction with ground-based or on-board prognostic systems.

6.3.2 Turbine Blade Case Study

Professional logistics, maintenance and manufacturing engineers are familiar with the distinction between calculated MTBF and operational MTBF (actual usage with real operating data), in which operational MTBF may be a factor of 20 different to the calculated MTBF [99].

The determination of predicted MTBF requires the development of prognosis expert systems that consider the specific stress and temperature histories of each major component on an individual basis and factor them into the physics-based damage accumulation models formulated at the microstructural/nano-structural level. A schematic of a typical prognosis system for analyzing hot section components in an aircraft jet engine is presented in Figure 6-5. This reflects the architecture of the XactLIFE™ software. The solution integrates combustor modelling, off-design engine modelling, thermodynamic analysis, and finite element modelling including a non-linear finite element solver, operational data filter and microstructural damage models on a single platform. The system provides a choice of damage models, for steam as well as gas turbine applications such as creep, Low Cycle Fatigue (LCF), stress corrosion, corrosion fatigue, cyclic oxidation and Thermal Mechanical Fatigue (TMF) analysis.

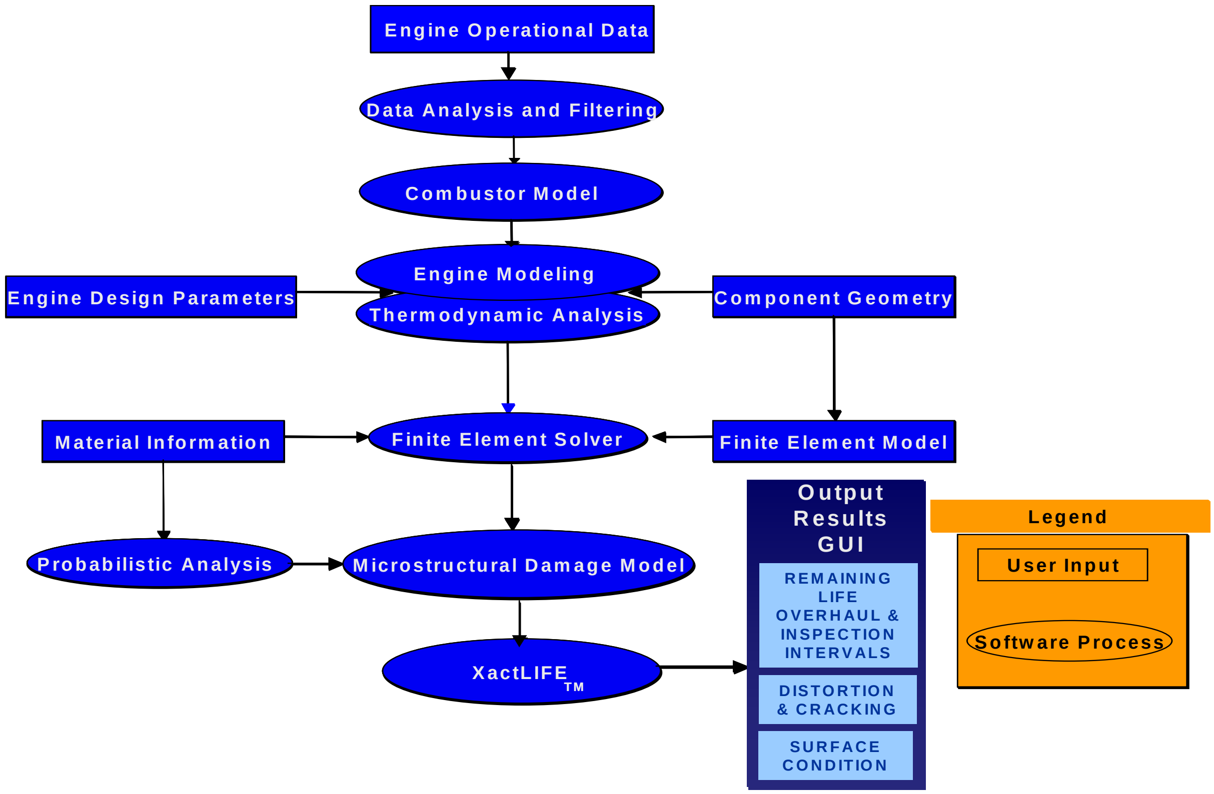


Figure 6-5: Engineering Flow Diagram for the Prognosis System Designed and Implemented by Life Predictions Technology Inc. (Patent Pending).

The software is also capable of predicting Safe Inspection Intervals (SII) for other critical parts such as discs, spacers, cooling plates and shafts. The system flow diagram further indicates that the expert system is capable of anticipating the risk of future failures, based on variability of microstructure and assumed operating conditions, using probabilistic analysis techniques.

At present, the Original Equipment Manufacturers (OEM), users, and Repair and Overhaul (R&O) organisations use FMECA to assess the engine fleet reliability. However, OEM, R&O organisations, and users continually have to revise their reliability predictions based on actual operating experience. This situation arises because a statistically significant amount of service experience is required to make reliability predictions. Often OEMs use past experience with similar engine designs to make reliability predictions. Users must wait a few years before enough failure data is accumulated to make reliable predictions. It is precisely this ambiguity in FMECA type technologies that can be easily addressed by physics-based prognosis technology.

In this study, the prognosis system was used to conduct probabilistic blade creep life analysis of RRA 501KB first stage turbine blades under steady state conditions. Typical engine operating data from the field in terms of engine speed and average Turbine Inlet Temperature (TIT) was used in the analysis, Figure 6-6. The subject RRA 501KB blades is made out of conventionally cast Mar-M246 material and the airfoil is internally convection cooled using compressor discharge air.

Cumulative Time (hr:min:s)	RPM	Temperature (^oC)
0:00:00	0	15
0:00:10	14,250	1,035
21:00:10	14,250	1,035
21:05:10	0	15

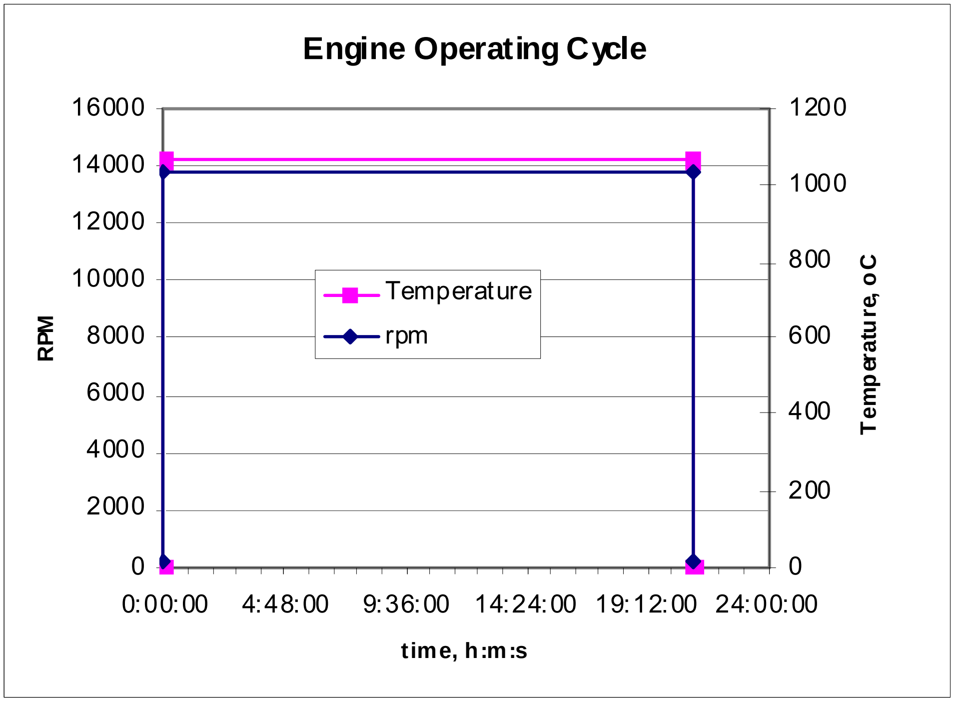


Figure 6-6: Typical Engine Profile in Terms of Turbine Inlet Temperature and Speed.

6.3.2.1 Mechanical Structural Analysis Requirements

The first step involved in the prognosis is the creation of the blade geometry using the geometry analyser software and this is followed by the creation of a fully meshed finite element model of the blade, Figure 6-7. The temperature dependent material properties data such as elastic modulus, Poisson ratio, yield strength and work hardening coefficients are also required for non-linear finite element analysis. These data were collected from [100] prior to performing the thermal-mechanical stress analysis (Table 6-1 and Table 6-2). A constant Poisson ratio of 0.28 was assumed.

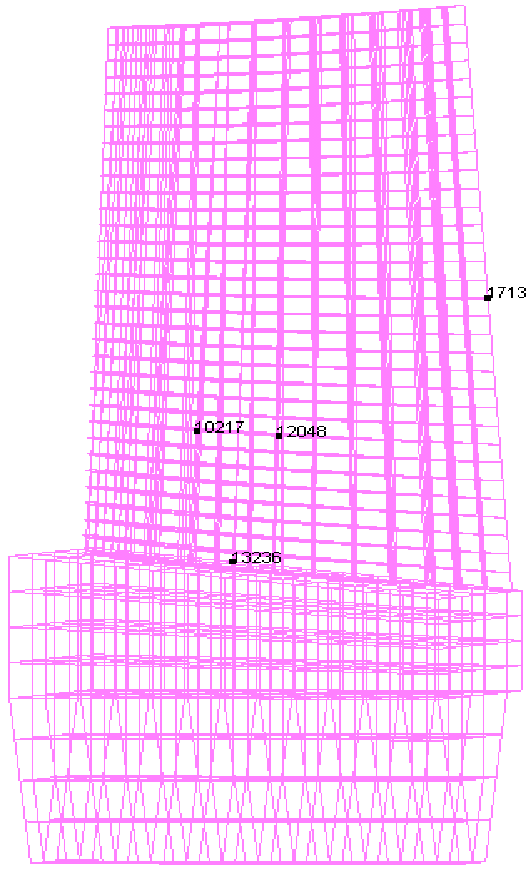


Figure 6-7: Finite Element Model of the Blade with Some Life-Limiting Nodes Displayed.

Table 6-1: Dynamic Modulus of Elasticity and Shear Modulus for Mar M246 Alloy [100].

Temperature (K)	Elastic Modulus (GPa)	Shear Modulus (GPa)
288	210	82
317	208	81.4
995	168	65.7
1,020	166	64.8
1,053	163	63.7
1,083	160	62.6
1,116	157	61.2
1,258	139	54.2
1,269	137	53.5

Table 6-2: Tensile Properties of Mar M246 Alloy [100].

Temperature (K)	351	473	569	1073
Yield Strength (MPa)	844	845	841	748
UT Strength (MPa)	986	990	994	986
Elongation (%)	4.3	4.23	4.23	4.36

6.3.2.2 Engine Modelling and Thermal Boundary Conditions

The prognosis system uses the actual average TIT or Exit Gas Temperature (EGT) or power for the specific engine. Known on-design engine parameters such as rpm, mass flow, exhaust pressure ratio, generator efficiency, mechanical efficiency, etc., are used to compute the pitch line airfoil temperatures at different stages of the turbine under off-design (changing ambient temperature and pressure) engine operating conditions. To account for off-design engine parameters, compressor and turbine maps were generated for the RRA 501KB engine and these maps form a standard input into the prognosis system. Convection cooling effects are also considered in the thermodynamic analysis of the blade airfoil. Another important input into the system is the TIT profile and this profile is computed using the average TIT or EGT in conjunction with semi-empirical or Computational Fluid Dynamics (CFD) combustor modelling procedures. The computed TIT profile is shown in Figure 6-8. These inputs are used in the advanced thermodynamic module to compute the blade metal temperatures in both the radial as well as the chord-wise directions. The metal surface temperatures are then estimated along each cross-section of the blade including the leading and trailing edges, Figure 6-9, and this output of the thermodynamic module defines the temperature boundary conditions for thermal-mechanical stress analysis.

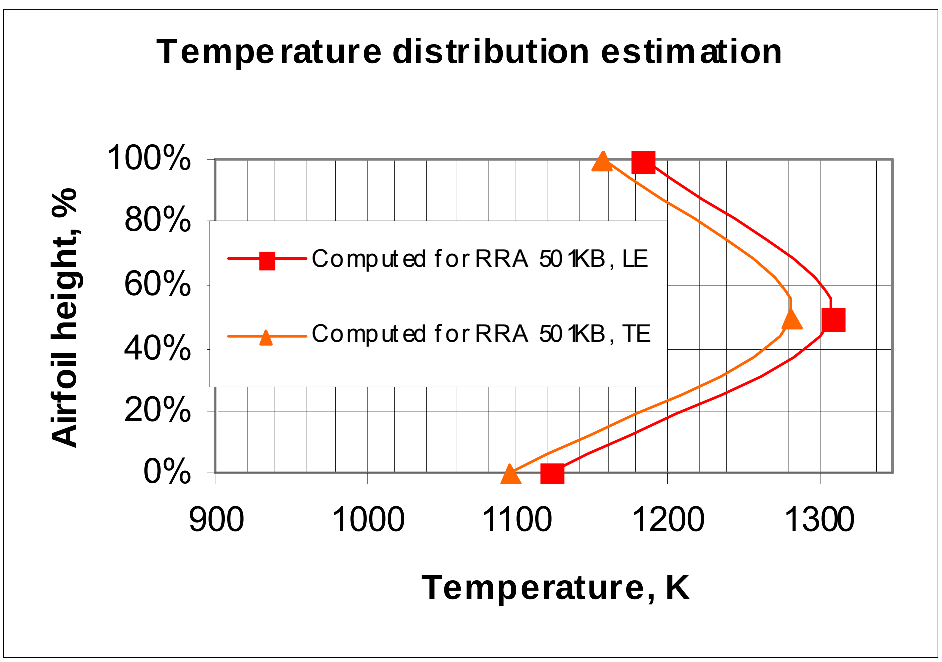


Figure 6-8: Computed Leading and Trailing Edge Temperature Distributions.

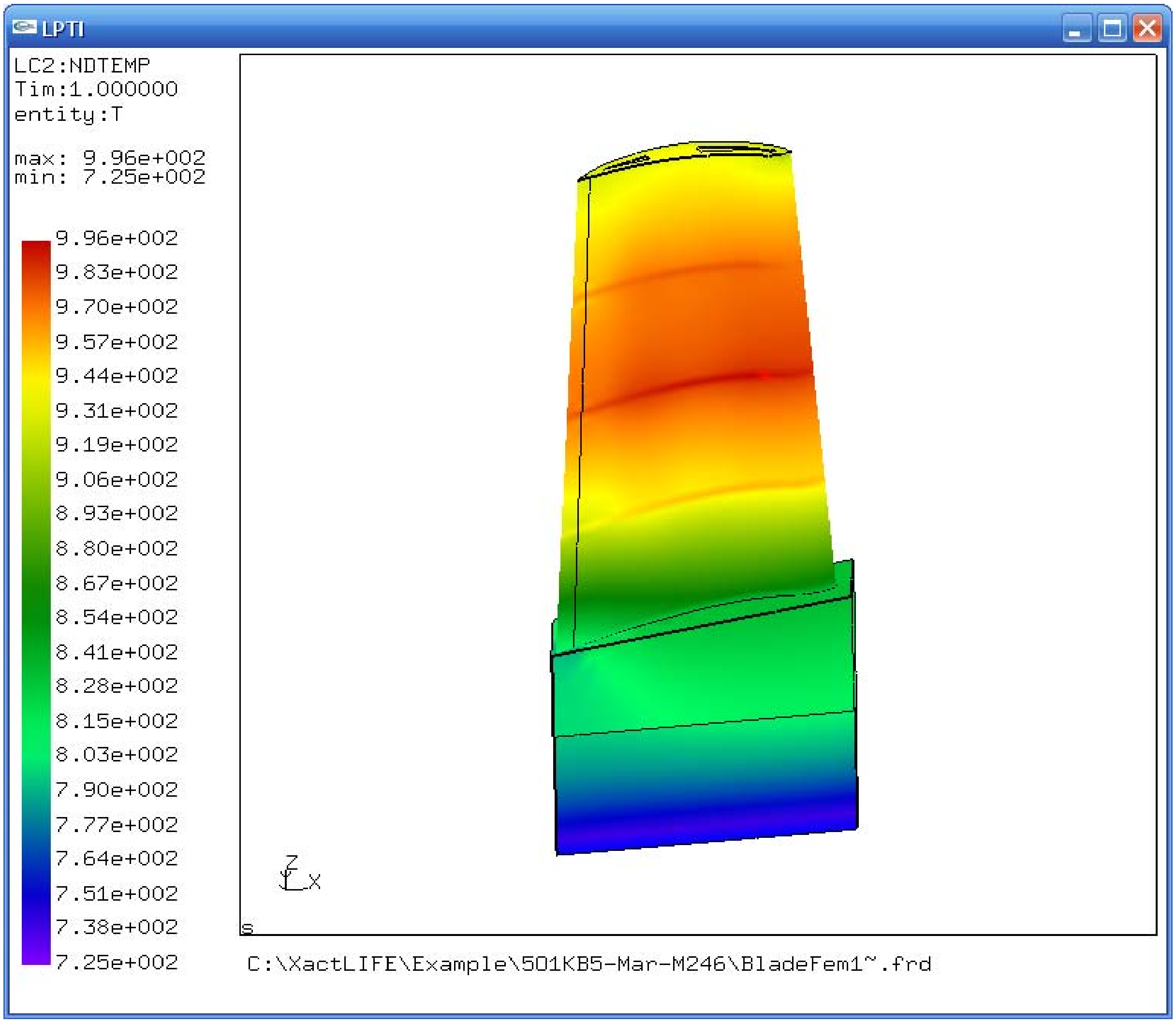


Figure 6-9: Temperature Profile for RRA 501 KB.

6.3.2.3 Thermal Mechanical Stress Analysis

The built-in FEA solver in the prognosis system automatically carries out the thermal-mechanical stress analysis using the nodal temperature distributions and the maximum engine rotational speed as boundary conditions for FEA. It is noteworthy that the 501KB blade is shrouded and the mass of the blade shroud was taken into consideration while calculating the centrifugal loads on the blade airfoil by adjusting the density of the blade tip nodes. The computed thermal-mechanical stress distributions along the blade are shown in Figure 6-10. The non-linear FEA revealed that none of the blade airfoil regions had undergone any plastic deformation under the influence of the loading conditions examined. This is significant, because only time dependent deformation would thus be expected to occur during service. The stress distribution was generally quite uniform along the airfoil although, as expected, higher stresses were prevalent in the blade root section.

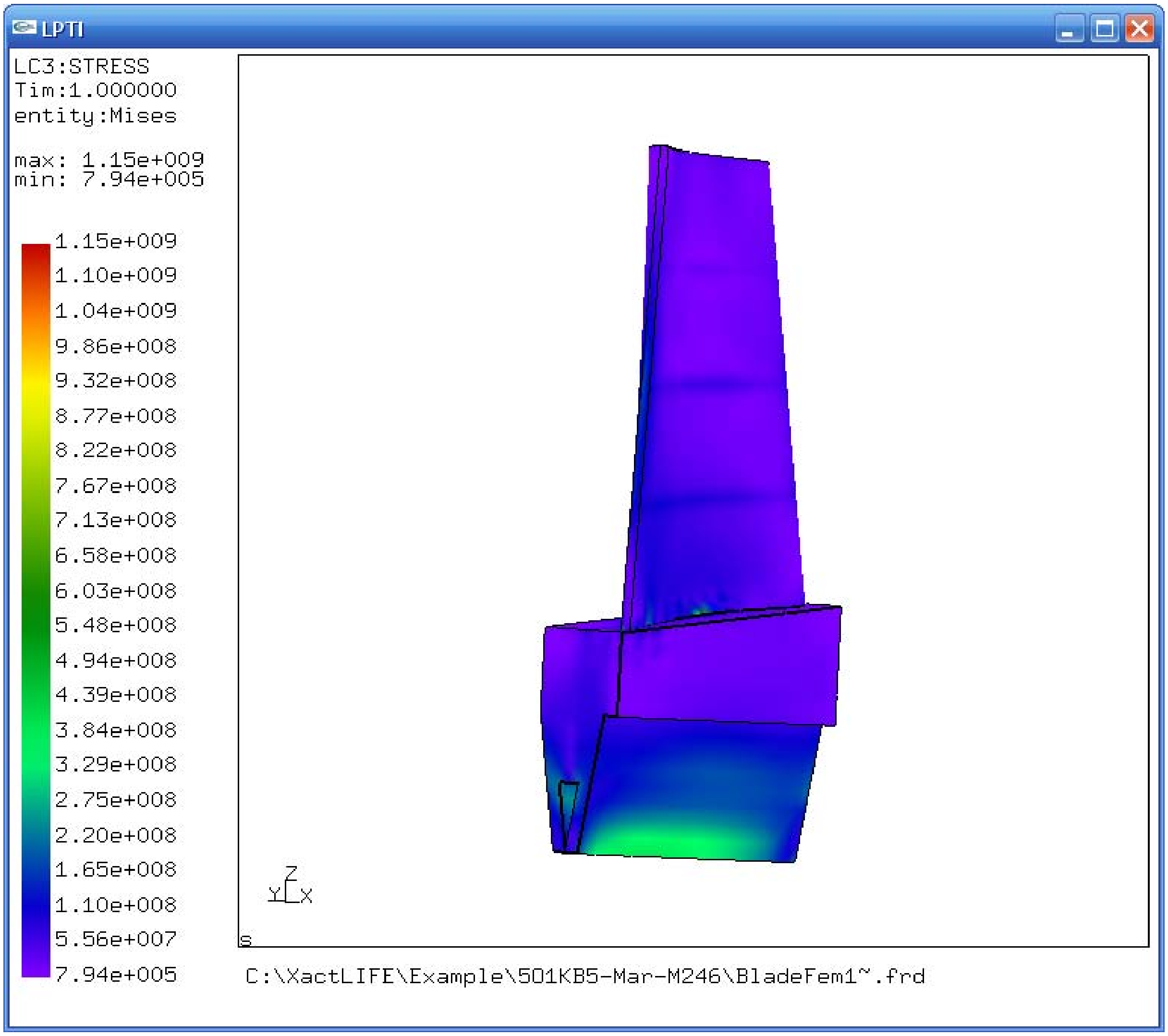


Figure 6-10: Von Mises Stress Profile of the Blade.

6.3.2.4 Probabilistic Creep Damage Analysis

Prior to conducting a detailed probabilistic analysis, a deterministic analysis was carried out to establish the probabilistic analysis of the critical nodes by introducing microstructural variability. Deterministic life depicts the lower bound nodal life and details of the methodology used can be found elsewhere [101]. Essentially, deterministic nodal life is computed by assuming worst case assumptions for all variables. In deterministic analysis, a combined creep deformation model that considers deformation along grain boundaries and within the grain interiors together with the oxidation damage accumulation along the boundaries was used to take the FEA solver input at maximum rotational speeds to compute the creep lives of all nodes and to establish the primary fracture critical location of the blade. The fracture critical location of the blade was defined as the lowest creep life location in the airfoil. The quantitative microstructural information required to execute the damage analysis was collected up-front and this included microstructural variables such as the grain size, grain boundary microstructural parameters, intragranular microstructural parameters, etc. A combination of deformation mechanisms such as intragranular dislocation movement and multiplication, grain boundary sliding accommodated by a number of deformation processes, creep cavitation, and a variety of dislocation-precipitate interactions including the evolution of microstructure due to deformation are considered in the overall creep deformation process.

In keeping with the bulk material deformation rationale, the nodal creep strain at failure was set at 5%. It is recognized that the failure strain in the case of cast alloys is dependent on the soundness and the size of a casting.

Table 6-3 provides the creep life of four life limiting nodes in the airfoil section along with the respective temperatures and stresses operating at these locations. It is evident that the primary fracture critical location lies along one third of the airfoil height on the suction side of the blade (see FEM model in Figure 6-7). The average blade creep life of blades is then calculated by averaging the lives of nodes in the immediate vicinity of the fracture critical location within a finite volume of the material. This life is in the range of 70,000 hours. According to this analysis, conventionally cast Mar-M246 blades should be inspected after 35,000 hours, the MTBF interval was predicted by using a safety factor of 2 [101]. The untwist data available for service exposed subject blades indicate that the blades start bulk creep deformation at approximately 60,000 operating hours. Some internal oxidation of cooling passages is also observed during service. If this effect is taken into account in prognostics analysis, then the predicted usable life of blades would be slightly lower than 70,000 hours. Prognosis-based numbers thus match favourably with the field experience.

Table 6-3: Nodal Creep Life Prediction Results of Subject RRA 501KB Turbine Blade.

Node	Stress (MPa)	Temp (K)	Life (Hrs)
13236	367.4	855	53,297
10217	173.5	950	45,097
12048	151.2	945	61,496
1713	166.7	975	33,823

In the case of cast equiaxed blades, grain boundary deformation and oxidation plays a dominant role in the creep crack initiation process. As a result, grain size (d), grain boundary precipitate size (r) and inter-particle spacing (λ) also play a major role in the creep deformation process. Typical probabilistic distributions of these microstructural features, that take into account the variability of these features from one blade to another, are shown in Figure 6-11, Figure 6-12, and Figure 6-13.

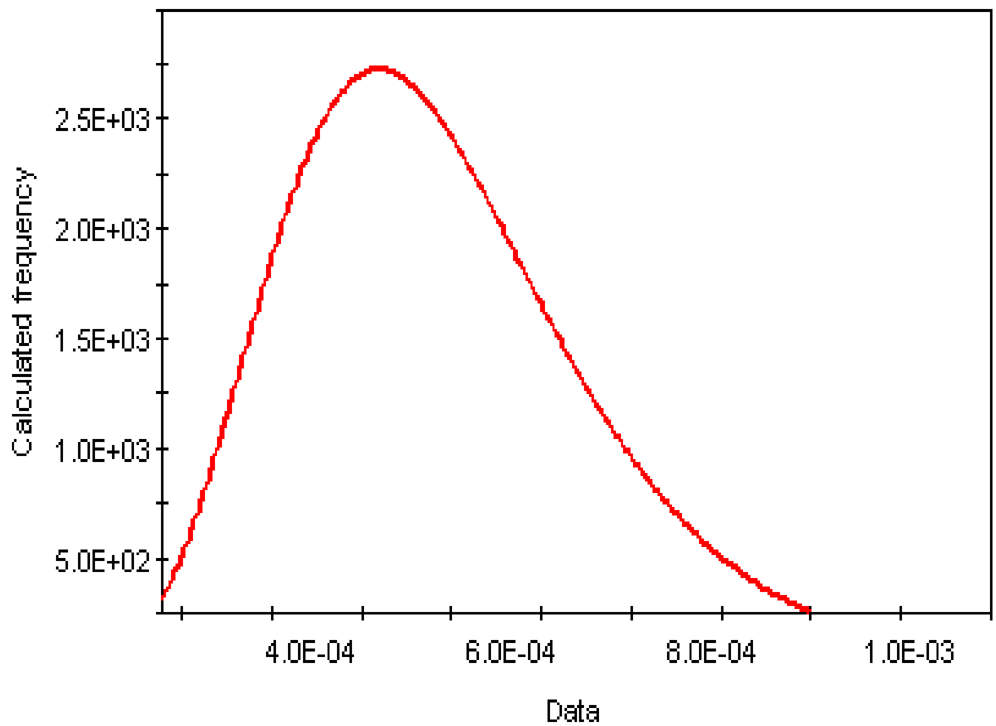


Figure 6-11: Grain Size Variation in MAR M246 Blades.

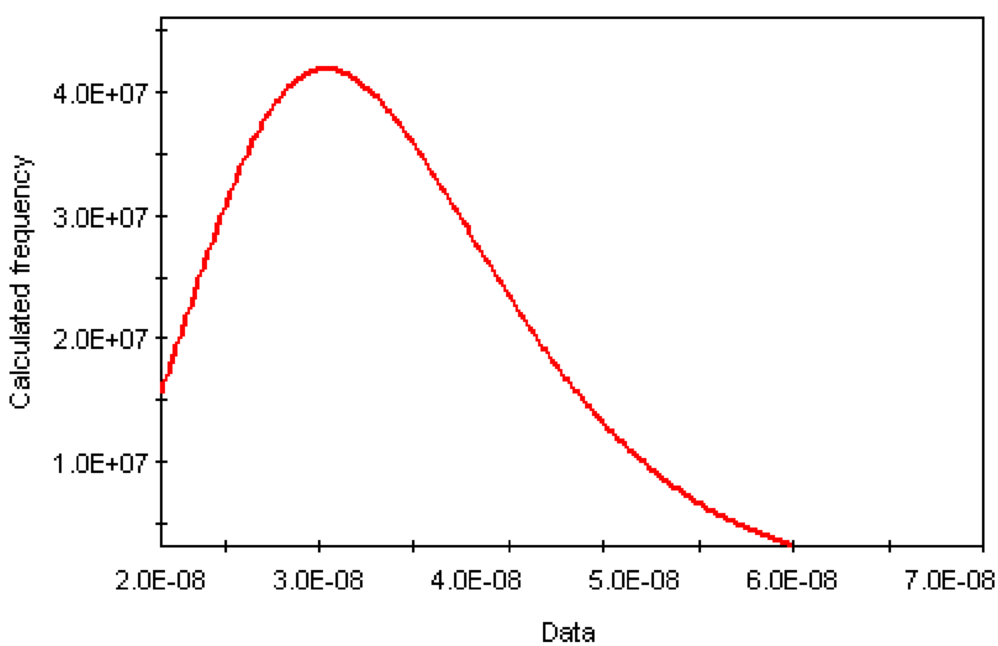


Figure 6-12: Grain Boundary Carbide Particle Radius Variation in MAR M246 Blades.

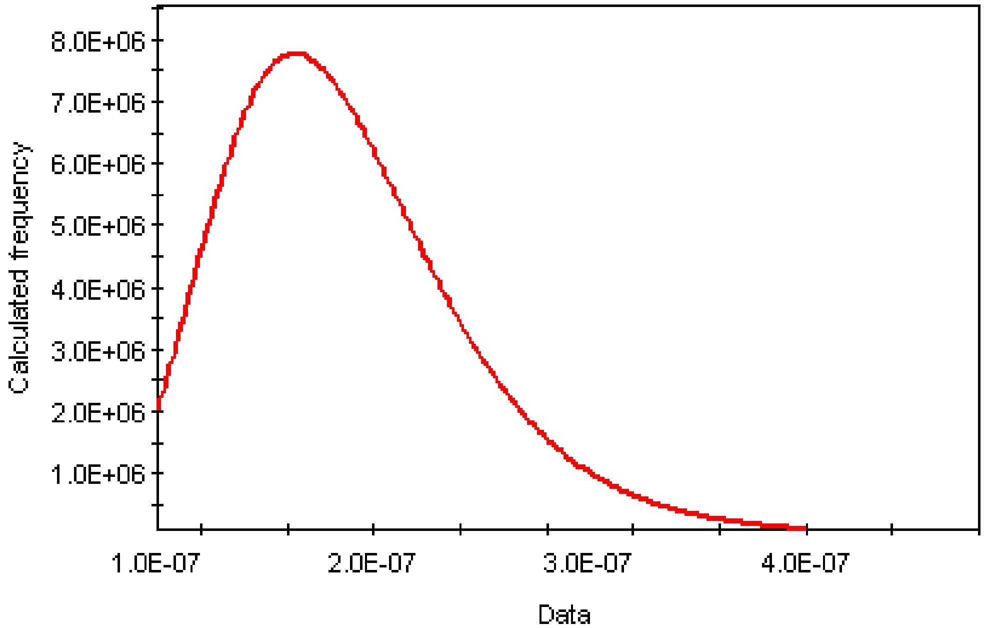


Figure 6-13: Grain Boundary Carbide Inter-Particle Spacing Variation in MAR M246 Blades.

Most microstructural features possess a lognormal probabilistic distribution [102]-[104] that can be written as:

$$\text{Log}\,(d, r, \lambda) = \text{Gau}\,(\mu'_{(d,r,\lambda)}, s_{(d,r,\lambda)}) \tag{1}$$

where μ' depicts the mean of the microstructural feature and s is the standard deviation of the variable.

Upon randomizing these microstructural variables, probabilistic life calculations were carried out under steady state operating conditions. Two parameter Weibull creep life distributions were computed for the four critical airfoil nodes given in Table 6-3. A two parameter Weibull distribution is described by:

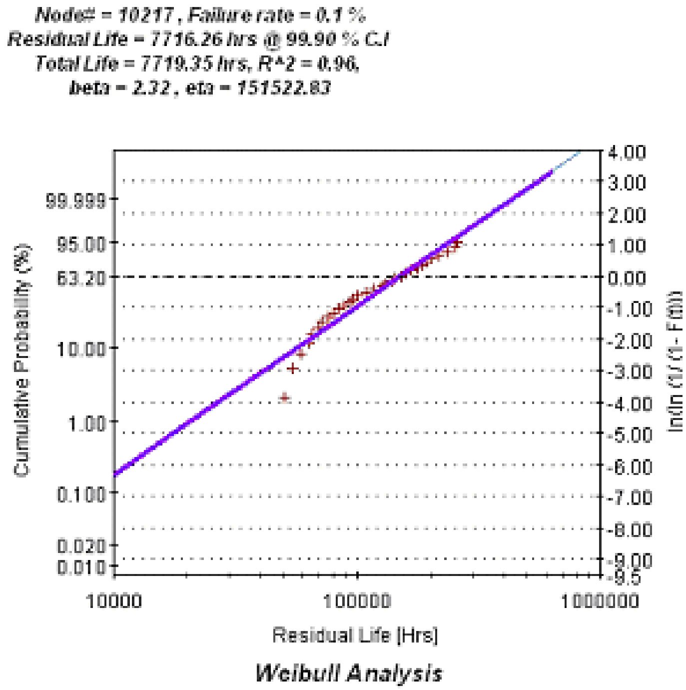
$$F(t) = 1 - \exp -(t/\eta)^{\beta} \tag{2}$$

where F(t) is the cumulative probability of failure, t is the creep life, η is the characteristic life and β is the Weibull modulus.

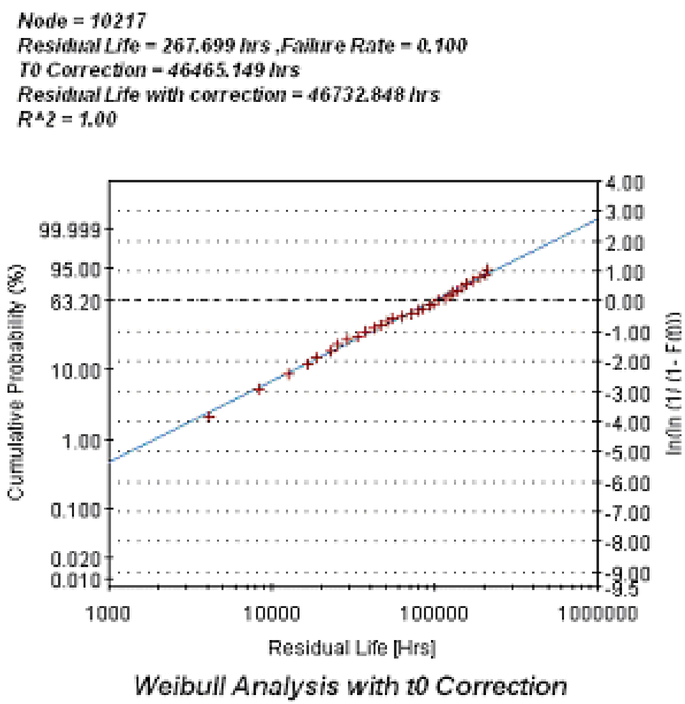
The probabilistic distribution of creep life of node number 10217 (see Figure 6-7) is plotted in Figure 6-14(a) in the form of two-parameter Weibull distribution. It is evident from Figure 6-14(a) that a threshold value of creep life exists and a three-parameter Weibull distribution, that uses t_0 correction to account for the threshold life, is required for accurate representation of the probabilistic creep life data. The three-parameter Weibull distribution is represented by:

$$F(t) = 1 - \exp - [(t-t_0)/\eta)]^{\beta} \tag{3}$$

where t_0 is the threshold value obtained from the two-parameter Weibull plots.



(a) Two-parameter Weibull distribution.



(b) Three-parameter Weibull distribution.

Figure 6-14: Weibull Distributions of Creep Life for Node Number 10217.

All four critical nodes analyzed revealed a similar life pattern. The t_0 corrections were thus applied to all four cases and the resultant creep life distributions of the four nodes were plotted. The corrected Weibull distribution for node number 10217 is shown in Figure 6-14(b). A correlation coefficient of greater than 0.99 indicates was obtained in all cases.

The creep lives of all four nodes at a cumulative probability of failure of 0.1%F (approximately 1 in 1000 chance of crack nucleation at the node) are shown in Table 6-4. Deterministic nodal life values are also presented for comparison with the 0.1% F probabilistic analysis results in Table 6-4. In all cases, the lower bound deterministic values match favorably with the 0.1% F probabilistic data. These data indicate that the deterministic crack initiation life values or microstructural variability based 0.1% F probabilistic analysis results can be used as a guide for predicting MTBF for new blades. Therefore, in light of these findings, FMECA-based reliability predictions are not necessary for fleet maintenance if prognostics tools are available for life prediction. However, it is necessary to conduct physics-based prognosis for accurate MTBF prediction. Previous investigations have shown that empirical creep life prediction approaches such the Larson-Miller parameter-based calculations can be off by as much as a factor of 20 relative to observed field experience [105].

Table 6-4: Probabilistic Distribution of Nodal Creep Life.

Node	Two Parameter Weibull Life (hr)	Three Parameter Weibull Life (hr)	Deterministic Life (hr)
10217	7,719	46,732	45,097
13236	13,133	57,323	53,297
12048	19,144	59,595	61,496
1713	4,870	33,643	33,823

The microstructure-based prognostics analysis can also be used to assess the effects of repairs and refurbishment processes simply by assessing any changes in the key microstructural features such as the grain size, precipitate size, etc., to quantify the MTBF of repaired or refurbished parts rather than waiting for field experience to accumulate to judge the reliability of repairs. The microstructural information is easy to generate and once the case is set in the XactLIFE™ system, scenario analysis can also be carried out to assess the cost effectiveness of the repairs from a usage perspective.

6.3.2.5 Conclusions

Prognosis-based deterministic and probabilistic creep life analysis was carried out on the subject RRA 501 KB first stage turbine blades at maximum operational speeds and turbine inlet temperature. The deterministic analysis was used to predict the fracture critical location in these blades and the primary fracture critical location was predicted to lie along one third of the airfoil height on the suction side.

Probabilistic creep life analysis was carried out on the four fracture critical nodes in the airfoil section by taking into account the variability of grain size and grain boundary microstructural features such as the grain boundary precipitate size and inter-particle spacing. The average blade creep life of conventionally cast Mar-M246 blades was computed to be over 70,000 hours yielding a lower bound deterministic MTBF of over 35,000 hours. Internal oxidation effects were not considered in the present analysis and this would reduce the predicted creep life and MTBF for the blade.

At 0.1%F, the probabilistic nodal creep life values match favourably with the deterministic nodal creep life values. These data can be used to establish blade reliability and to make decisions about MTBF for fleet maintenance. Microstructure-based prognosis can also be used to establish the reliability of repairs by generating the relevant microstructural information and conducting future usage-based scenario analysis.

6.4 INSPECTION USING NON-DESTRUCTIVE EVALUATION (NDE)

6.4.1 The Role of NDE

This section identifies existing and emerging Non-Destructive Evaluation (NDE) technologies that can be used to reduce the downtime for maintenance. NDE is also referred to as Non-Destructive Inspection (NDI) and Non-Destructive Testing (NDT). For the purposes of this report, no distinction will be made between the three terms.

Since NDE has historically been performed while the aircraft is on the ground by technicians using specialised ground equipment, and since it is a technology group that is applied in many different industries, it is regarded by some engineers as an “off-board” or “off-line” activity that is distinct from the growing use of automated, “on-board” methods of inspection. For this reason, it is treated as a distinct section in this report. Nevertheless, existing and emerging NDE technologies are being adapted for use in on-board inspection systems.

Automatic Test Equipment (ATE) is sometimes used to perform inspections of electrical and electronic equipment. ATE is usually treated as separate technology group to NDE. However, the inspection of wiring for incipient failures may be regarded as NDE rather than ATE.

The primary application of NDE in aircraft maintenance is in “on-condition” and “failure-finding” inspections. These were explained in Chapter 5 in connection with the RCM concept. Such inspections are usually scheduled for application at 3rd and 4th Line, but may be applied at 1st and 2nd Line in some situations. Reductions in downtime may be achieved through reductions in either the duration or the frequency of inspection. For these purposes, one or more of the following attributes are sought: faster area coverage, higher resolution, higher Probability Of Detection (POD), improved multi-layer capabilities, and less disassembly for access.

As well as improving the efficiency of on-condition tasks, NDE is used to enable the use of on-condition rather than hard time tasks. This is one of the goals listed in the introduction to this chapter, and is explained in Chapter 2. NDE is also valuable in managing unexpected defects that threaten to ground the fleet, while a long-term solution is sought.

The remainder of this section is based on Papers 4.2.1a by Bruce and 4.2.1b by Manzke. It discusses existing and emerging NDE technologies and how they can be harnessed to improve aircraft availability. The cost implications are discussed in general terms.

6.4.2 NDE and Aircraft Life Management

In Paper 4.2.1a, Bruce points out that NDE is an integral part of the damage tolerance (on-condition) approach in structure and other mechanical components. Although it should not be required in principle for a safe life aircraft, NDE is used on all aircraft types within the safe life period. The requirement for NDE may arise from experience with fatigue testing, from fleet experience, or from changes in operating conditions. Increasingly, as aircraft approach the end of their safe lives, there is a pressure to extend the life to save replacement costs. This often increases the NDE requirement, because the airframe and components are effectively being operated on a damage tolerance basis after the safe life has been exceeded. In such situations, fleet availability may depend on NDE.

6.4.3 NDE Related Costs and Cost Savings

Simple NDE instruments cost from US$5,000, while more sophisticated NDE systems cost between US$20,000 and US$200,000. NDE systems costing more than US$200,000 are difficult to sell. The capital cost of NDE equipment is enough to limit the use of NDE in some industries, but is usually insignificant compared to the overall support costs of military aircraft.

The cost of manpower for NDE is usually greater than the cost of the equipment, but is still small in relation to other support. The recruitment and retention of NDE personnel are problematic, and training and certification are growing concerns.

Current R&D in NDE is directed towards exploiting NDE as a means of cutting overall maintenance costs and improving aircraft availability. The demand to increase the amount of structure that is treated as damage tolerant requires the development of NDE techniques capable of increased speed for large areas of accessible structure and improved penetration into the structure for inaccessible areas or components. It also requires techniques to deal with complex geometry and multi-layered structures.

Increasing inspection intervals would clearly reduce inspection-related costs. Inspection intervals can be increased by using inspections with greater resolution, so that smaller defects can be detected. However, it is generally more important to schedule NDE together with other maintenance work to minimise the cost of gaining access t the components to be inspected. This is because the time required to prepare an aircraft for inspection often exceeds the inspection time, sometimes by an order of magnitude or more.

6.4.4 Improvements to NDE Methods

Improvements can be made in some cases by adopting radically new methods. However, evolutionary development of existing methods can often bring about the necessary increase in capability, particularly when the recent improvements in computing power and automation are utilised.

Traditional inspection methods such as Ultrasonics or Eddy Current were originally devised for much more limited applications. They operate by scanning a small probe over the area or features of concern. While they are ideal for limited area inspection, they are relatively slow, require intimate access to the flaw location, and are usually only semi-quantitative. Often, defects are not even “sized” by the primary inspection, and follow-up investigations are required of any indications. These traditional inspection methods can be greatly improved by incorporating them into scanning systems, either manual or automated, particularly for the inspection of large areas. This approach provides improved efficiency and better details of any damage. Automation in scanning and data processing and storage also improves data fidelity and can reduce the skill level required by operators.

Further improvements to traditional methods have involved the development of multiple array probes using many parallel channels to allow more rapid scanning. Incorporation of automated data analysis allows rapid, real-time analysis of the huge data sets generated and allows more sophistication, provided the presentation is simple.

Examples of advanced NDE systems based on traditional technologies that have been adopted by the UK and US Armed Forces include:

- *Ultrasonic Inspection of Composite Structure for Barely Visible Impact Damage (BVID)* – Ultrasonic scanning with a greater rate of data acquisition through the use of a wide array probe greatly reduced inspection times, mapping damage using a manual scanning system. Inspection of a fighter sized wing (AV-8B Harrier II) using a single element hand held probe required 6 days. The use of a 16-element array reduced this to 5 hrs.
- *The Boeing-USAF MAUS Automated Scanning System* – A further step in improved inspection appropriate for large structures is a portable automated scanning system which attaches to the aircraft skin, such as the Boeing-USAF MAUS. It can carry out raster scans without supervision and can be used with various NDE techniques including Ultrasonics and Eddy Current. The MAUS system features automated setup and data-processing, it is currently used for corrosion detection on USAF KC-135, B-52, and E-3 aircraft.
- *Engine Disk Inspection System* – Larger fixed automated scanning systems are appropriate for inspecting large numbers of complex components. Robotic eddy current inspection systems enabled a "Retirement for Cause" (on-condition inspection) strategy to be used for F-100 engine disks, which otherwise had an unacceptably short fatigue life. The use of periodic inspections (for potential failures) allowed the component life to be doubled, and yielded an estimated cost saving of US$850 million. Further improvements and savings are projected under the Engine Rotator Life Extension (ERLE) programme.
- *Robotic Radiography – MAX (Multi-Axis X-ray –.* Recently, the USAF commissioned an automated digital X-ray system and gantry robot for inspecting the complete F-15 empennage. The initial costs were justified by expected labour savings over an existing manual task of US$200,000 to US$300,000 per year. Additional benefits include the elimination of chemical film processing, increased operator safety, and the ability to examine and adjust images in real time.
- *Dedicated Fastener Hole Inspection Systems* – Fastener holes are commonly sites of fatigue cracking, and sometimes many holes must be inspected in a given location. For example, the C-130 wing centre section was found to suffer from hidden cracking around fasteners, and there were several hundred fasteners which required inspection. Similar problems affect commercial aircraft. The original inspection required the removal of the fasteners to allow the insertion of a rotating probe eddy current scanner. Later, eddy current systems were developed using rotating probes or multi-element arrays which can inspect the holes without removal of the fasteners. They can measure the angle, size and depth of any crack. These systems reduced the inspection time to a few seconds per fastener and avoided the risk of collateral damage and rework. A Magneto-Optic Imaging (MOI) system was also developed. Although less sensitive than the eddy current instruments, it is claimed to be around 20% faster. Also, since it has no requirement to locate the fasteners, which are imaged automatically, it can be used to inspect through paint or surface coatings.

The above examples all show how conventional NDE methods can be adapted to meet new requirements. There has been considerable R&D effort on new techniques based on imaging rather than scanning technologies for the inspection of large areas. The following have been the principal techniques investigated:

- Thermal methods.
- Pulsed thermography.
- Lock-in thermography.
- Sonic IR / thermosonics.
- Optical methods.

- Holographic interferometry.
- Electronic Speckle Pattern Interferometry (ESPI).
- Shearography.

The following NDE techniques have limited resolution and depth of penetration, but continue to be developed for monitoring large areas of structure quickly:

- Acoustic methods.
- Guided waves.
- Acousto-ultrasound.
- Acoustic emission.

Thermal methods have very limited penetration into monolithic structures, especially if they are electrically conducting and consequently have a high thermal conductivity. They have been used successfully for inspection of lightweight structures, including the leading edge of the space shuttle. Thermal methods are useful for locating disbonds. In one example, the German Air Force developed a thermographic technique to detect disbonding of engine intake heater mats. Thermography has also been used in the production inspection of components, including Glass-Reinforced Polymer (GRP) helicopter rotor blades.

Optical methods are similarly limited in their penetration into structural materials. They have been used mainly for production inspection of thin skinned sandwich structures.

The acoustic methods have very different limitations, being most suitable for inspection of large, heavy weight, thick-section structures. The guided wave method is now routinely employed in the inspection of pipes and storage tanks. However, it cannot be used for large area inspection in complex airframe structures, since there are too many features to perturb the guided wave pulses. One advantage of guided waves is their ability to be directed through structure to otherwise uninspectable locations. This technique allows internal components to be inspected from outside a structure. It has been used in nuclear reactors. It has also been used for inspecting for cracks at fuel drainage (weep) holes inside C-141 wings and spar caps inside C-130 wings. By eliminating the need for any disassembly, the technique reduced the total inspection downtime by 40 hrs to 50 hrs per aircraft.

Acoustic emission (based on passive detection) has also been used successfully in simple, heavy structures. However, despite persistent attempts and continued development, it is has not been possible to use it in aircraft applications due to the difficulty of distinguishing defect-related acoustic events from background structural noise.

One method of reducing the cost of access to internal structure is the use of NDE probes or imaging systems on endoscopes. This approach has been used in conjunction with digital cameras, laser ultrasonics and eddy current probes. Robots and permanently installed sensors have also been used for specific applications.

6.4.5 Incorporation of NDE into System Level Life Management

Bruce provided some concluding comments on the probability of detection of NDE of airframe and engine structure. The reliability of the inspection determines the safety level, and so the reliability of the NDE technique must be assessed. The inspection interval is determined by the minimum detectable flaw size, the reliability of the inspection technique/method/operator, the defect growth rate, and the damage tolerance of the structure.

NDE reliability is often described by Probability of Detection (POD) curves. In planning damage tolerance inspections, the characteristic defect size $a_{90/95}$ is usually used as the “minimum detectable flaw size”. This is the defect size that can be detected with 90% probability with a 95% level of confidence. In situations where this approach appears inadequate, the inspection technique or interval can be adjusted to provide a higher level of safety. Currently accepted methodology for cracks only deals with simple POD based on one defect size parameter. There is no analogous standard approach for image data, such as might be used in corrosion detection, especially where automated data analysis is used.

“Unanticipated” corrective maintenance can be very expensive in terms of aircraft availability. There is growing interest in detecting potential failure early enough to allow corrective action to be planned within scheduled maintenance tasks. Predictions of safe operating time and the likely severity of future damage, known as prognostics, can be made from usage monitoring, Structural Health Monitoring (SHM) and/or ground-based NDE. It will be crucial to understand how uncertainties in the current knowledge of the condition of a component propagate to give uncertainty in the future condition. Prognostics based solely on usage monitoring and SHM may not allow remaining useful life to be predicted with sufficient reliability and precision. Ground-based NDE could provide more reliable and precise information on the current damage state than an on-board SHM system, and could enable the deferment of corrective action when necessary. However, the limitations of the inspection must be well understood and reflected in the strategy. The scope for savings and life extension could be impressive, for example the USAF Engine Rotor Life Extension (ERLE) programme has projected a doubling of engine component lives resulting in cost avoidance of US$1.3 billion arising from just engine monitoring.

6.4.6 NDE/I Applications Case Studies

In his Paper 4.2.1b, Manzke provides several examples of the effective use of advanced NDE by EADS Military Air Systems on military aircraft fleets in Europe. Some of the important tasks at the Manching plant are the repair and overhaul of the German Air Force fleet as well as the final assembly of new generation fighter aircraft. The tasks of the NDI-department extend from the detection of cracks and corrosion in metallic structures to the detection of delaminations and disbonds in composite structures.

As a fleet of aircraft ages, the rate of structural problems like corrosion, fatigue cracks, and delaminations/ impacts tend to increase. The preventive maintenance program needs to be adjusted accordingly. This may mean adding inspections and increasing the frequency of existing inspections. To avoid net increases in inspection downtime, there is pressure to develop faster NDI techniques. This section describes some practical examples of how inspection time can be reduced through the use of more advanced NDI technologies.

6.4.6.1 AWACS E3A – Detection of Corrosion in Wing Skin

The inspections for corrosion in the wing skins of the AWACS E3A (Figure 6-15) include visual inspections of the areas around fasteners. Any corrosion found has to be blended out, and the skin thickness after repair has to be checked using a dial gauge. Using an ultrasound scanning system the inspection time can be reduced by up to 50%. Moreover, a continuous thickness map is obtained automatically.

Figure 6-15: AWACS E3A Aircraft – Detection of Corrosion in Wing Skin.

6.4.6.2 AWACS E3A – Detection of Debonds in ROTODOME Structure

To detect debonds in the double honeycomb structure of the ROTODOME of the AWACS E3A (Figure 6-16), the technical order currently prescribes a resonance inspection technique with multiple sensors. This is a quick inspection with moderate defect resolution. Nevertheless, it could be reduced by using a new optical technique known as shearography. A technique is under development at EADS Manching.

Figure 6-16: AWACS E3A Aircraft – Detection of Debonds in ROTODOME Structure.

6.4.6.3 F4-F Phantom – Detection of Fatigue Cracks in Stiffener at Upper and Lower Wing Skin

Inspections for fatigue cracks in stiffeners at the upper and lower wing skin of the F4-F Phantom are currently performed using manual ultrasound. The inspection consists of three steps:

a) Locating and marking the stiffener position.

b) Inspecting longitudinally.

c) Inspecting transversely.

The inspection is strenuous and time-consuming. The inspection can be preformed in one step, and the active inspection time can be reduced by 50% using an ultrasound phased array. Moreover, the data is automatically recorded for later review and analysis on a desktop computer.

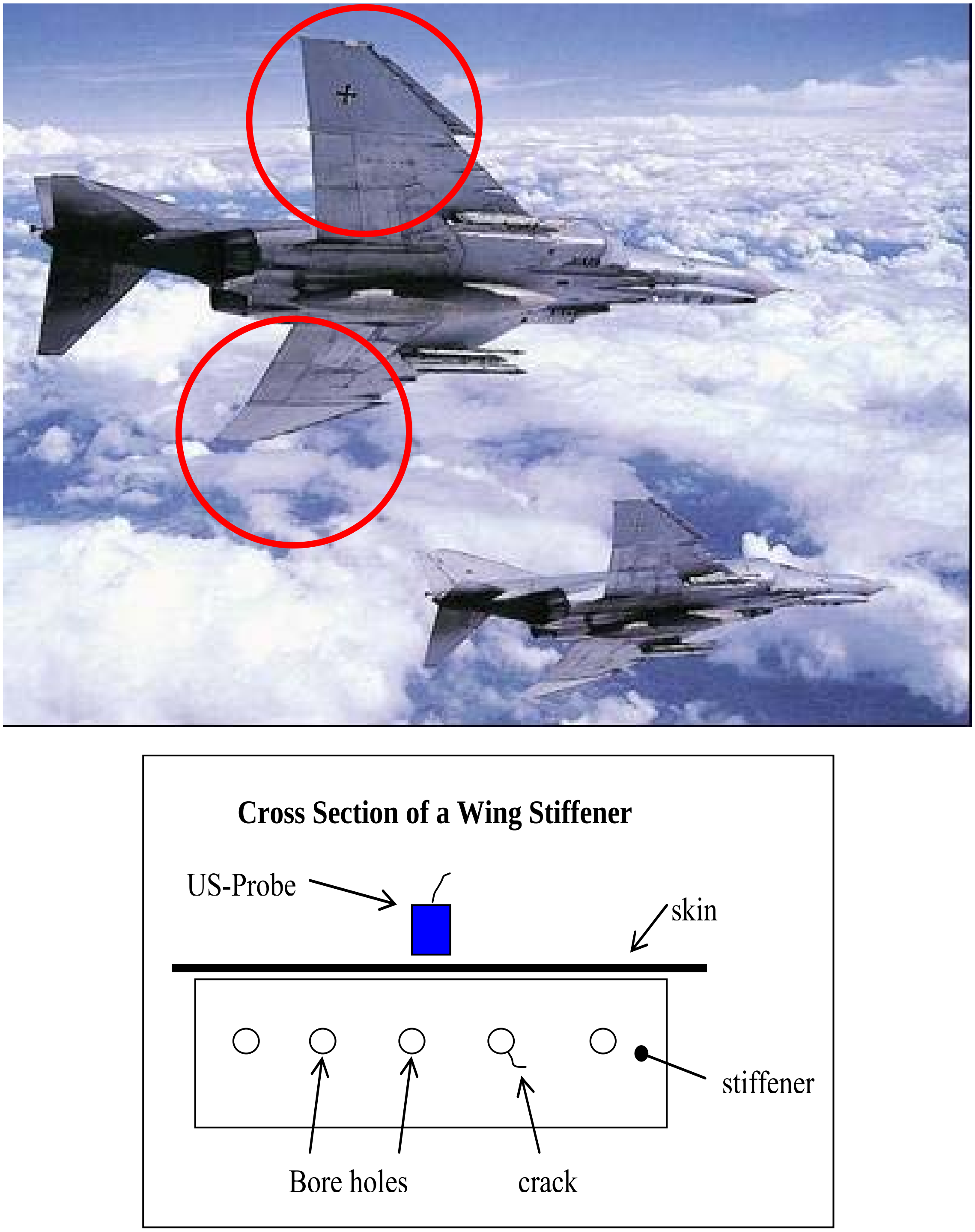


Figure 6-17: F4-F Phantom Aircraft – Detection of Fatigue Cracks in Stiffener at Upper and Lower Wing Skin.

6.4.6.4 Tornado – Detection of Corrosion at the Wing Diffusion Joint

Inspection for corrosion at the wing diffusion joint of the Tornado is currently performed visually with the help of an endoscope. The depth of corrosion cannot be measured this way, and so all detected corrosion must be immediately repaired at great cost. The same inspection can be performed more accurately using ultrasound on a robotic scanner from outside the aircraft. With this technique, the corrosion can be detected and mapped early and subsequent damage growth can be monitored, such that corrective action can be planned and performed more efficiently.

Figure 6-18: Tornado Aircraft – Detection of Corrosion at the Wing Diffusion Joint.

6.4.6.5 Breguet Atlantic – Detection of Debonds in Honeycomb Structure

In a European technical project named INCA, a shearography demonstrator has been developed for wide area inspection for debonding in honeycomb structure. The demonstration on the Breuget Atlantic was successful. Only suspect areas have to be examined more closely using ultrasound or resonance inspection. A net reduction in inspection time of about 50% is believed to be achievable, and so further development of shearography for this application has been undertaken.

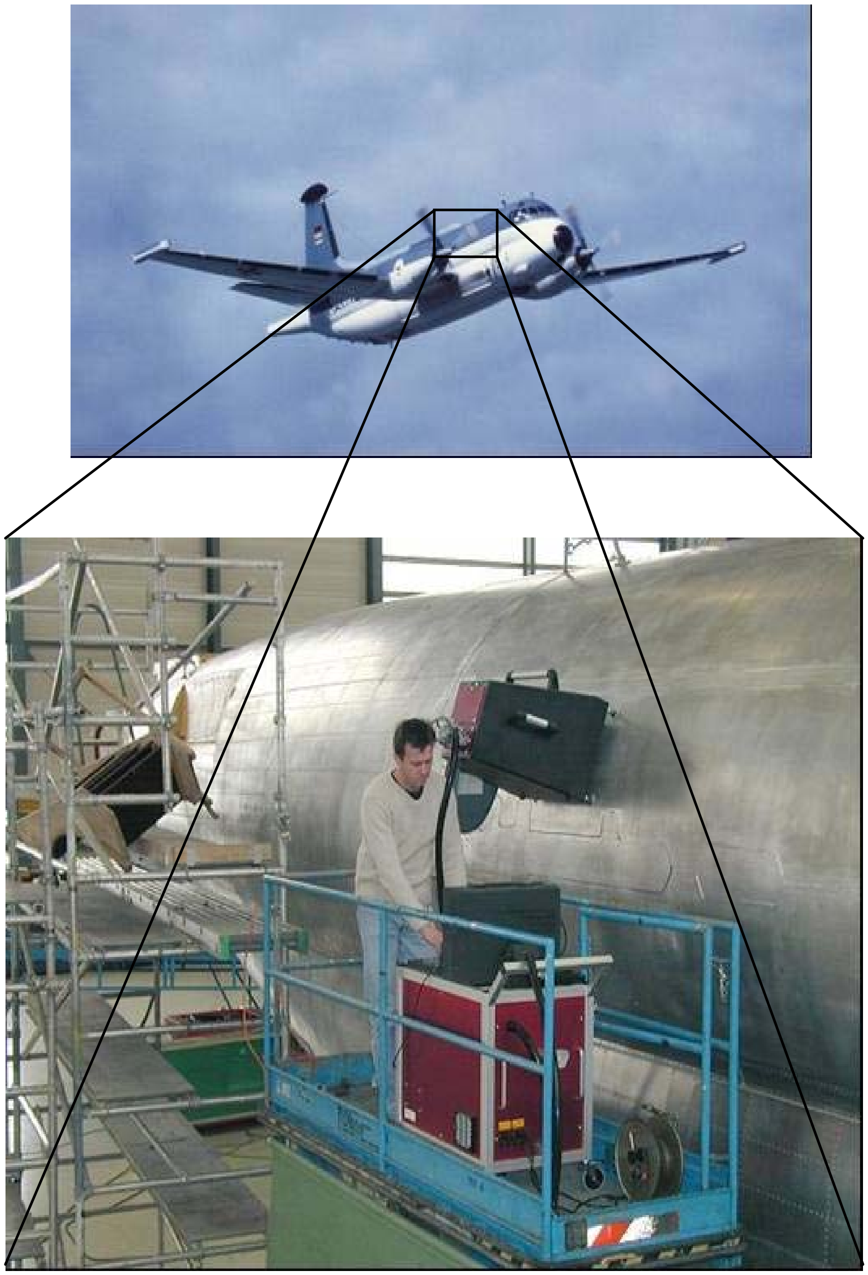


Figure 6-19: Breguet Atlantic Aircraft – Detection of Debonding in Honeycomb Structure in the Fuselage and Wing.

6.5 SENSORS FOR ON-BOARD MAINTENANCE SYSTEMS

6.5.1 Introduction

While great advances have been made in the speed, efficiency, and accuracy of ground-based (NDE) inspection technologies, the concept of performing inspections for failures and potential failures using embedded sensors remains attractive for several reasons:

a) The downtime, cost, and risk (of collateral problems) associated with accessing the component for inspection can be avoided. The embedded sensor can be interrogated remotely by an inspector on the ground or an on-board maintenance system.

b) In cases where the inspection is part of an on-condition failure management strategy, continuous inspection using an on-board maintenance system reduces the risk of failure and provides earlier detection of potential failure, compared to periodic inspections on the ground. These advantages translate into improved mission reliability and, in some cases, the flexibility to defer maintenance for efficiency or operational reasons.

c) It may be the only way to enable an on-condition failure management strategy for a component with a short potential failure interval (Chapter 5).

d) It can help to identify and diagnose those potential failures and hidden failures that are difficult to detect and assess on the ground.

e) In some cases, it is useful for the aircrew to have immediate notification of a failure in a redundant component or dormant safety system that would otherwise have been a “hidden failure”.

In on-board maintenance systems, also referred to as “Health Management (HM) systems”, the role of sensors is to contribute to usage monitoring, the detection of failure and potential failure, and in some cases the measurement of the rate of degradation. A variety of sensors may be used for these purposes, depending on the nature of the component in question, the expected failure modes, the local environment, and the parameters that provide the desired indications of usage or failure.

This section contains a description of general sensor technologies based on Supplementary Paper #2 by Mrad. This is followed by more information on corrosion sensors based on Paper 4.2.2 by Harris and Mishon.

6.5.2 General Sensor Technologies

The content of this section is based on Supplementary Paper #2 by Mrad.

6.5.2.1 The Roles of Sensors

Depending on the application and desired outcome, an HM system varies in complexity from simple (e.g. detect and alert) to more complex (e.g. detect and advise). Figure 6-20 [109] illustrates how an HM system combined with advanced communications could link in real time with the broader maintenance/support system. This concept is being pursued on the F-35 JSF under the name of “Autonomic Logistics”.

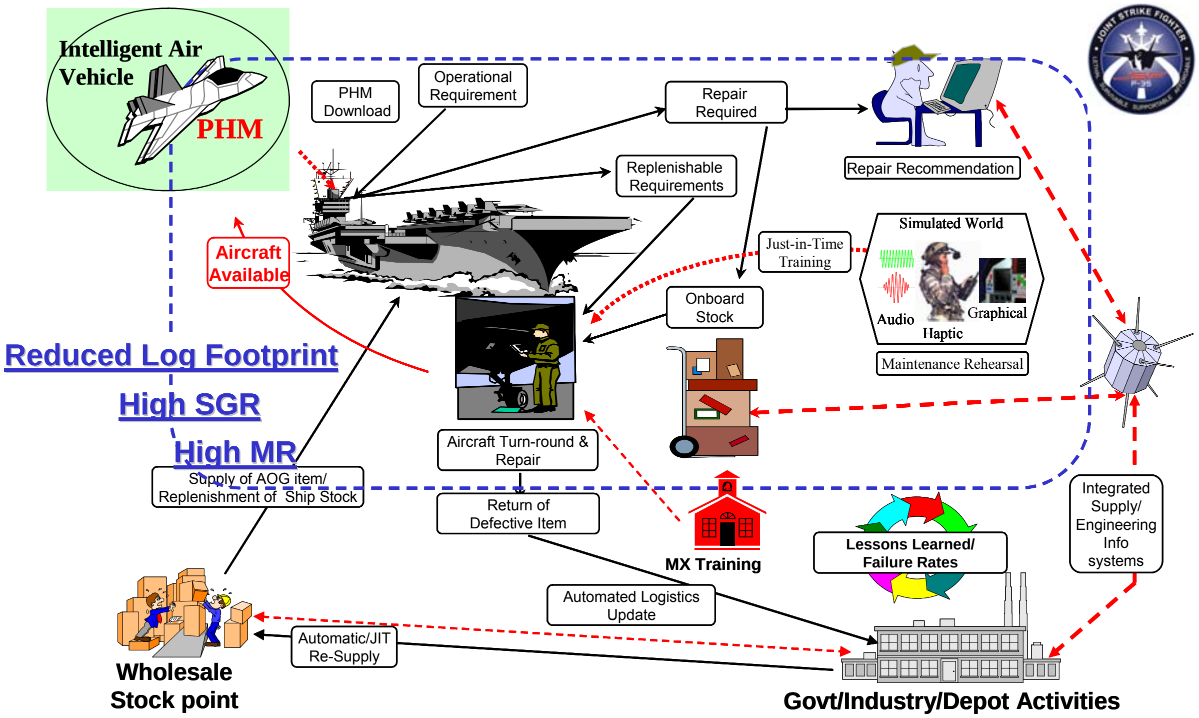


Figure 6-20: An On-Board Health Management System Linked Through Advanced Communications with the Broader Maintenance/Support System.

Irrespective of the simplicity or complexity of the system architecture, the core architecture and structure of an HM system can be considered to comprise four blocks: sensor networks, a usage and damage monitoring reasoner, a life management reasoner, and a decision support reasoner, including a user interface. In a fully Integrated Vehicle Health Management (IVHM) system, the usage and damage parameters acquired via wired and wireless sensor networks are transmitted to an on-board data acquisition and signal processing system. The sensor data is developed into environmental and operational usage and damage histories by algorithms in the usage and damage monitoring reasoner. The life management reasoner predicts the remaining useful life of components. Finally, the HM system provides user-friendly output to assist aircrew and/or groundcrew with mission and maintenance management. When it is not necessary or cost-effective to perform all data processing on board, sensor data is stored for download and analysis on the ground.

Sensors must be energy efficient, accurate, reliable, robust, small size, lightweight, immune to radio frequency and electromagnetic interferences, easily and efficiently networked to on-board pre-processing capability, capable of withstanding operational and environmental conditions, require no or low power for both passive and active technologies, and possess self-monitoring and self-calibrating capabilities.

Several sensing technologies and Non-Destructive Evaluation (NDE) techniques are currently in use or under investigation for HM system development. NDE techniques refer to the array of non-destructive evaluation techniques and processes that monitor, probe, measure, and assess material response to internal or external stimuli. The measured response, generally conducted off-line, is related to a desired material property and characteristics reflecting the state of its health or its structural integrity. Existing and emerging NDE technologies were discussed earlier in Section 6. NDE techniques currently in wide use are visual inspection, liquid penetrant inspection, magnetic particle inspection, radiographic inspection (x-ray and gamma ray), eddy current inspection, ultrasonic inspection, and thermographic inspection. Although, each of these methods is dependent on different basic principles in both application and output, repeatability and reproducibility depends significantly on specific understanding and control of several factors, including human factors [110]. These techniques are not necessarily the best candidates for a real-time, on-line environment; however, due to their maturity, they are important tools for the validation of emerging sensor technologies.

Advanced sensors often referred to as "smart" sensors, sensor networks, or sensor nodes perform several functions delivered by NDE techniques in a real-time on-line environment with added integrated capabilities such as signal acquisition, processing, analysis and transmission. These highly networked sensors (passive or active) are suitable for large platforms and wide area monitoring and exploit recent development in micro and nano-technologies. Some of these sensors include:

- MicroElectroMechanical Systems (MEMS) sensors [111].
- Fibre optic sensors [112].
- Piezoelectric sensors [113].
- Piezoelectric wafer active sensor [114].
- Triboluminescent sensors [115].
- SMART layer sensor networks [116].
- Nitinol fibre sensors [117].
- Carbon nanotube sensors [118].
- Comparative vacuum sensors [119].

Regardless of the extensive development of sensor technology, efficient sensor networks, sensor power consumption and conservation, efficient network topologies, data transmission security, miniaturized and fully integrated electronic and signal acquisition and processing (Lab-On-a-Chip), only a handful of emerging sensors present a real potential for integration into an HM system. This document presents a selected few sensor technologies that have recently seen significant development or nearing full commercial exploitation. These technologies are identified as advanced non-traditional sensors employing advanced concepts or simply advanced sensing technology.

To put into context the significance of such advanced sensing technology; the market for general industrial sensor systems in the USA was US$6.1 billion in 2004 and expected to grow at an annual rate of 4.6% to US$7.7 billon by 2009. The market for MEMS-based sensors is expected to grow at a rate of 7.6% and reach a value of US$2.5 billion by 2009. The market for fibre optic sensors of several microns in size was US$175 million in 1998, and is expected to reach US$600 million by 2011 [120]. Because of the large interest in industrial sensor systems, it is likely that there will continue to be important developments in sensor technologies for aircraft for many years.

6.5.2.2 Smart and MEMS-Based Sensors

The word smart is defined as "intelligent or able to think and understand quickly in difficult situations" [121]. For example, smart devices are defined as ones that operate using computers (e.g. smart bombs and smart cards.) The same source defines the word intelligence as "the ability to understand and learn well and to form judgments and opinions based on reason". Furthermore, the definition of advanced is said to be "highly developed or difficult". According to the IEEE 1451 Standard 17, a smart or intelligent sensor is defined as "one chip, without external components, including the sensing, interfacing, signal processing and intelligence (self-testing, self-identification or self-adaptation) functions". Figure 6-21 [122], illustrates the smart sensor concept as defined by IEEE 1451.

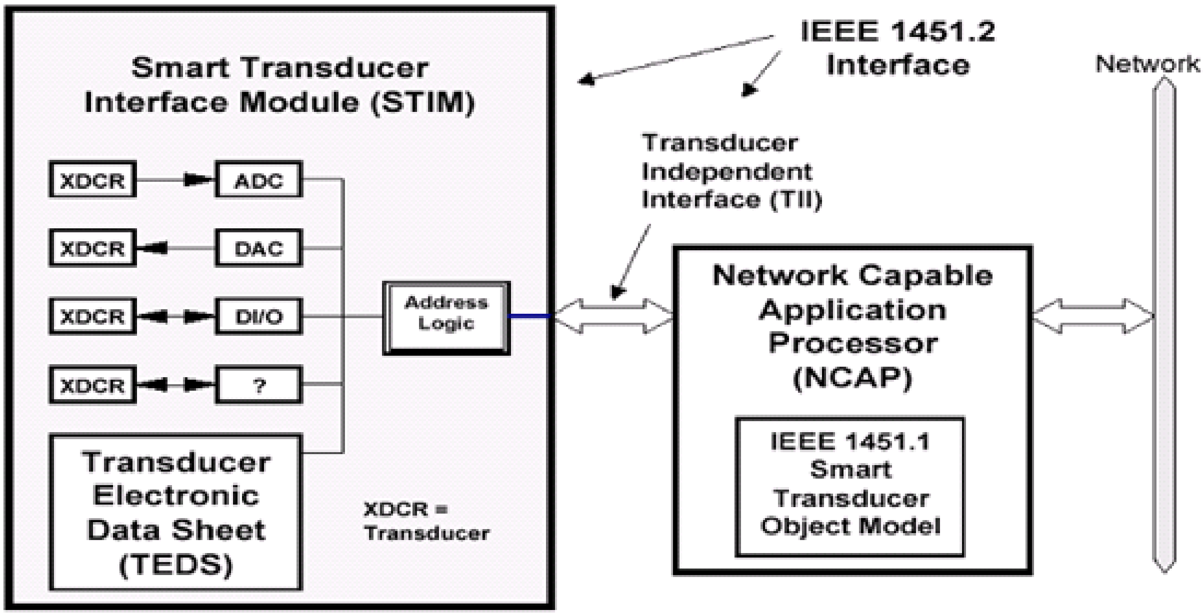


Figure 6-21: Smart Sensor Concept Defined by IEEE 1451.

Sensors based on this smart sensor concept generally exploit development in MEMS and nano fabrication along with advanced electronics and wireless devices using radio frequency communications technologies. Figure 6-22 [123] depicts a prototype of a smart sensor, known as sensor node, for multi-parameters sensing. The sensor node contains four major components:

a) A 3M's MicroflexTM tape carrier.

b) Two MEMS strain sensors.

c) A Linear Polarization Resistor (LPR) sensor to detect wetness and corrosion.

d) An electronics module.

The electronics module is composed of a Micro Controller Unit (MCU), a signal conditioning unit, a wireless Integrated Circuit (IC) unit, a battery and an antenna. Employing this node design, Niblock et al. [124] developed an Arrayed Multiple Sensor Networks (AMSN) for materials and structural prognostics. Some of the observed benefits employing smart sensors system include the wealth of information that can be gathered from the process leading to reduced downtime and improved quality; increased distributed intelligence leading to complete knowledge of a system, sub-system, or component's state of awareness and health for 'optimal' decision making [125]. Additionally, due to their significant small size and integrated structure, these sensors can easily be embedded into composites structures or sandwiched between metallic components for remote wireless and internet-based monitoring. Intelligent signal processing and decision making protocols can also be implemented within the node structure to provide ready to use decisions for reduced downtime and increased maintenance efficiency.

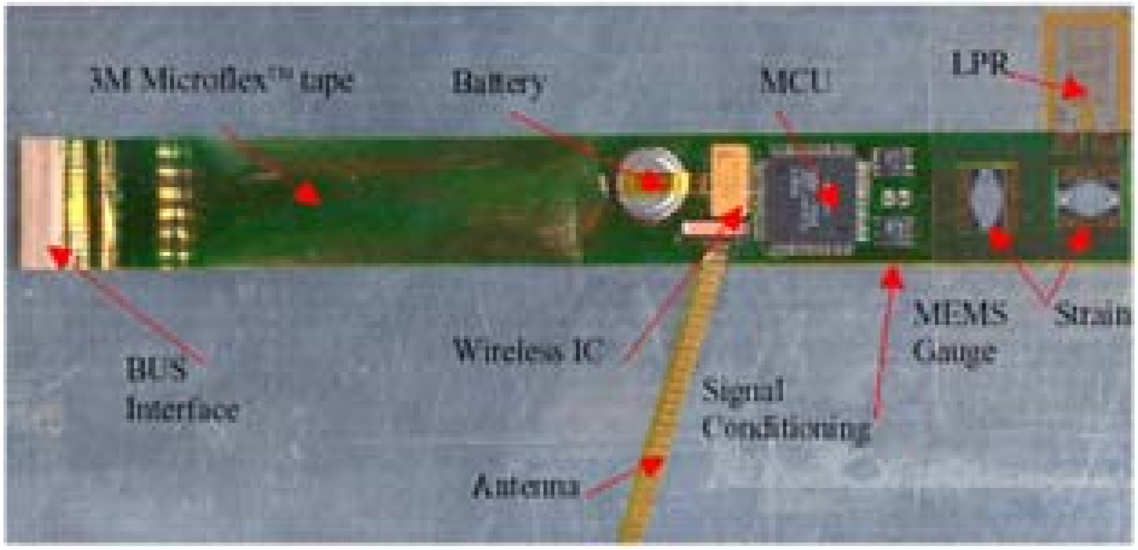
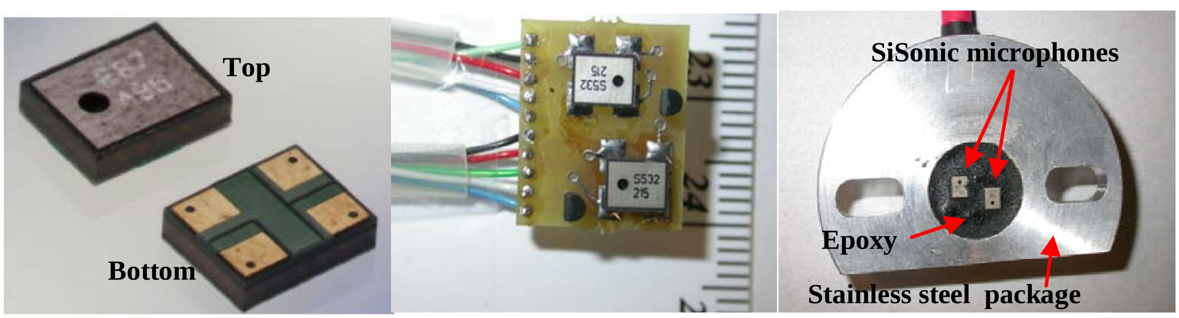


Figure 6-22: MEMS-Based Smart Sensor Node.

Recently, Mrad et al. [126] demonstrated, on a commercial Gas Turbine Engine (GTE), the suitability of a MEMS-based pressure transducer for fan speed measurement to infer blade health condition. Such MEMS pressure transducer, shown in Figure 6-23, was placed in front of the fan blades on a spacer as an alternative to directly placing it over the fan blades as necessitated by most engine manufacturers. Figure 6-24 illustrates the sensor placement and its output for a full engine thrust (take-off thrust condition of 14,000 RPM).



Pressure tranducer | Circuit board layout | Pressure sensor assembly

Figure 6-23: MEMS-Based Pressure Sensor for Gas Turbine Engine Applications.

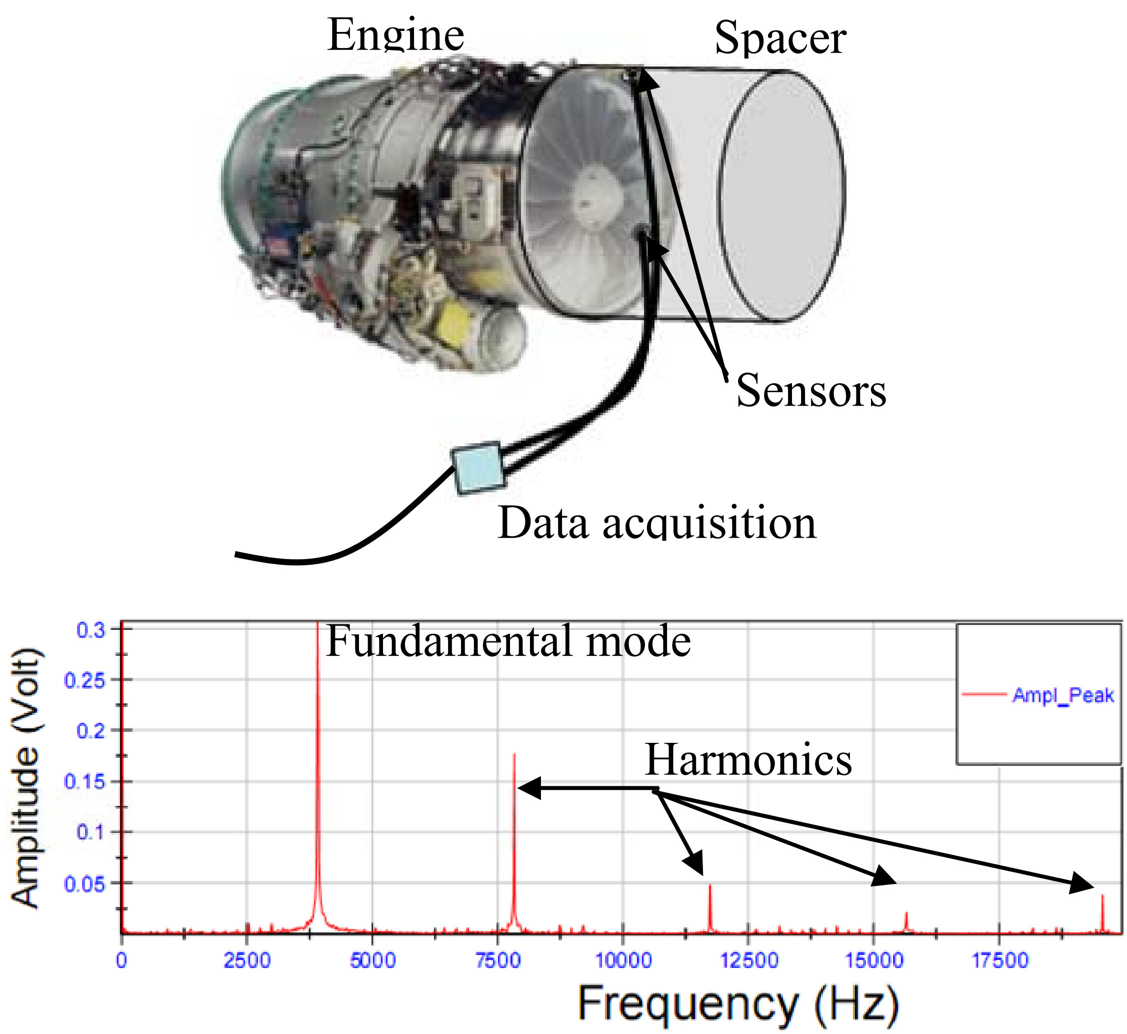


Figure 6-24: A Typical Gas Turbine Engine with the MEMS Pressure Transducer, and a Typical Frequency Response for a Full Thrust Condition.

6.5.2.3 Piezoelectric-Based Sensors

Piezoelectricity dates back to its discovery in 1880 by the Curie brothers. Materials possessing these characteristics are generally referred to as dual function or smart materials and have been used extensively in the development of innovative small size and effective actuators and sensors technologies. Piezoelectric actuators are generally made of ceramics and employ the indirect effect; whereas piezoelectric sensors are made of thin polymers and employ the direct effect. Both materials are exploited in the development of MEMS-based sensors and actuators as well as advanced structural health monitoring and prognostic health management systems [127]-[129].

In recent years, significant research was devoted to the development of structural health monitoring capabilities based on piezoelectric materials. Masson et al. [130] demonstrated a number of modelling tools and damage detection strategies in low and medium frequency ranges. A number of sensing and actuation technologies including arrays of piezoelectric sensors and actuators, shape memory alloys, and micro-accelerometers were also demonstrated for application to structural health monitoring at higher frequencies. Employing piezoelectric transducers' arrays, shown in Figure 6-25 and a time reversal approach, damage detection and localization were demonstrated. Furthermore, Mrad et al. [131] exploited these smart materials characteristics to detect exfoliation damage in metallic structures through the use of arrayed sensors, as shown in Figure 6-26. These novel transducers, analogous to nano-coatings, are known as integrated thin film paint-on Ultrasonic Transducers Array (UTA). The fabrication novelty and flexibility in producing UTA with different sizes, thicknesses, for different aerospace applications is documented and demonstrated by Kobayashi et al. [132].

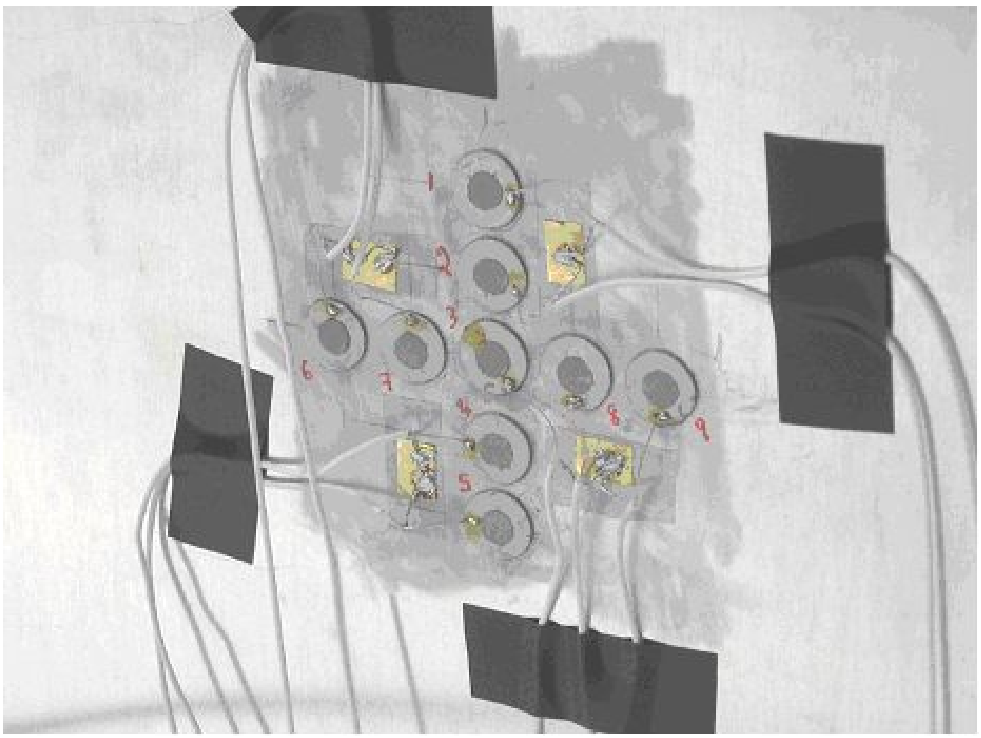


Figure 6-25: Arrayed Piezoceramic Sensors Used for Damage (Crack) Detection and Localization.

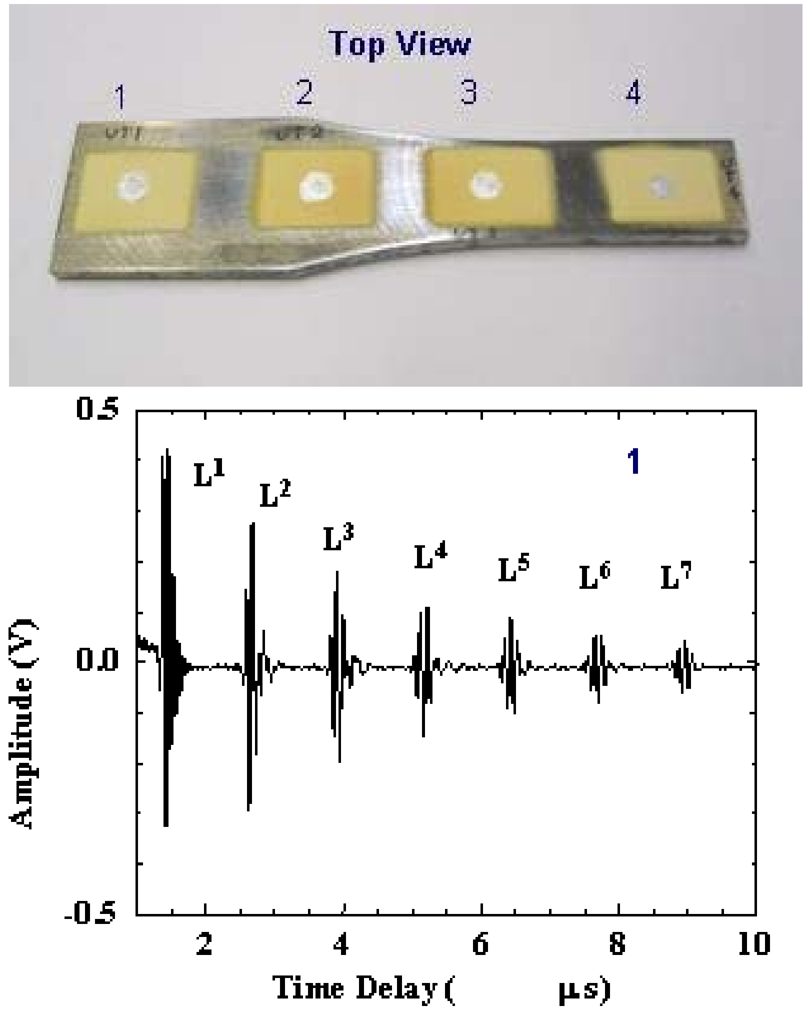


Figure 6-26: Exfoliated Test Article with Four Integrated Ultrasonic Transducers Arrays (UTA) and a Typical UTA Response.

Piezoelectric material can be used both for active and passive defect detection employing network of sensors. As illustrated in Figure 6-27 [133], in the active mode, an electric pulse is sent to a piezoelectric actuator that produces Lamb waves within the structure under evaluation. The array of piezoelectric sensors will pick up the resultant Lamb waves for processing and analysis. If defects such as cracks, delamination, disbond or corrosion exist within the array of sensors, a change in the signal results, which is distinct from the reference healthy or non-defect component's signature. These systems rely on a reference signal in the structure before they are placed in service. The location and the size of the defect can generally be determined from the degree of signal change. In the passive mode, sensors are used continuously as "listening" devices for any possible damage initiation or propagation. Sensors within the network can detect energy emitted from impact events and defects generation, including crack formation, delamination, disbond, and possibly non-visible impact damage. In this mode, arrays of sensors are used to monitor or detect such events that generally have a particular energy signal associated with them. Cracks of length 0.005 inches from a distance of six inches on flat plate samples [134] were detected using these sensors. The latter mode is generally desired as it requires little or no power for its operation.

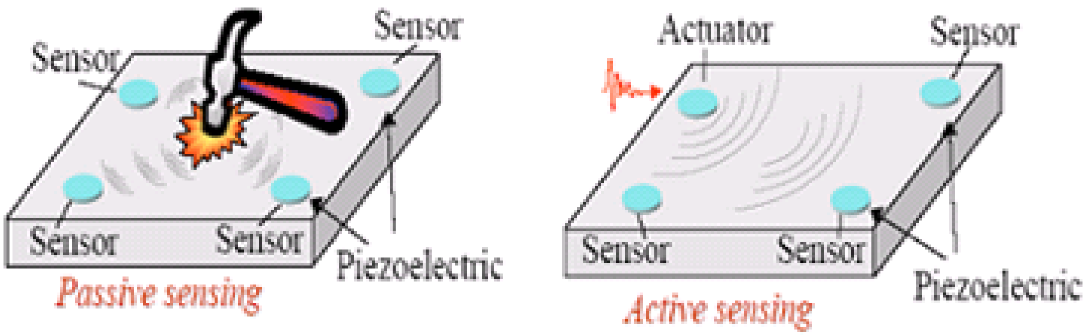


Figure 6-27: Passive and Active Sensing Mode Using Piezoelectric Materials.

Systems based on this dual concept of passive and active monitoring have been developed [135]-[136]. Stanford Multi-Actuator-Receiver Transduction (SMART) Layer-based system has been developed and demonstrated for several aerospace structural health applications. The system is designed and built around a set of piezoelectric sensors networked and embedded into desired configurations in a single polyimide layer, known as SMART Layer®. Using dedicated diagnostics software, analysis tools and graphics user interface packaged into a SMART Suitcase™ portable diagnostic hardware, the damage severity and location can be easily identified. Figure 6-28 [135]-[136] depicts this approach with two applications: composite bonded patch repair health monitoring and integrity assessment and damage detection under fasteners.

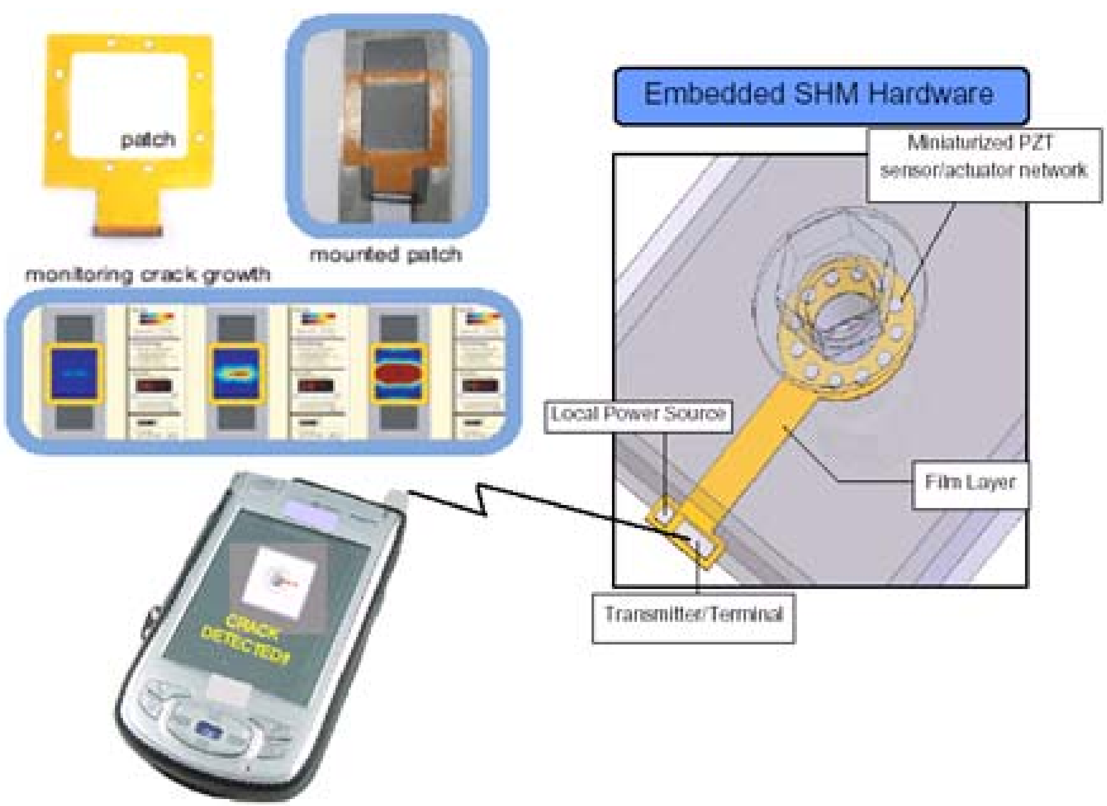


Figure 6-28: A SMART Technology-Based Structural Health Monitoring System.

This sensor technology provides significant potential in the development and implementation of HM capability due to the high sensor multiplexing capability, the suitability of the sensor array in harsh environment, and its sensitivity to pressure, temperature, vibration, and strain. However, when this technology is used in either mode of operation (passive or active) it presents several challenges that require further research. In the passive mode, background noise (AE from non-defect events) needs to be accommodated for; thus, requiring significant experience and additional expertise to accurately diagnose the presence of damage from the acquired data. In the active mode, sensors/actuators must be spaced properly and excited with certain frequencies at selected energy level to be able to detect damage with certain sizes and region as demonstrated by Pinsonnault [137]. Additionally, from a hardware perspective, the reliability of sensors and actuators wiring, networking and bonding requires validation. Costs associated with added weight, complexity and system certification needs to be weighed against the value added in the integration of this technology as a component of an HM system. Tremendous progress was reported in this area; however significant research is needed to bring this technology to practical deployment and to facilitate its qualification and certification on air vehicles.

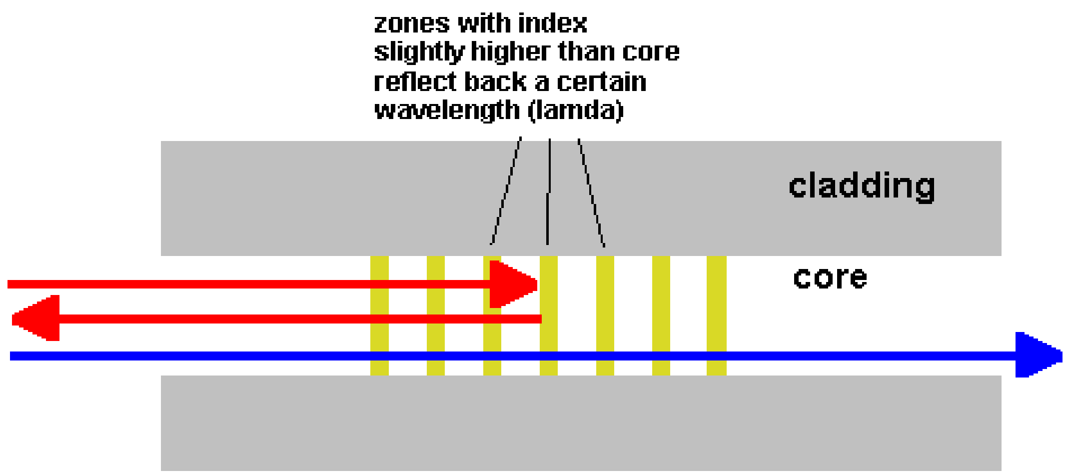
6.5.2.4 Fibre Optic Based Sensors

The fibre optic sensor development that capitalized on the 1950s successful discovery of communication optical fibres has been underway since the early 1970s. Only in recent years, accelerated progress was experienced due to the significant development of new, low-cost materials and devices, the emergence of micro and nano technologies for the telecommunications industry, and the increased interest in the development and implementation of HM systems. The shape and form of optical fibres are similar to those reinforcing fibres used in fibre-reinforced composite materials. However, the diameter of optical fibres is much larger, usually in the order of 40 to 250 microns, compared to glass and carbon fibres used in composites that are typically 10 microns or smaller. Optical fibres consist of a light waveguide inner silica-based core surrounded by an annular doped silica cladding that is protected by a polymer coating. This optical fibre can also be made using other materials, such as plastic [138]. The fibre core refractive index is relatively large compared to that of the cladding index. The change in refractive indices, between the core and the cladding, provides the required mechanics for light propagation within the fibre core. Depending on the wavelength of the light input, waveguide geometry and distribution of its refractive indices, several modes can propagate through the fibre, resulting in the so-called, single and multi-mode optical fibres. Both fibre types are used in the construction of fibre optic sensors. However, single mode fibres are more sensitive to strain variation and are thus the preferred choice for HM applications. A summary of the typical properties of various optical fibre types is presented by Krohn [139].

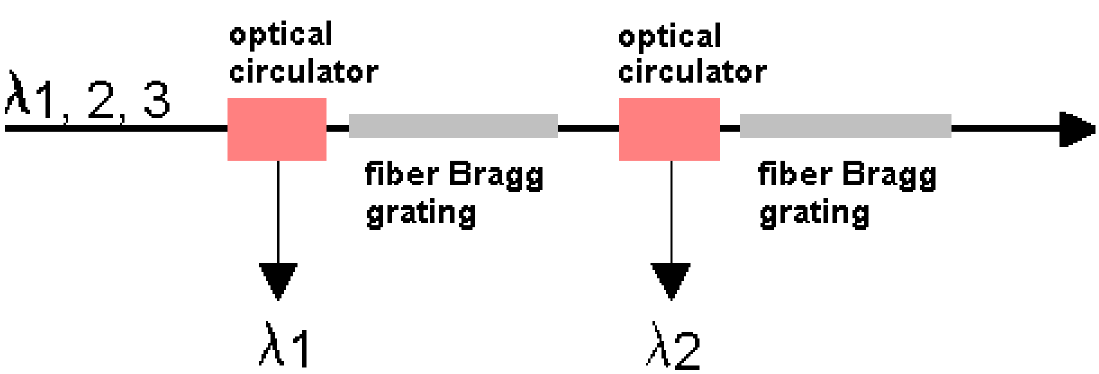
Compared to more traditional measurement techniques, fibre optic sensors offer unique capabilities such as monitoring the manufacturing process of composite and metallic parts, performing non-destructive testing once fabrication is complete, enabling structural and component health monitoring, and structural control for component life extension. Because of their very low weight, small size, high bandwidth and immunity to electromagnetic and radio frequency interferences, fibre optic sensors have significant performance advantages over traditional sensors. In contrast to classical sensors that are largely based on measurement of electrical parameters such as resistance or capacitance, fibre optic sensors make use of a variety of novel phenomena inherent in the structure of the fibre itself. Some of these phenomena are extensively discussed in the literature [140]-[141]. In general these sensors can be classified into two classes, the discrete and distributed class. The distributed class of sensors includes Michelson and Mach-Zhender interferometer as well as sensors based on Brillouin scattering. These are generally seen in infrastructure applications where spatial resolution, system's weight and size are not as critical and long range sensing is desired [142].

The discrete class of sensors have cavity- or grating-based designs and are commonly used for the measurement of strain, deformation, temperature, vibration and pressure, amongst other parameters. Cavity-based designs utilize an interferometric cavity in the fibre to create the sensor and define its sensor gauge length. Extrinsic and

Intrinsic Fabry-Perot Interferometers (EFPI, IFPI), along with In-Line Fibre Etalon (ILFE) are the most known ones. Grating-based designs utilize a photo-induced periodicity in the fibre core refractive index to create a sensor whose reflected or transmitted wavelength is a function of the periodicity that is indicative of the parameter being measured. Fibre Bragg Gratings (FBG) and Long Period Gratings (LPG) are the most commonly used sensors in this class and are the most attractive for integration into advanced diagnostic and prognostic capabilities. Grating-based designs, particularly traditional FBG, have emerged as the leading technology in multiplexing and dual parameter sensing. The principle of operation of Bragg gratings-based sensors is shown in Figure 6-29 [143]. Additionally, as shown in Figure 6-30 [144], these sensors can be used to monitor bondline integrity in bonded joints, acoustic emission resulting from structural damage and corrosion monitoring. When integrated with a centralized monitoring system, as shown in Figure 6-31, on-line real-time corrosion sensing and health prediction can be performed using very high number (up to 1000) of sensors networked on a single strand fibre.



(a)



(b)

Figure 6-29: Fibre Bragg Gratings Principle of Operation.

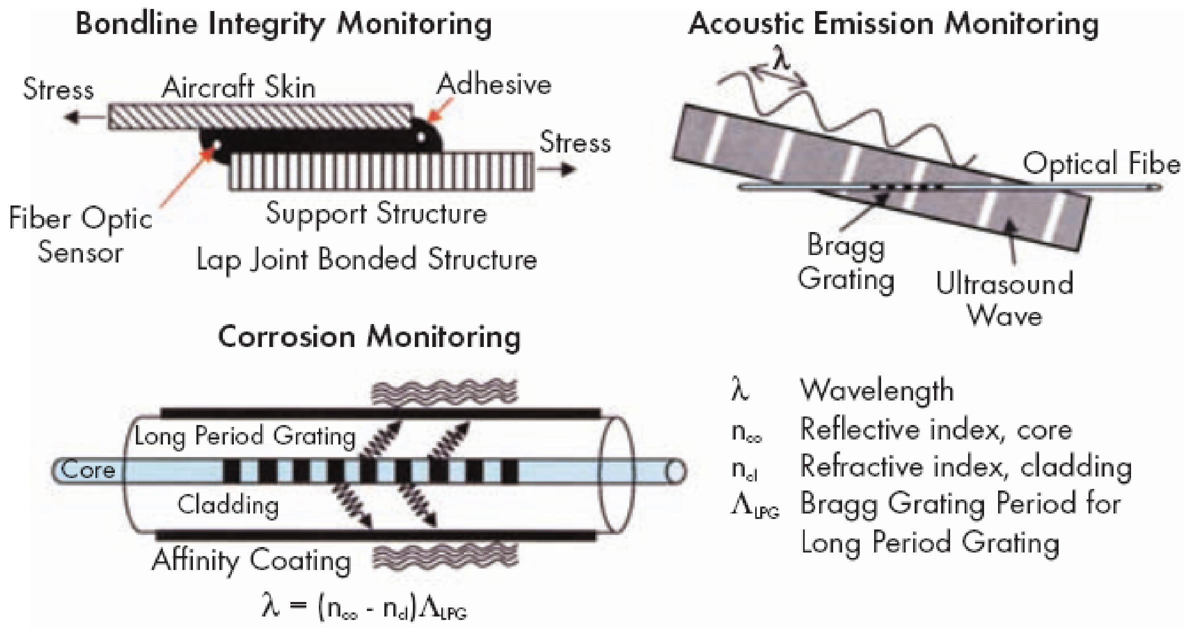


Figure 6-30: Bragg Grating-Based Sensing.

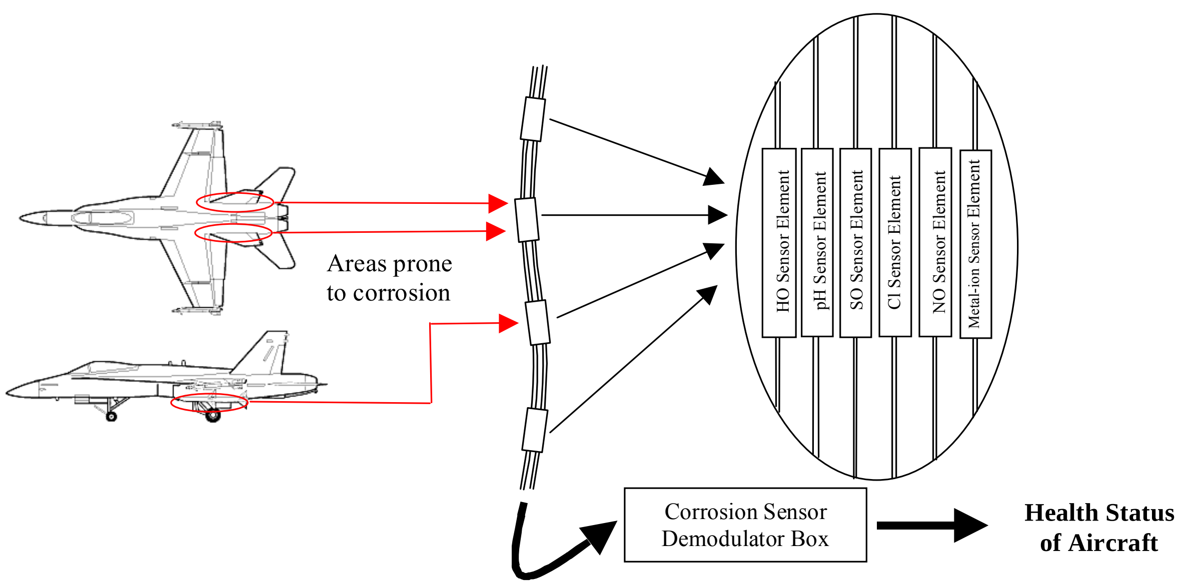


Figure 6-31: Illustration of a Fighter Jet Health Monitoring System.

Several sensor output interrogation techniques and their associated modulation systems have been developed and implemented [145]. These systems are found to be costly and impractical for in-flight applications due to their significant size, weight and power requirements. Recent efforts have focused on developing an increased level of understanding of the issues impeding the implementation of fibre Bragg gratings (single or multiplexed) into aerospace and military air platforms [146]-[149] and developing a micro fibre optic interrogation system for increased sensor networks and reduced size and weight. Figure 6-32 [150]-[152] illustrates the developmental effort in exploiting the enabling area of MEMS technology to develop a micro arrayed highly multiplexed FBG interrogation system providing significant advances in air platforms diagnostics and prognostics.

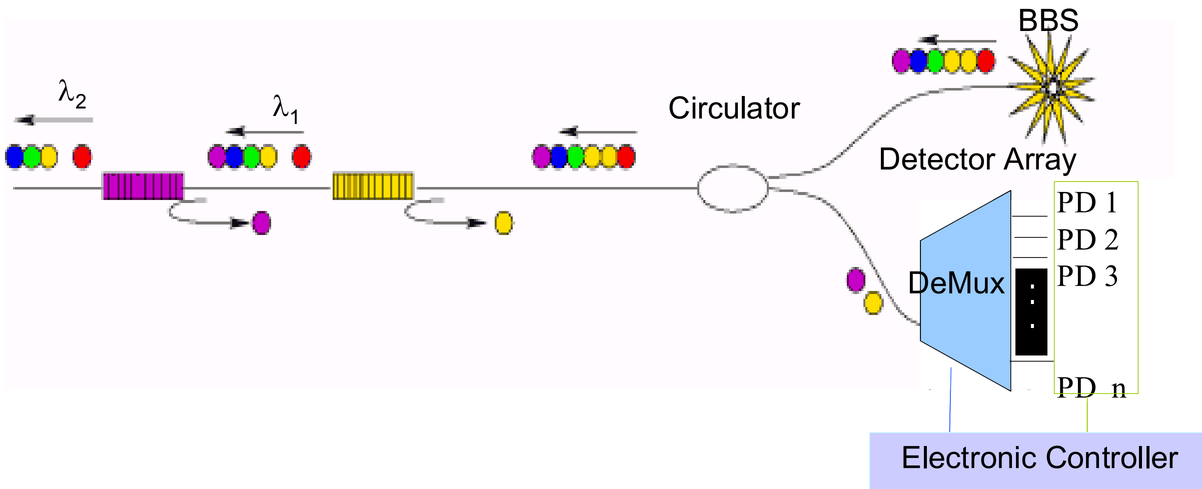


Figure 6-32: Conceptual Illustration of a Micro-Arrayed Highly Multiplexed FBG Interrogation System.

Regardless of the extensive and successful outcome of several investigations supporting aerospace platform HM requirements, research effort continue to address the critical issues for practical implementation that include adhesive selection, bonding procedures, quality control processes; optimum selection of sensor configuration, sensor material and host structure for embedded configurations; characterization of embedded fibre optic sensors at elevated and cryogenic temperatures; resolution optimization for desired parameters from multi-gratings as well as sensitivity to transverse and temperature effects; development of an integrity assurance procedure for embedded sensors, particularly sensor protection at egress/ingress points.

6.5.2.5 Comparative Vacuum Monitoring (CVM) Sensors

Comparative Vacuum Monitoring (CVM™) technology has been developed for detecting cracks and measuring their rate of growth. Among the wide range of sensor technologies that have emerged in recent years as damage detection sensors, Comparative Vacuum Monitoring (CVM) technology is assessed to be a mature technology, for both Non-Destructive Testing/Inspection (NDT/NDI) and Condition Monitoring (CM) of structural integrity, that is ready for deployment onto operational platforms. The state of maturity of this technology coupled with the desire of the aerospace industry to deploy an automated inspection method that does not have reduced accuracy and that could take place with personnel remote to the inspection area has triggered a desire to evaluate this technology within an aerospace environment. Recently, Boeing, FAA, Airbus, Northwest Airlines, the United States Navy (USN) and Royal Australian Air Force (RAAF) initiated independent verification trials with this technology. These trials involve laboratory, environmental and on-aircraft tests. A validation trial within the US Navy has successfully demonstrated the detection of a crack [153]-[154].

CVM technology consists of three primary components; a sensor, a pressure differential flow meter and a stable host reference vacuum source. Figure 6-33 and Figure 6-34 [155] illustrate a typical CVM system and an example of crack detection process on a component, respectively. The sensor is linked to a reference vacuum source through a flow meter, which contains impedance to the flow of air molecules through the system. The flow meter measures the pressure difference across the impedance. The vacuum source provides the flow meter with a continuous stable reference vacuum and power to maintain vacuum at a stable level.

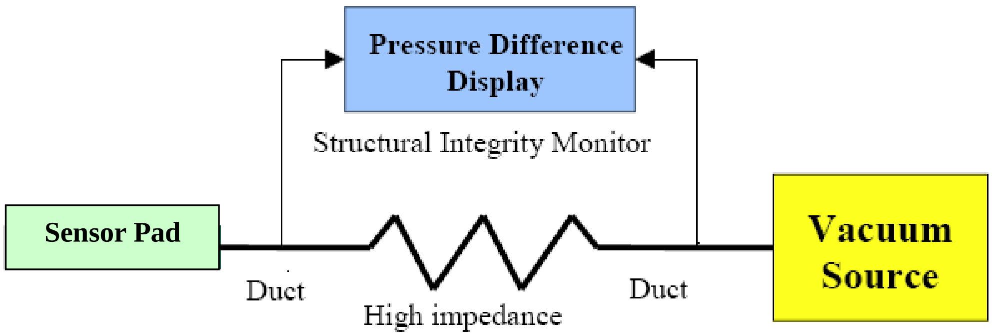


Figure 6-33: Conceptual Model and Principle of Operation of a Typical CVM™ System.

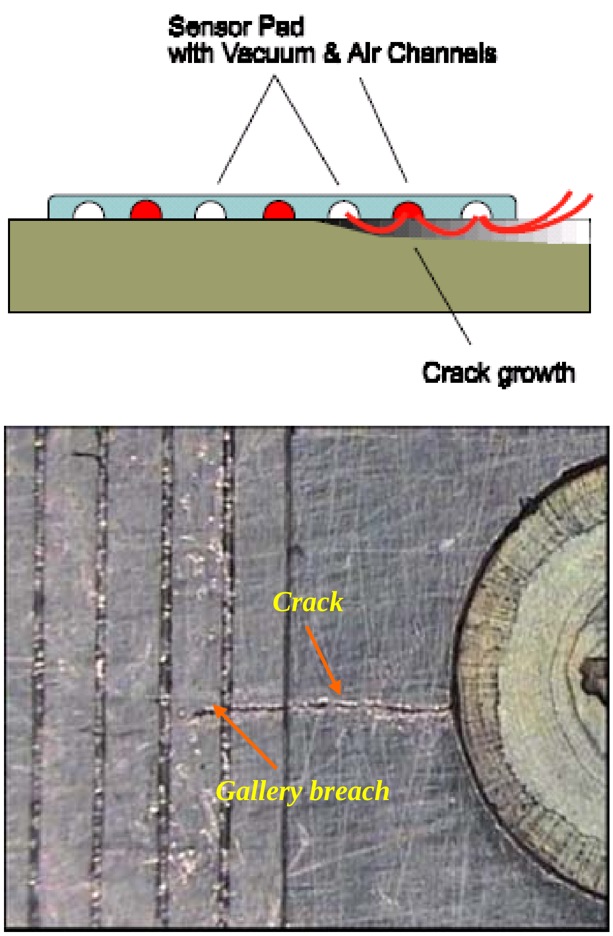


Figure 6-34: Illustration of Crack Detection Using CVM™ Technology.

The fundamental principle of the CVM operation is the detection of pressure difference caused by a crack in a vacuum channel, known as 'gallery' within the sensor pad. If there is no damage and since the sensor is sealed to the test article there should be no leaks or change in pressure difference and hence a balance is maintained between the sensor and the vacuum source. If there is damage, a leak occurs at the location of the sensor pad and a pressure increase is detected by the flow meter. The rate of growth of the damage (crack) is determined by the rate of pressure change. The increase in pressure is measured as a differential pressure in relation to the reference vacuum level. This is significantly more sensitive to micro fluidic air flow than conventional air flow meters.

An example of the operation of the commercially available system is also shown in Figure 6-35 [156].

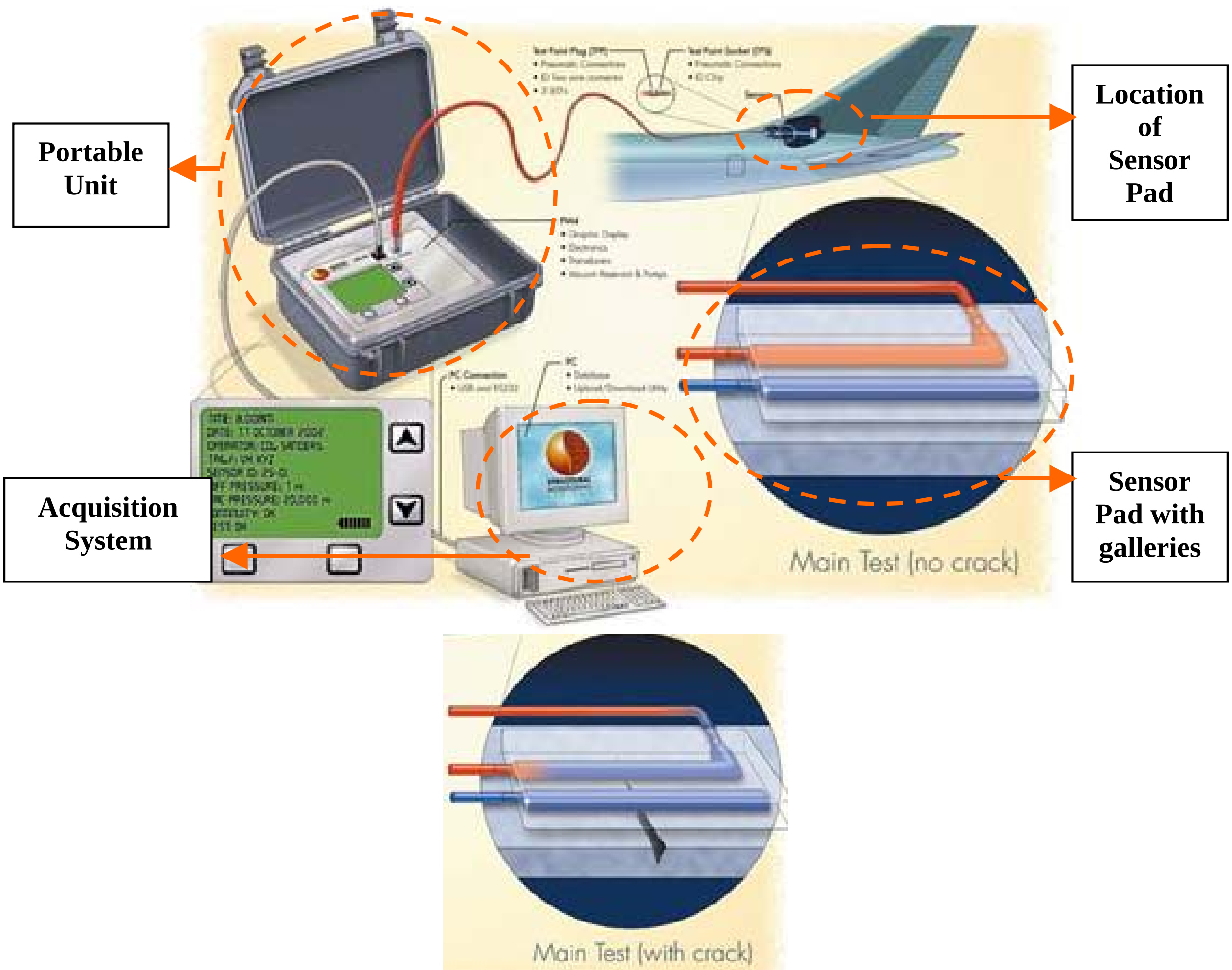


Figure 6-35: Commercial CVM™ System – With and Without Crack.

The extensive work in the open literature indicates that there is rapid growth in the use of this technology for both military and civilian aircraft [157]-[158]. CVM™ sensors are suitable for localized damage detection but not for global system and component health monitoring. CVM sensors are often compared to resistive crack detection gauges. Even though networks of multiplexed sensors have been demonstrated, their application is currently limited to hot spots and other situations where false positives and the additional weight can be tolerated. While the CVM technology is mature, it still has applications challenges common to other sensor technology discussed in this section.

6.5.2.6 General Status of Sensor Technology

The interest in on-board maintenance systems has provoked considerable R&D in sensor concepts and technologies. The challenges in the use of sensors in on-board maintenance systems include minimising the impact of the distribution, networking and communication of sensors on aircraft weight and cost, and ensuring that the maintenance downtime of the sensor system itself is not excessive. Sensor systems based on fibre optic, piezoelectric, and CVM™ technologies are commercially available, but there is considerable scope for further development of the sensors and their systems. Also, new sensor concepts and technologies continue to be discovered that will assist with the automation of aircraft inspection and diagnostics.

6.5.3 Corrosion Sensors

The content of this section is based on Paper 4.2.2 by Harris and Mishon.

6.5.3.1 The Need for Corrosion Sensors

Corrosion sensors have often been proposed for monitoring the degradation of civil and military airframes. There are many types of possible sensors and several different approaches to using them but there is little information available that allows sensor outputs to be simply related to the state of the surrounding structure. Sensors for corrosion and perhaps other forms of environmentally-induced degradation can only be used for managing and supporting aircraft in service if there is a way to interpret the sensor information into an easily understood message of what actions, if any, are required for the maintenance support engineers.

With the trend for customers to force the risks associated with operational service onto the supplier, reliable quantitative information that describes corrosion and other degradation may well be useful. Such quantitative information can also be used to support estimates of residual value if assets need to be moved on. In addition, legislation will force operators and manufacturers to use new corrosion protection schemes such as non-chromate treatments and paints that may perform differently to their “traditional” predecessors. Michelin (2003) [159] has described some of the requirements of chromate-free primers and Kinzie (2003) [160] discusses the cost of corrosion for military aircraft which, for the USAF, exceeded US$1 billion in 2001 with some aircraft types costing more than US$200,000 per year per airframe in direct corrosion costs.

6.5.3.2 The Process of Environmental Degradation

A typical aerospace structure is commonly fabricated from aerospace qualified aluminium alloys with metal fasteners. The structure is generally protected from the elements by treating the aluminium surface through anodising or conversion coating with a chromate containing primer overlaying the surface. Finally a top coat is applied. Around the fasteners and fastener holes there is often applied a high quality sealant. It is generally hoped that the protective surface is perfectly flawless but on a large structure undergoing the rigours of everyday service this cannot be the case. Impact damage, in flight, during landing and take – off or on the ground is a common occurrence. Damage during maintenance (tools and spilt fluids) can occur as well as paint cracking at high stress points around joints and at fasteners. Paint can also crack due to high thermal cycles and fatigue [161]-[162]. The progress of the degradation of the structure from operational degradation is illustrated in Figure 6-36. A typical flaw structure is shown in Figure 6-37.

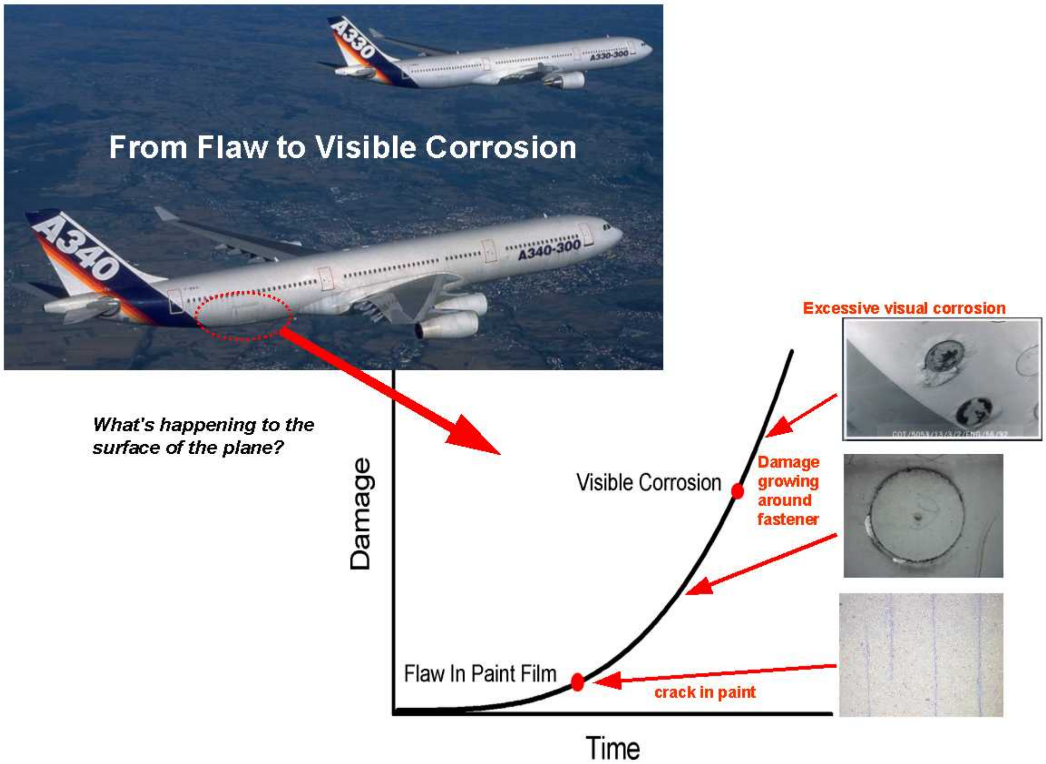


Figure 6-36: Progress of Degradation in a Protection Scheme.

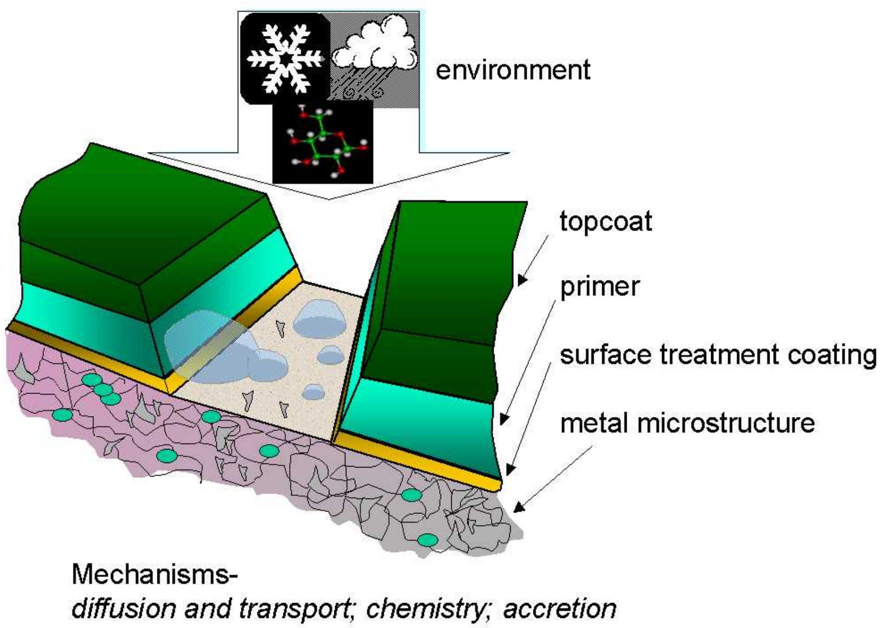


Figure 6-37: Structure of a Flaw in a Standard Protection Scheme Illustrating Environmental Factors in Chromate Exhaustion and Metal Degradation.

6.5.3.3 General Approaches to Corrosion Sensing

Corrosion sensors are not new but they have mainly been applied to large fixed installations such as pipelines and offshore structures. These applications are not usually weight-sensitive and much of the sensor technology has not been directed towards aerospace needs in terms of low mass, operating conditions, sensitivity and materials. In recent years, however, the potential benefits of corrosion monitoring, often as part of a larger strategy on corrosion management, have generated a substantial body of research for aircraft use. Additionally, changes in the business environment and advances in fabrication methods and datalogging have now made aircraft corrosion sensors a viable technology that is being closely examined.

There are four basic approaches to corrosion monitoring using discrete sensors: direct measurement of corrosion effects, measurement of corrosivity by relating the degradation of the sensor itself to the degradation of an adjacent structure, measurement of corrosion products and measurement of climate (or microclimate) to input into a predictive model. These are described briefly below.

6.5.3.4 Direct Measurement of Corrosion Effects

It is possible to measure corrosion effects directly using electrochemical sensors such as EIS (Electrochemical Impedance Spectroscopy) or MEMS-based sensors that have been postulated. This approach may be suitable for monitoring localised areas but is unlikely to offer large area coverage without using many sensors. Another approach would be to use corrosion-indicating paints whose optical signature changes when the pH of the underlying structure changes due to corrosion.

6.5.3.5 Measurement of Corrosivity of Environment

The term *corrosivity sensors* can be used to describe several types of sensor whose response to corrosive conditions may be correlated to the corrosion of an underlying structure. For example, galvanic sensors might indicate time of wetness or the corrosion of metallic elements in a sensor can be monitored via their change in electric resistance. The output of corrosivity sensors needs to be related to the underlying structure by calibration, and it is this aspect, especially when dealing with complex painted structures, that needs careful attention. Some corrosivity sensors can incorporate analogues of the underlying structure and can also be painted and treated in the same way as the structure so that their response to the environment and contaminants is similar to that of the structure they are monitoring.

6.5.3.6 Measurement of Climate (or Microclimate) to Input into a Predictive Model

For general in-service degradation based on the environmental and service history of the aircraft it is possible to construct an entirely non-invasive model to predict the onset and progress of corrosion. To overcome the difficulties of modelling pollution accretion, UV damage, and unexpected atmospheric circumstances a predictive model could be supplied with data from environmental sensors which measure the climate or microclimate of a components or group of components. Unfortunately, the modelling and sensor technologies are not yet ready for operational deployment on aircraft.

6.5.3.7 Measurement of Corrosion Products

Chemical sensors can indicate the presence of specific ions that would arise from a corroding structure. These could be located in bilges or in locations where corrosion products might accumulate and would therefore, in effect, be able to indirectly monitor large areas. To date, however, such sensors cannot demonstrate stable longevity or resistance to poisoning by contaminants. Some corrosion indicating paints can also change their fluorescent properties when they react with certain corrosion products.

6.5.3.8 Types of Sensor

Categories of corrosion sensors are listed in Table 6-5. The various stages of corrosion and the availability of sensors to detect the physical phenomena associated with each stage are illustrated in Figure 6-38.

Table 6-5: Several Types of Corrosion Sensor, Principally Aimed at Aircraft Structures.

SENSOR TYPE	COMMENT
Corrosion Coupons	Corrosion rate is determined by weight-loss measurements. Coupons can be used as witness plates for calibrating other sensors.
Electrical Resistance	The resistance of a metallic track is measured. Loss of metal due to corrosion changes the electrical resistance.
Galvanic	The galvanic current or voltage generated by separated electrodes made of dissimilar metals can be used to measure the presence of a conducting, and hence corrosive, environment.
Electrochemical Impedance Spectroscopy (EIS)	Electrochemical Impedance Spectroscopy (EIS) can be used to assess the degradation of coatings. Portable systems are available. Also, it may be possible to embed electrodes beneath the coating. Such systems model the coating, substrate and electrolyte as elements in an AC circuit. The resistance and capacitance of each circuit element is inferred from observations of changes in impedance with the frequency of a small applied potential. The inferred values indicate the state of the coating.
Electrochemical Noise (EN)	Electrochemical Noise (EN) sensors measure the rapid fluctuations in corrosion current and voltage between electrodes. Corrosion potential fluctuations can indicate the onset of events such as pitting, exfoliation, and Stress Corrosion Cracking (SCC).
Acoustic Emission (AE)	Laboratory tests indicate that Acoustic Emission (AE) can be used to monitor the propagation of corrosion and stress corrosion cracking.
Chemical Sensors	Chemical sensors measure corrosive chemical species or corrosion products. There are many different technologies, including Ion Selective Electrodes (ISE), Ion-Selective Field Effect Transistors (ISFET), and optical sensors (see below). Lack of long-term stability and vulnerability to poisoning may be issues.
Corrosion-Indicating Paint	Corrosion-indicating paints are under development. The paint responds to chemical changes associated with corrosion by changing colour or fluorescence. Examples of relevant chemical changes are, change in pH; oxidation, and complexing with metal cations.
pH Sensors	ISE-based sensors are likely to be the best technology for measuring pH, but the issue of long-term calibrated performance remains.
Biological Sensors	Biologically-induced corrosion, or “biocorrosion”, can be monitored using electrochemical sensors. In general, biosensors have limited lifetimes and at present are unsuitable for long-term exposure.

SENSOR TYPE	COMMENT
MEMS-Based Sensors	Micro-Electromechanical (MEMS) devices are usually fabricated in silicon and have been proposed for corrosion sensors. Micro-cantilever systems whose vibration characteristics change according to the mass of the beam can form the basis of a range of sensors.
Ultrasonic	Active ultrasonic sensors comparable to those currently used in NDE can measure thickness loss directly under a sensing head. Guided ultrasonic waves that propagate along surfaces and interfaces might detect corrosion over larger areas. SAW (Surface Acoustic Wave) devices are in theory much more sensitive.
Optical Sensors	An optical fibre with Bragg gratings can be coated with an electrochemically active species that changes colour as a result of the corrosion reaction. These sensors can be embedded in sealant and can monitor long lengths of structure. Lack of long-term stability and vulnerability to poisoning may be issues.

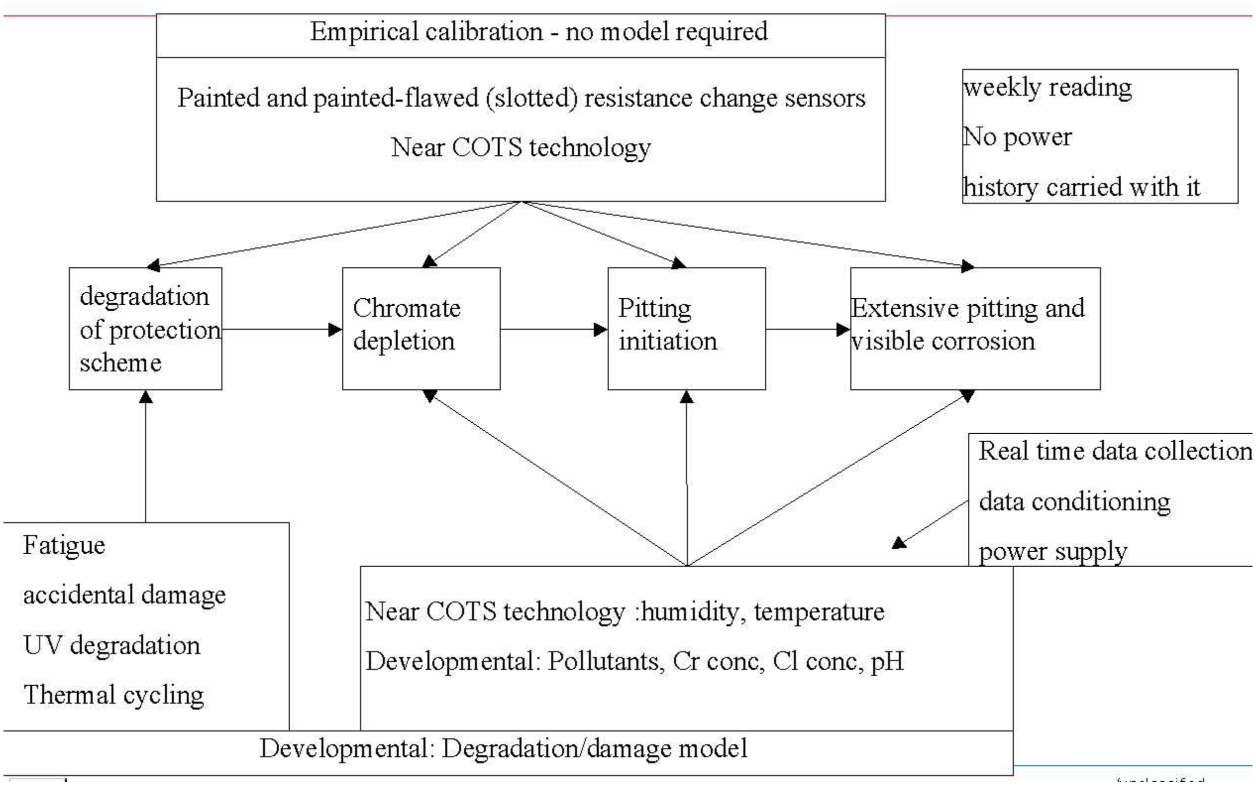


Figure 6-38: The Various Stages of Corrosion and the Availability of Sensors to Detect the Associated Physical and Chemical Phenomena.

Corrosion sensor systems and corrosion modelling are emerging technologies. In the short term, simple, passive sensor systems are achievable. These require no continuous power or real-time datalogging, carry their history of degradation with them, and react almost exactly as the surrounding structure would react. Such systems are currently being flight tested. They could be used for usage monitoring, i.e. to provide a record of the environments experienced to date. They could also be used as an inspection surrogate, such that degradation of a sensor would indicate that comparable degradation had occurred in an inaccessible component. Both functions could help in minimising the need for inspection and the associated downtime.

An example of a simple, unpowered, passive system is the BAE Systems Sentinel (Figure 6-39). This indicates the breakdown of the protection scheme, the onset of corrosion, and the progress of corrosion. The degradation rate is measured using a multi-meter or by existing on-board systems. No additional instrumentation is necessary. There is no requirement for additional software, modelling, or maintenance activities to handle data or change batteries. The result is in the single reading. Sentinel has been installed on the Tornado aircraft and various land-based assets, and has been selected for the F-35 JSF.

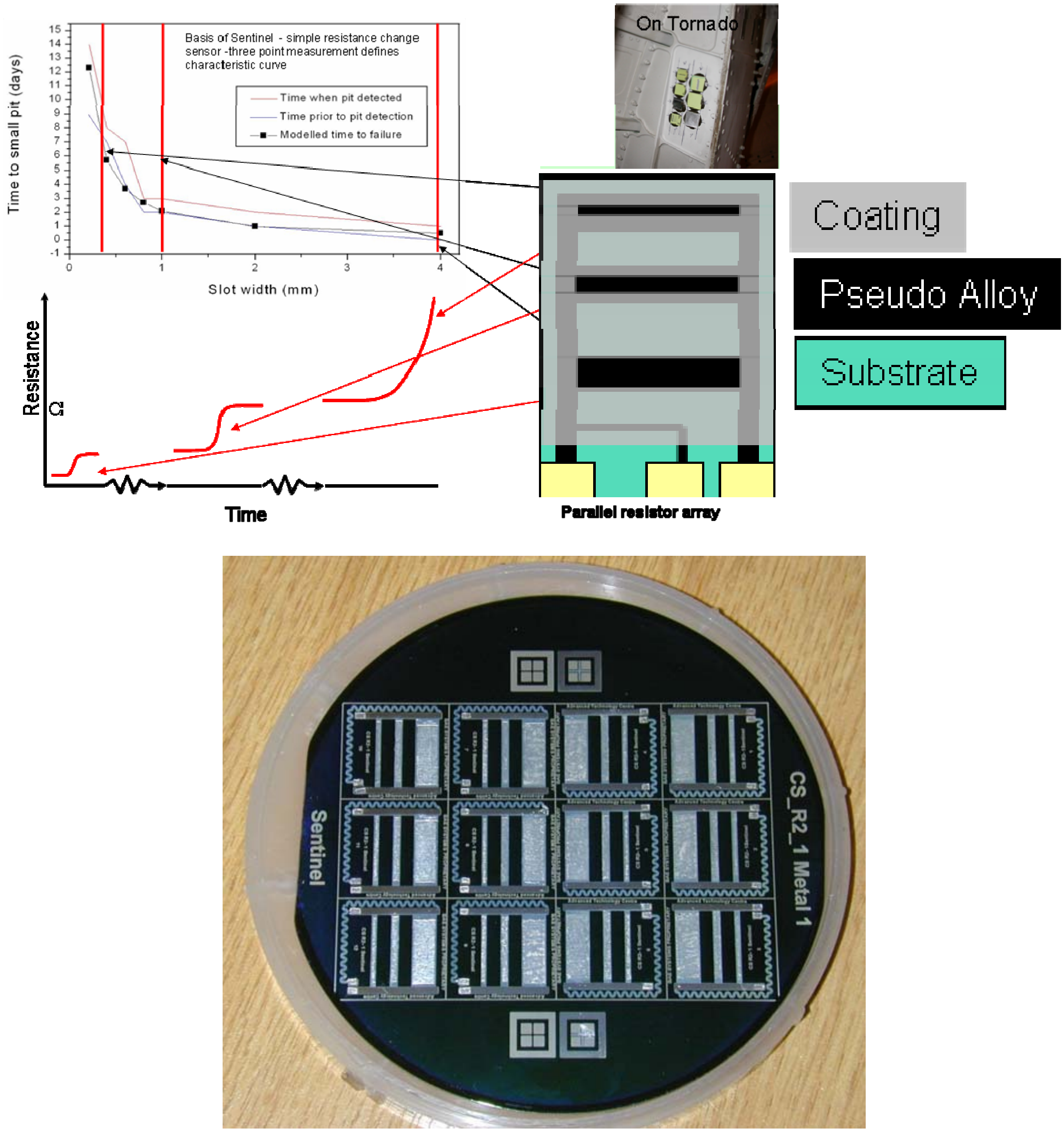


Figure 6-39: Sentinel Coating Degradation Sensor by BAE Systems. Indicates breakdown of protection scheme, onset of corrosion, and progress of corrosion. Fitted to Tornado, selected by JSF, and fitted onto MOD UK land-based assets.

Monitoring of basic environmental parameters can be performed with Commercial Off-The-Shelf (COTS) systems such as the datalogger by Zeta-tec illustrated in Figure 6-40. COTS dataloggers are available for temperature, voltage, resistance, temperature and humidity, event times, etc.

Figure 6-40: Illustration of a Multi-Channel/Higher Performance COTS Datalogger System. COTS dataloggers are available for temperature, voltage, resistance, temperature and humidity, event times, etc.

Future development in corrosion sensor systems could streamline and improve the accuracy of the "usage" and "inspection" functions mentioned above and make it possible to apply them to a larger range of components. The integration of different types of sensor and advanced corrosion modelling could result in further increases in accuracy and scope of application. It could also provide prognostics (estimates of remaining useful life) for corrosion and corrosion/fatigue interaction that would allow corrective action to be planned in advance for efficiency or deferred indefinitely. Groups of sensors can be manufactured on a single chip (Figure 6-41) and multiplexed for area coverage.

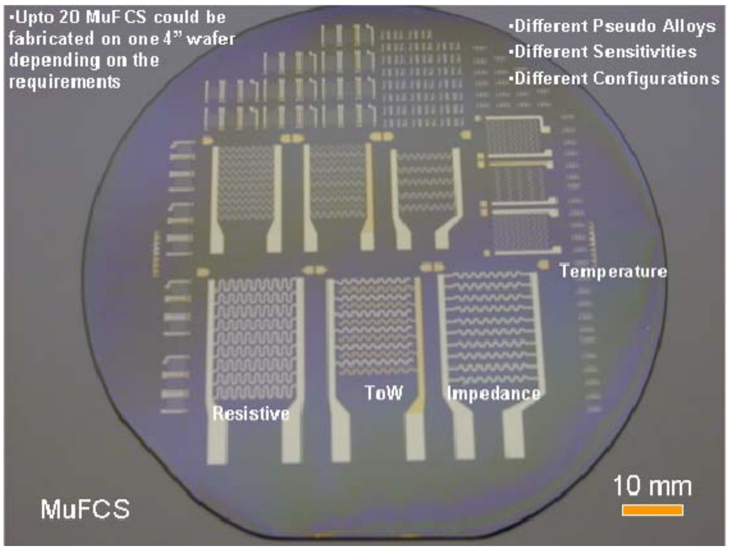


Figure 6-41: Multi-Functional Sensor (MuFCS) by BAE Systems – Different Environmental Sensors on a Single Chip.

No sensor system has yet been able to demonstrate adequate reliability for longer than ten years. There are credible strategies to address this problem, but it is likely that considerable development will be needed before on-board corrosion sensors can completely replace ground-based inspections for corrosion.

Sensors may not be cost-effective where corrosion can be measured directly and unambiguously, or where very simple indictors only are needed. Also, simple indicators may suffice if combined with a predictive capability and improved knowledge of degradation mechanisms.

6.6 DIAGNOSTICS FOR ELECTRONIC AND ELECTRICAL SYSTEMS

6.6.1 Introduction

This section identifies technologies for improving the diagnosis of electronic and electrical systems, to reduce aircraft downtime at 1st Line and improve mission reliability. These include smart diagnostic concepts for integrating Automatic Test Systems (ATS) – also known as Automatic Test Equipment (ATE) – with aircraft Built-In Test (BIT) systems and Maintenance Data Systems (MDS). The systems covered are all electronic and electrical systems, including weapon and payload systems, and all wiring and data buses. Advances in some relevant information analysis technologies are discussed later in this chapter.

"Diagnostics" (diagnosis) is defined in ARMP-7 as the detection, isolation and analysis of faults and failures. It is usually viewed as the first step in corrective maintenance. Without the help of specially designed on-board or off-board systems, such as Maintenance Data Recorders (MDR), BIT systems, and ATS, it can be very time-consuming to isolate faults and failures to components that can be repaired or replaced at 1st Line. Often, technicians at 1st Line are unable to reproduce a fault reported by the aircrew or on-board maintenance data system. This is referred to as a "Cannot Duplicate (CND)", "Re-Test OK (RTOK)", or "No Fault Found (NFF)" occurrence. Such occurrences can be accompanied by additional delay, unnecessary component replacements that add cost and reduce spares margins, and an implicit loss of mission reliability.

The CND problem also occurs frequently in electrical and electronic equipment at other levels of maintenance, despite the availability of special ATE. Consequently, Line Replaceable Units (LRU) are sometimes being returned to service with no resolution of the original CND problem. Sometimes, several "rogue" LRU accumulate in the spares pipeline and effectively degrade aircraft reliability. The only way of addressing this situation is either to replace the rogue units with new units, to enhance diagnostic capabilities at all levels of maintenance, and/or to increase the use of on-board diagnostic technologies that are designed into the aircraft and its sub-systems.

Further benefits can be gained by integrating on-board diagnostic functions with on-board self-correction functions that will allow a mission to continue despite failures.

The section aims to describe the improvements in the speed and reliability of diagnosis that can be realised with existing diagnostic concepts and technologies, and how further improvements will be obtained with the development of these and the use of emerging concepts and technologies, such as data fusion. Relevant information analysis technologies are discussed in more detail later in the current chapter.

6.6.2 Advances in Ground-Based Automatic Test Equipment

Recent and planned advances in ground-based Automatic Test Systems (ATS) are exemplified by the US DoD's program in this regard. This was described by Ross in Paper 4.3.2.

6.6.2.1 Background

Ross explains that in the early 1960s, the US Department of Defense (DoD) first defined three levels of repair: depot, intermediate, and organizational. Generally, on-system repairs and maintenance are a function of organizational level units and off-system repairs are generally performed by intermediate levels of maintenance. Intermediate-level maintenance also includes automatic and manual testing, printed circuit board repair, and fabrication or manufacture of some components. Depots perform major overhaul and complete rebuilding of parts. In practice, depot and intermediate repairs for avionics systems are often equivalent since both levels of maintenance use the same or similar testers and test programs.

The single largest problem facing automatic testing in DoD is the proliferation of automatic test equipment that occurred from the 1960s to the 1990s. Typically each new weapon system would develop and field its own set of testers. This led to a situation where there are over 400 different test systems in use across DoD. This proliferation problem led to implementation of DoD-wide Automatic Test Systems (ATS) policy.

The DoD ATS policy states that:

> "To minimize the life-cycle cost of providing automatic test systems for weapon systems support at DoD field, depot, and manufacturing operations, and to promote joint service automatic test systems interoperability, Program Managers shall use approved DoD ATS Families as the preferred choice to satisfy automatic testing support requirements. Commercial Off-The-Shelf (COTS) solutions that comply with the DoD ATS Technical Architecture should only be used if the Milestone Decision Authority concurs that an approved DoD ATS Family will not satisfy the requirement. Automatic Test System selection shall be based on a cost and benefit analysis over the system life cycle."

The policy lists the approved DoD ATS Families (Navy's Consolidated Automated Support System (CASS), Army's Integrated Family of Test Equipment (IFTE), the USMC's Marine Corps Automatic Test Equipment Systems (MCATES) and the US Air Force / Navy Joint Service Electronic Combat Systems Tester (JSECST)).

Also, four goals have been established to guide DoD's way forward as it modernized its ATS:

- Reduce the total acquisition and support costs of DoD ATS;
- Improve the inter- and intra-operability of the Services' ATS functions;
- Reduce logistics footprint; and
- Improve the quality of test.

Joint Service teams are working with industry to define needed interface standards (see Figure 6-42 below) that will help us meet our four "goals" and to develop and implement next generation test technologies. As legacy testers are modernized and the DoD moves to the next generation test systems, the number of tester types will be greatly reduced while inserting or selecting technologies which will make our systems cheaper, faster, scalable, interoperable, more capable, smaller and more mobile.

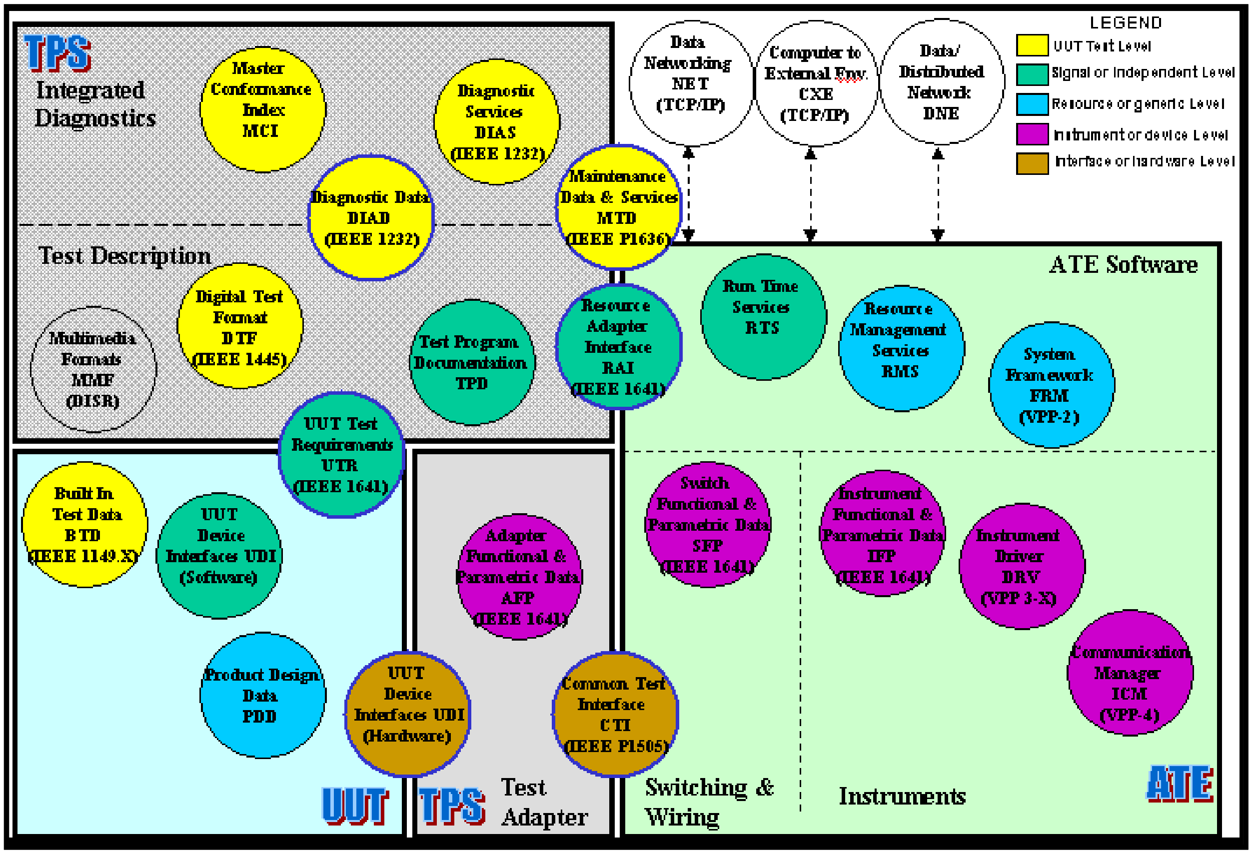


Figure 6-42: US DoD Automatic Test System (ATS) Framework. Note: UUT = Unit under Test (aircraft avionics); TPS = Test Program Set (test software, interface device, cables, and instructions).

6.6.2.2 ATS Architecture Framework

Architecture requirements for all DoD systems, including ATS, are detailed in the Defense Information Technology Standards and Profile Registry (DISR), the replacement for the DoD Joint Technical Architecture. The DoD ATS Framework, Figure 6-42 above, is a mandatory requirement for all DoD ATS acquisitions and contains the key elements and associated specifications and standards that form the open architecture approach for DoD ATS. The ATS Framework currently comprises 24 key elements in various stages of maturity, and will continue to evolve as test technology evolves. A Joint Services Framework Working Group has been established to continually assess the framework and to work with industry and standards bodies to develop and demonstrate the remaining undefined specifications and standards to satisfy ATS Framework requirements.

6.6.2.3 Test Technology Development

DoD's ATS strategy is to jointly develop and insert test technology while leveraging the Research and Development efforts of the Services, industry and coalition Nation partners. The Services work closely with industry through many organizations and consortia. The Joint Service Next Generation Test Technology (NxTest) Team periodically holds test technology reviews with industry, and has developed close working relationships with the ATS leadership in coalition partner countries.

There are two reasons for developing test technologies:

a) To add capability to our test systems to meet emerging weapon system test requirements (the technologies must be four times as accurate as the weapon system component being tested).

b) To replace existing test capability to address obsolescence, improve quality of test, improve through-put, satisfy new operational needs and provide scalable, mobile and smaller testers.

Following are some of these emerging hardware and software technologies being demonstrated and, in some cases, implemented by the Services in DoD. These technologies offer unprecedented opportunities for improvement in warfighter support throughout DoD including improved aircraft readiness and mission reliability.

6.6.2.3.1 Advanced Synthetic Instruments

Test and measurement requirements have been traditionally satisfied with a suite of test instrumentation that required a single test instrument for each type of test to be performed on any electrical/electronic signal. Present day commercial technology allows a signal to be converted into a digital representation that can subsequently be analyzed using high-speed Digital Signal Processing (DSP) techniques to verify the signal's characteristics. This approach to signal characterization is known as synthetic instrumentation, which can be thought of as "software instruments". As a result of implementing Synthetic Instruments, it is now possible to satisfy the signal's measurement requirements with one synthetic instrument thereby eliminating the need for numerous, dedicated, single-function measurement instruments. Synthetic instrument based test systems will facilitate the introduction of new test capabilities via software modification verses the introduction of peculiar new hardware and software. Synthetic Instruments will also allow for scalable systems capable of supporting all levels of maintenance.

Synthetic Instruments eliminate redundant Automatic Test Equipment (ATE) overhead, hardware, and ATE functionality, and create needed instruments/functions via software. For example, the CASS Modernization Program may replace at least 12 existing separate RF stimulus and measurement instruments with a small Synthetic Instrument package.

Synthetic Instrument demonstration programs are currently underway. The expected benefits include at least a 65% decrease in hardware (and associated support costs) and footprint.

6.6.2.3.2 Programmable Serial Bus Test

Current test systems require a separate test instrument card for each bus type used by avionics systems. We are working with industry, which has developed a synthetic Bus Test Instrument (BTI) capable of assuming a wide range of serial bus protocols required in military and aerospace test environments. The BTI possesses built-in "morph-ability" to assume the bus protocol language of serial communications buses used in operational or factory environments. Because it is able to both emulate and test serial buses, it eliminates the need for a broad range of individual, protocol-specific test instruments.

Each BTI has four independent bus modules that support Mil-Std-1553, Mil-Std-1773, TIA/EIA-RS-232, TIA/EIA-RS-422, TIA/EIA-RS-485, H009, ARINC 429, and more. With an innovative load-and-forget programming environment, native support for popular buses, and the flexibility to emulate custom buses or variations of standard buses, each of the four bus modules (channels) provides the option to emulate a wide variety of serial bus communications and test those protocols, at any time.

The expected benefits are a reduction in footprint (5 or more cards are replaced by 1 card) and higher quality tests with increased capability.

6.6.2.3.3 Reusing Diagnostic Data

Emerging software technologies based on a Windows-based operating system and a browser-based Test Program Set (TPS) developer interface using eXtensible Markup Language (XML) technologies will have many benefits, not the least of which is facilitating reuse of diagnostics data. The Automatic Test Markup Language (ATML), a sub-set of XML developed by industry and DoD for test software development, will facilitate improved integrated diagnostics. Standardized XML File Structures, Schemas and Tags will be utilized in a .NET environment as interface control standards between weapon system platforms and maintenance systems for high fidelity interoperability and to pass diagnostics data both up- and down-line.

The new environment will also provide the ability to develop Knowledge-Based TPS using Test Requirements Modelling. These significant software advances open the door to dynamic test strategies to make use of platform maintenance information to direct the flow of activity during TPS execution. Directed TPS will reduce the time to repair by sending the test software to the most likely cause of the failure instead of performing a full end-to-end run. Test strategies can be revised on the fly based on historic and real-time maintenance data.

“Smart” TPS concepts are being developed for improved test program performance. These use weapon system platform Built-in-Test (BIT) data to direct a start point in a test program based on this BIT data and yield a 25% runtime savings. Historical maintenance data captured automatically is reused to improve diagnostics decisions and to reduce fault isolation ambiguity. The Smart TPS project is currently being demonstrated at Naval Air Station Lemoore, California on the F/A-18 APG73 Radar Receiver and Super Hornet Flight Control Computer. Results to date have been promising, and plans are underway to expand Smart TPS to other weapon systems including V-22 and H-60S. The F/A-18 platform has also implemented Smart TPS with Raytheon to support a commercial repair contract for the ALR-67 weapon system.

6.6.2.3.4 Multi-Analog Capability (MAC)

The MAC Instrument sub-system is the technological breakthrough that is allowing traditional ATE to perform as functional testers. A single C-size VXI card provides 32 channels with 6 test instruments behind each test pin. Each of these 32 independent channels can function simultaneously as one of six instruments: function generator, arbitrary waveform generator, digitizer, digital multi-meter, limit detector, and timer counter. Additionally, each channel can share triggering with every other channel. This capability is being introduced into DoD testers with the first application being several F/A-18 units formerly tested on the Intermediate Avionics Test Set which are being rehosted to the Navy’s CASS. The functional test requirement would previously have been impossible to satisfy since CASS is a serial parametric tester. However, with three MAC cards installed, CASS now has 576 instruments that can all be used simultaneously making CASS capable of parallel, functional test.

Although the MAC provides tremendous improvement in parallel processing capability, the traditional analogue instruments cannot be 100% replaced as the current MAC has only 80% range and accuracy of the traditional instruments. An enhanced MAC version that sacrifices pin count for greater range and accuracy has been developed to replace the current MAC.

The demonstrated benefits include a significant reduction in some test program runtimes and a real-time functional test which will yield higher quality diagnostics and improved test verticality.

6.6.2.3.5 High Density Analog Instrument

The High Density Analog Instrument provides a parallel stimulus and measurement capability for high-speed functional and operational analogue testing. It has eight single-ended system-per-pin channels, including up to sixteen 200 MHz universal timers, 50 M sample/second 12-bit digitizers and 50 MHz 12-bit arbitrary waveform generators. It also includes a 6.5-digit digital multi-meter and a 2-channel 500 MHz digital sampling oscilloscope. The High Density Analog Instrument accurately emulates complete system-level operation of the traditional test instruments.

Since this single card can completely replace several traditional instruments on a card, the expected benefits are significantly reduced test times (parallel testing) and reduced footprint.

6.6.2.3.6 Common Tester Interface (CIT)

An Industry/Government Working Group is developing a common standard pin map for the physical mating of the interface device to the automatic tester. Specification requirements include scalability, frequency coverage from DC to light, cost, reliability, etc. An IEEE standard P1505 is in process.

The key benefit of implementing the CTI is that it for the first time could provide a standard test system interface to help effect interoperability across DoD testers. The CTI is scalable, allowing a smaller interface on smaller systems while allowing the smaller test system's test program adapter to interface with a larger test system using CTI.

6.6.2.4 System-Level Demonstration

The Agile Rapid Global Combat Support (ARGCS) Advance Concept Technology Demonstration project is demonstrating most of the test technologies discussed above in a combat support system that will provide electronic systems support at all levels of maintenance. ARGCS can be used to test, troubleshoot, and repair a wide range of digital, radio frequency, analogue, and electro-mechanical units. The concept is a DoD-common core system using common control and support software with complementing/augmenting power, and stimulus and measurement hardware as necessary to meet specific test and diagnostics requirements. Integrated diagnostic feedback capability will be included so that diagnostic data captured during the maintenance cycle can be reused.

Reconfigurable and scalable, ARGCS will be easily and quickly deployable worldwide with reduced airlift and logistics footprint requirements. A key performance parameter will be interoperability among weapon systems of not only the US Services but also those weapon systems used in coalition partner Nations. At the completion of the ARGCS development effort, the system will be evaluated starting in April 2007 as part of the Joint Military User Assessment and the End User Evaluation.

6.6.2.5 An Example: The US Navy Story

The Consolidated Automated Support System (CASS), the Navy's standard automatic test systems family, is being fielded to replace over 30 legacy automatic testers. Analysis shows that CASS will bring a reduction in Total Ownership Costs of US$3.8 billion. To date, CASS has fielded over 600 mainframe testers and will ultimately support almost 3,000 Navy and Marine Corps avionics and electronics units. The CASS program was initiated in the early 1980s in response to many problems with automatic testing identified by a special study team chartered by the Secretary of the Navy. The actual design of CASS dates from the mid- to late-1980s. The initial CASS stations were ordered in 1990 and CASS entered the fleet in 1994. The last of the

613 production Mainframe CASS stations was ordered in 2002 and delivered in December 2003. The initial CASS stations are 15 years old. Modernization of the early CASS stations is driven by several factors including instrument age and associated obsolescence, condition of the station infrastructure (rails, wiring, etc.), inflexibility of the architecture, and emerging test requirements that cannot be economically satisfied by the current CASS station configurations.

Goals of the CASS Modernization Program, called eCASS, include incorporating the test technologies needed to satisfy weapon system testing and operational requirements, implementing a modern open architecture based on the DoD ATS Architecture Framework to facilitate future upgrades, ensuring that test programs are fully transportable, providing for interoperability with other Services, and reducing ownership and obsolescence costs. The Navy's vision for eCASS is that it will have a much smaller footprint with more test capability; have faster run times; implement multi-lingual test environments; facilitate factory-to-field use of test software; be interoperable with other Services' ATE; be more scalable to needs; reduce acquisition and support costs; implement the "Smarter" diagnostics concepts; provide faster and better diagnostics; and reduce the "no fault found" rate.

Figure 6-43 illustrates the past and future development of the US Navy's ATS.

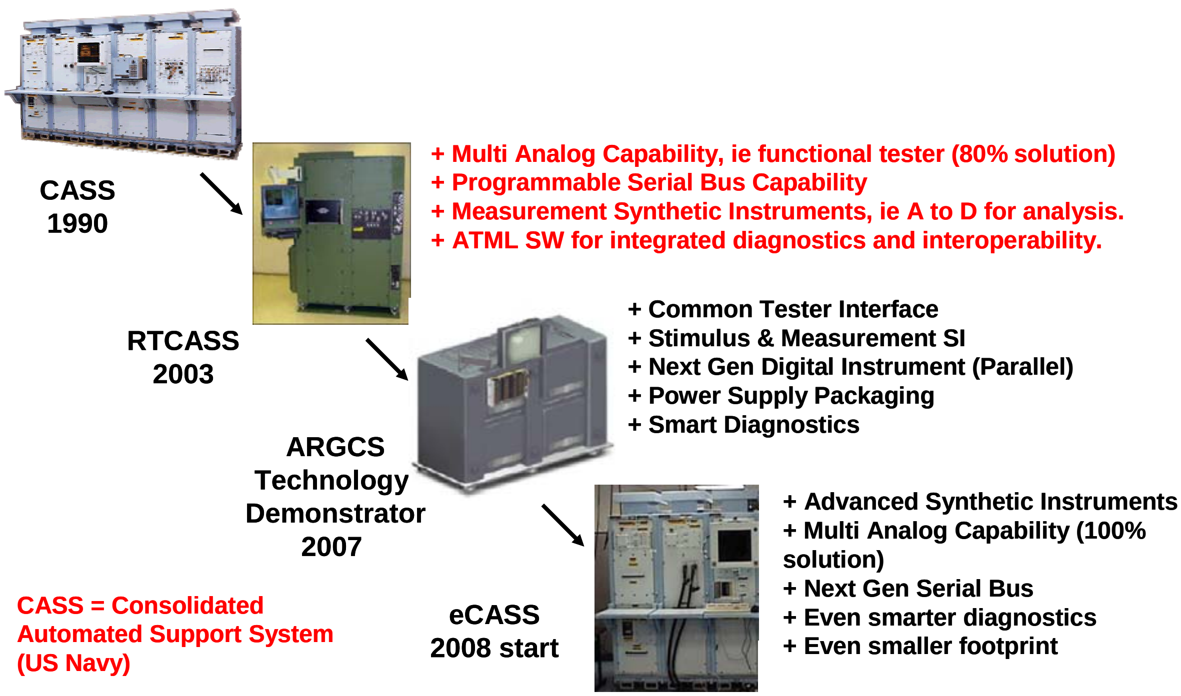


Figure 6-43: Past and Future Development of ATS in the US Navy.

6.6.2.6 Impact of the Test Technology Developments on Weapon System Readiness

In addition to satisfying DoD's four main ATS goals (reducing ownership costs, facilitating interoperability, reducing footprint, and improving the quality of test), the test technologies discussed in this paper improve weapon system readiness by reducing the turn-around time for off-system repairs. Mission reliability will be improved because the new test technologies will enable the next generation testers to provide a more thorough verification of system readiness. Since many test instruments will be replaced by a few synthetic instruments, the new testers will be smaller and have fewer test assets. This will lower acquisition and support costs and reduce logistics footprint, enabling the systems to be more easily be transported where needed world-wide.

6.7 AUTOMATED INSPECTION AND DIAGNOSTICS FOR MECHANICAL SYSTEMS, STRUCTURE, AND ENGINES

6.7.1 Introduction

As with electrical and electronic LRU, the downtime and cost associated with replacing and repairing mechanical LRU, such as flight control actuators, brake systems, flight control surfaces, and some airframe structure at 1st Line can be substantial. The downtime may in general be greater than with electronic LRU, because of the more complex interface with the aircraft and difficulties of access. The implications for availability and cost are potentially greater with engines. Therefore, fast and accurate on-aircraft diagnosis of failures and anomalies at 1st Line is important.

An overview of the current capabilities and future potential for automated inspection and diagnostics for mechanical systems and structure in general is provided by Schmidt in Paper 4.4.3. The scope for using advanced inspection and diagnostic technologies in the design of new engines is illustrated in Paper 4.4.1 by Massé, which deals with the M88 engine in the Rafale fighter. The scope for inserting advanced diagnostic technologies in an ageing fleet of engines is described in Paper 4.4.2 by Wicks, which deals with the PW TF30 engine in Australian F-111 aircraft.

6.7.2 Overview of Automated Inspection and Diagnostics for Mechanical Systems and Structure

6.7.2.1 Introduction

There are a variety of methods to improve the diagnosis of mechanical systems. Many of these methods can be applied to aircraft already in service, while others require the diagnostic tools and sensors to be designed-in at the beginning stages of the system development. These diagnostic tools and techniques fall into essentially three categories: data fusion methods, retrofitable troubleshooting systems, and fully integrated sensor suites. The objective of each system is slightly different, but the overall thrust is to increase the availability of the aircraft, and to reduce the amount of maintenance time required to keep the aircraft in a ready state.

6.7.2.2 Data Fusion

Data fusion methods, or statistical fleet monitoring approaches involved using software and database systems to archive and analyse recorded data from each aircraft in a specific fleet. These concepts are currently applied in the civil aviation arena as FOQA (Flight Operations Quality Assurance) and MOQA (Maintenance Operations Quality Assurance). Data from the aircraft flight data recorder or quick access recorder is downloaded, stored and analysed by a central system. Historical trends can be produced and exceedences can be captured. There are a variety of companies offering systems to perform this analysis. Among the leaders in this market is Sagem Defense / Securité with their Analysis Ground Station (AGS) suite of products. The AGS system handles the downloading, archiving, analysis, and reporting on a fleet of aircraft. Using technology developed through a NASA research effort, the AGS is capable of running complex heuristic analyses on data to highlight not just pre-set limits, but also to spot anomalies. This functionality is called the '*morning report*' and it is an important tool to spot early warning signs of impending system failures.

An alternative system is offered by SAAB Avitronics (formerly Aerospace Monitoring Systems Pty.). Their ground station is uniquely configurable to work with a variety of data recording devices. While the Sagem DS offering is aimed at FOQA and MOQA, the Avitronics ground station incorporates the capability to perform structural analyses and fatigue damage counting. Their ground station (and associated data recorders) is in service with a variety of BAE Systems Hawk fleets.

Ground analysis systems can be put in place for aircraft that have some form of downloadable recorder. The usefulness of the resulting data analysis will, of course, depend heavily on the measurement parameters available. Retrofit data recording systems are available that record information present on aircraft data busses (Mil-Std-1553, ARINC-429, etc.) These vary from the Aircraft Condition Monitoring System (ACMS) by Sagem DS which offers a full suite of measurement capabilities to the Avionica miniQAR, which is a palm sized data bus recorder.

Trending and analysis of existing data can provide significant maintenance benefits. In the civil aviation world, Federal Express was able to reduce maintenance costs on their fleet of A300 aircraft by using an ACMS system to detect slat system mis-rigging. Highlighting the mis-rigged configuration early on allowed a savings on the order of millions of dollars per year.

Innovative analysis techniques looking at the large quantities of data already generated on aircraft can lead to signature detection, and the ability to identify failing components before they compromise flight safety and mission availability. The National Research Council of Canada has performed work in this area. In addition, the Morning Report analyses developed by NASA and exploited by Sagem in their ACMS include some aspects of this functionality.

However, some systems may not have appropriate sensors currently installed on the aircraft. In some instances, it may be helpful to retrofit sensor systems to allow for improved maintenance.

6.7.2.3 Retrofitable Troubleshooting Systems

There are two sub-categories of retrofitable systems: those that meet an ongoing maintenance need, and those that are employed to solve a short-term problem.

One area where a recurrent, ongoing maintenance need can be alleviated through a retrofit system is the landing gear shock strut. Most aircraft employ an oleo-pneumatic shock strut (air spring and oil damping). These systems require frequent pressure checks with manual comparison against a servicing chart. These single point checks (so-called because they involve simply checking the air pressure at one shock strut position) do not reveal if oil has been lost in the shock strut. To complete a full servicing check, the aircraft must be jacked, and measurements be taken at two positions of the shock strut. This is a time consuming approach. The addition of shock strut measurements – pressure, temperature, and position, and a recording system to take measurements both in flight and on the ground, can alleviate the requirement to perform any manual inspections on the shock struts.

The changing economic environment for operators, one where there is significant pressure to reduce total cost of ownership, and to reduce lifecycle costs, presents an opportunity for service state monitoring systems to be designed into landing gear offerings. The airframe manufacturers are beginning to see the benefits of this concept – the Airbus A380 has some shock strut monitoring capability and Airbus intends to include full monitoring capability on its new widebody airliner.

Internal studies conducted at Messier-Dowty Inc. have indicated that an operator of a regional aircraft could expect to save 180 hours over the life of the aircraft just by eliminating the need to perform annual dual point servicing checks. Significantly more regular maintenance is reduced by automating line pressure servicing checks.

Technically, there are several approaches that could be followed to determine the shock strut service state. For any oleo pneumatic, single state shock strut there are four important parameters – nitrogen pressure, oil volume, temperature, and shock strut position. Mathematically, the simplest approach would be to measure all four parameters. This would allow an instantaneous assessment to be made as to the appropriate servicing state. However, there are several design considerations that make this approach less than ideal. Having four sensors means high cost. The oil volume sensor, by design, must be internal to the shock strut – making field repair impossible, and requiring an additional hole to be drilled in the shock strut wall (for the extraction of the measurement wires).

An alternative approach is to include the element of time in the measurement. In this system, the oil volume sensor is not included, and two measurements (at different shock strut positions) are made. The simplest approach is to make one of these measurements prior to landing, and the second once the shock strut has settled (potentially at the gate).

This “two-point” method allows the shock strut state to be determined reliably with conventionally available sensors. Particular attention needs to be paid to the maintainability of these systems – if the system is not rapidly repairable, or requires the aircraft to be removed from service, then the value to the operator is significantly reduced.

Monitoring systems analogous to the shock strut servicing system can be applied to aircraft hydraulic systems, accumulators, and compensators.

There are often occasions when a short-term, or unexpected problem occurs that necessitates an on-going inspection, such as a structural inspection. These inspections may be of a crack detection nature, employing eddy current probes, ultrasonic inspection, or other non-destructive inspection techniques. In order to alleviate the inspection requirements somewhat, it may be possible to permanently attach the NDT probe in the problem location. Alternatively, newer NDT methods such as Jentek Sensors Inc. MWM sensor technology may lend itself well to permanent mounting.

When cracks occur in service, it may be desirable, as part of an aircraft structural integrity programme, to determine what the actual fatigue loads on the structure are, and to relief the part accordingly. This can be done using existing HUMS or data recorders if the channels of interest are already recorded, or if spare channels exist that can be added to the recorder.

In those cases where additional channels cannot be added, it may be desirable to use a stand-alone data logger to collect data from the area of interest. Messier-Dowty’s Strainlogger technology, a battery powered, flight qualified data logger is designed for exactly such an occurrence. The Strainlogger is useful where no connection to the aircraft electrical system is desired (for ease of installation, and de-installation) and where short-term (on the order of months) recording is required across a sample of the fleet. Features in the Strainlogger systems, such as removable battery / memory modules allow rapid servicing of the recorder unit by minimally trained personnel. Output from the Strainlogger is a strain vs. time history for each channel measured.

Where longer-term structural life monitoring is required, an aircraft powered recorder is recommended.

In moving aircraft structure from an intensive maintenance inspection regime to a monitored, on-condition regime, the certification basis of the structure needs to be considered. Older airframes, and major components of new aircraft (such as the landing gear) are certified using *safe life* criteria. New aircraft are predominantly design using *damage tolerant* approaches. In the former, no cracks are permitted in the structure. Structural monitoring of safe life structure is essentially limited to measuring strains or loads in the components and then performing fatigue life computations. Monitoring of damage tolerant structure offers a multitude of possibilities all geared towards the measuring of crack length.

There exist several crack detection technologies, both flyable and ground inspection based non-destructive test means. Recent developments in NDT technologies have improved the probability of detection of small cracks and corrosion.

Jentek Sensors Inc. of the United States is actively marketing and developing a ground-based NDT system utilizing an array of Meandering Winding Magnetometers (MWM). Significant modelling capability and sophisticated software allow portions of airframe and equipment to be scanned with the MWM arrays to measure material conductivity (or permeability in permeable materials). The system can rapidly display full colour two dimensional plots of scanned areas, highlighting discontinuities – crack locations. Jentek is involved in a research program to develop their technology for in-flight use. The technology is already in use for specific inspections with United States forces.

For in-service determination of crack growth, the Comparative Vacuum Monitoring (CVM) system, mentioned earlier, is attractive from a practical point of view. A moulded silicon patch is placed over a crack (or suspected crack) location. Small alternating channels moulded into the silicon patch are connected to either atmosphere or an accurate, metering, vacuum pump. The existence of a crack will allow air to flow from the atmospheric channel to the vacuum channel. Larger cracks allow more airflow, and so it is possible to determine the crack size and crack growth with time. The patches are essentially inert, and the tubing to each patch is relatively small, light, and easily routed. CVM systems would not normally be monitored in flight, but would be used to alleviate a more intrusive NDT inspection.

Ultrasonics can be used to monitor structural assemblies as well as discrete components. Direct signal/echo methods are routinely used for the detection of cracks and inclusions. More advanced ultrasonic technologies are under development for detecting fatigue cracking and battle damage in structural assemblies during flight.

6.7.2.4 Fully Integrated Sensor Suites

The concept of fully integrated sensor suites is now coming to fruition in aircraft like the F-35 JSF. Disparate sensors, each suited to their specific task, are connected to the aircraft databus and a central diagnostic system. The aircraft is able to assess damage, faults, and inconsistencies and recommend to the pilot or maintenance technician an appropriate course of action. This might include operating the weapon system with reduced capability.

New algorithms and new sensor systems are being developed to expand on-board inspection and diagnostic capability. Their application has to be based on a cost-benefit analysis. The full potential of such systems can only be realised when the appropriate infrastructure is established to compare and contrast data across a fleet and provide timely and correct information to maintenance personnel.

6.7.3 The Application of Advanced Diagnostics in the Engine of the Rafale Fighter

The diagnostic system on the SNECMA M-88 engine for the Rafale fighter was described by Banet, Brouse, and Massé in Paper 4.4.1. This system is integrated with condition monitoring and prognostic systems. These systems work together to reduce maintenance downtime and improve mission reliability.

The integrated maintenance system on the M-88 is referred to as the Engine Condition Monitoring System (ECMS), and has two parts, as shown in Figure 6-44. One part is referred to as the O Level (Operational/ Organisational) and the other as the I Level (Industrial/Intermediate). In O Level there is on-board diagnosis, and ongoing diagnosis and prognosis. In I Level there is the capability for complementary tests, performed without a test bench and with the engine turned off. The tests include fuel leakage tests, fault localization tests, control loop tests (e.g. inlet air control system), tests of the anti-icing vane, tests of the fuel flow meter, etc.

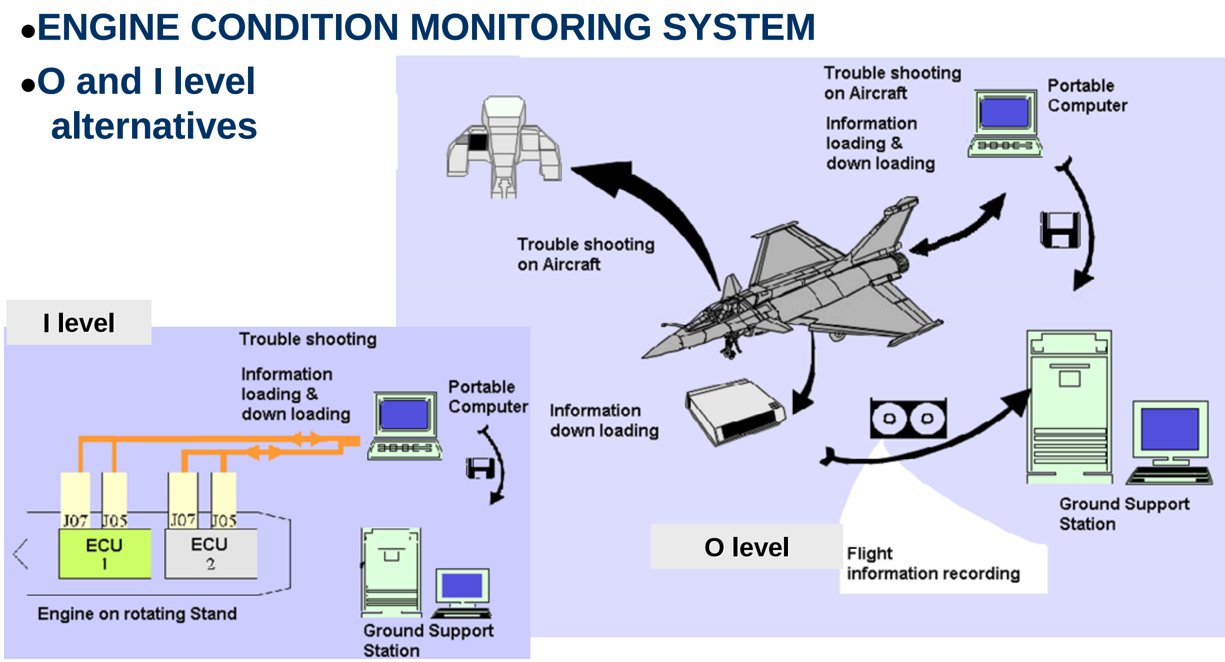


Figure 6-44: Integrated Maintenance Concept for SNECMA M-88 Engine in the Rafale.

Some ground support equipment for transportation, rotation, and complementary testing are shown in Figure 6-45.

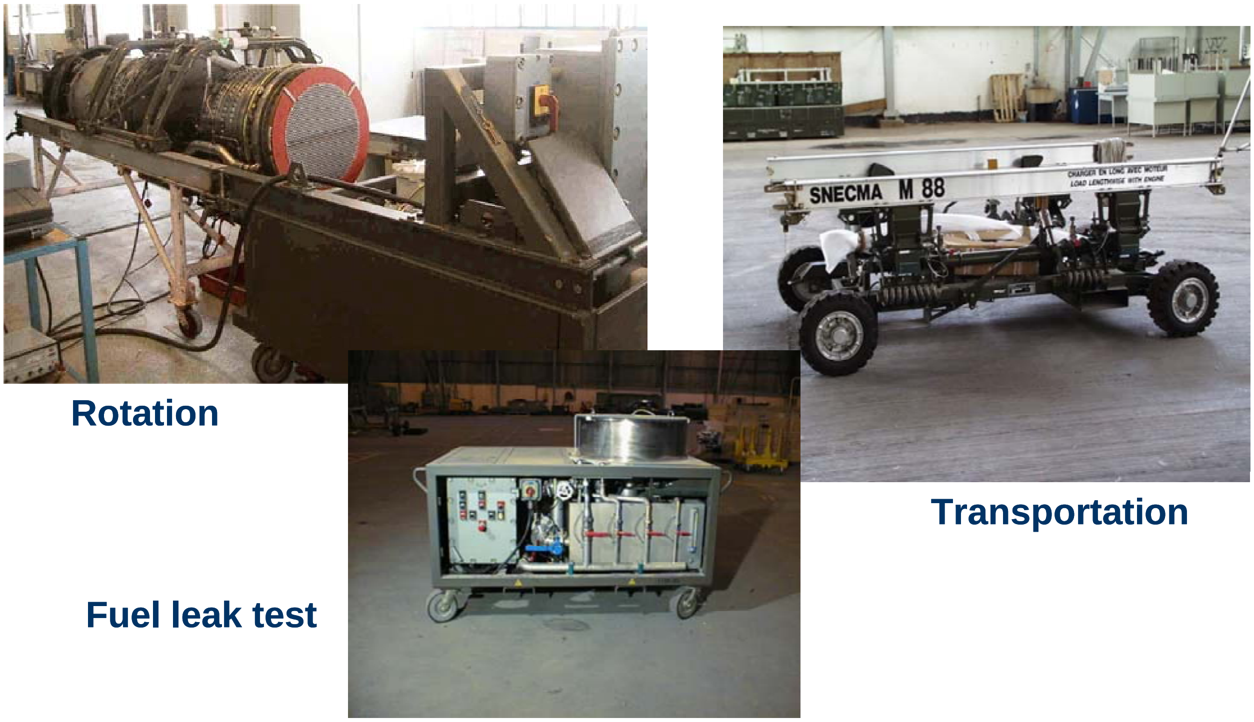


Figure 6-45: I Level Ground Test Utilities for Trouble Shooting.

On-board diagnosis uses the same sensors as those for engine monitoring (Figure 6-46). There are a few sensors for vibration surveys, which are very useful for anticipating bearing distress. Periods of inverted flight are also recorded, because these are detrimental to the lubrication of the bearings. There are also electrical oil and fuel filter-clogging indicators.

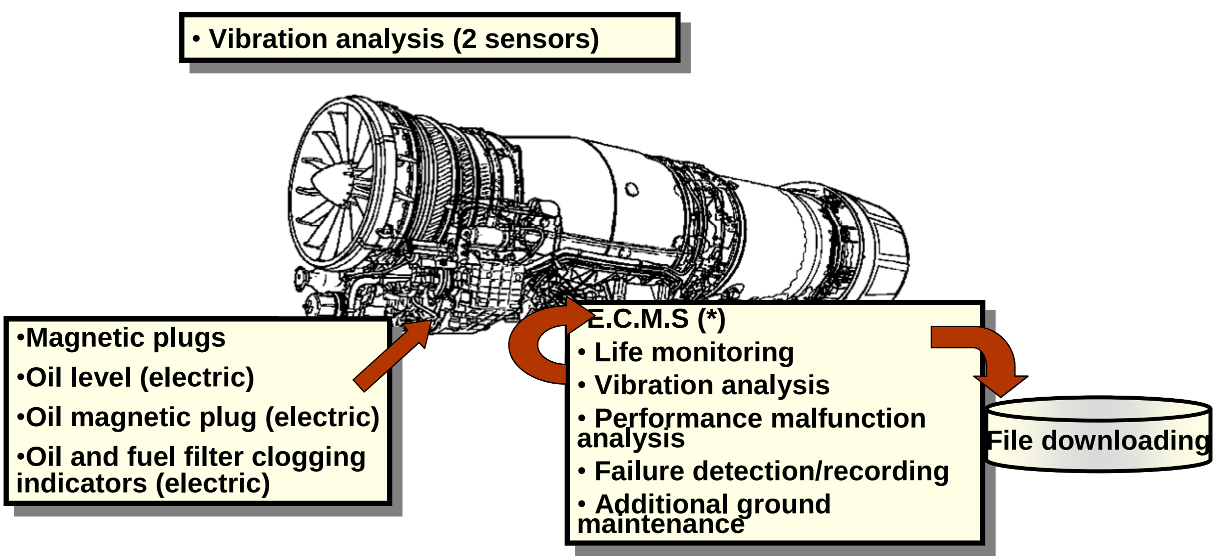


Figure 6-46: On-Board Diagnosis – Specific Sensors and Indicators in Addition to Engine Controls.

There is a comprehensive set of in-flight tests. For example, accelerometers are used to monitor balance of the HP and LP rotors through vibration responses filtered by rotation speeds. Imbalance triggers an alarm after a few seconds of corroboration.

The system incorporates usage monitoring. This is crucial on a fighter, because the stresses from one flight to another may vary by a factor of 80. The usage data includes flight hours, the number of post combustion lightings, and the number of engine starts. The data is used in models of general fatigue, high cycle fatigue, and crack propagation. Those models then calculate the remaining life.

The M-88 also features some performance malfunction analysis. Various malfunctions are recorded for this purpose. They include start sequence anomalies, such as overheating, stall, and slow start. They include other performance anomalies such as long rotation, turbine overheat, electronic control unit overheating, compressor stall, HP or LP shaft overspeed, and post-combustion anomalies. To minimize false alarms, there are two monitoring channels, which are continuously compared. If necessary, other data is used to resolve discrepancies between channels. If there is a control loop malfunction, a snapshot of all data at the moment of the event is recorded.

For full prognosis (estimation of remaining life), Snecma's SIAD system is interfaced with Dassault's HARPAGON ground-support system (Figure 6-47).

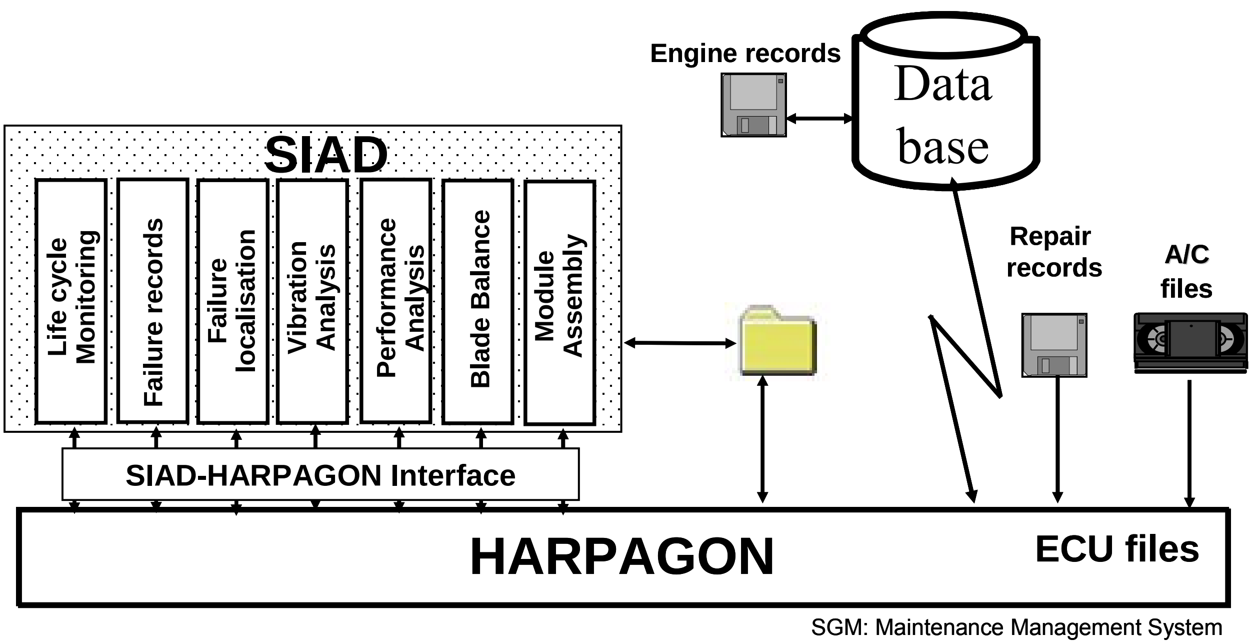


Figure 6-47: HARPAGON Ground Support Station.

HARPAGON also performs additional analysis of failure, vibration, usage, and performance data. In Figure 6-48 there is an example of output data that indicates some imbalance on the low-pressure rotor.

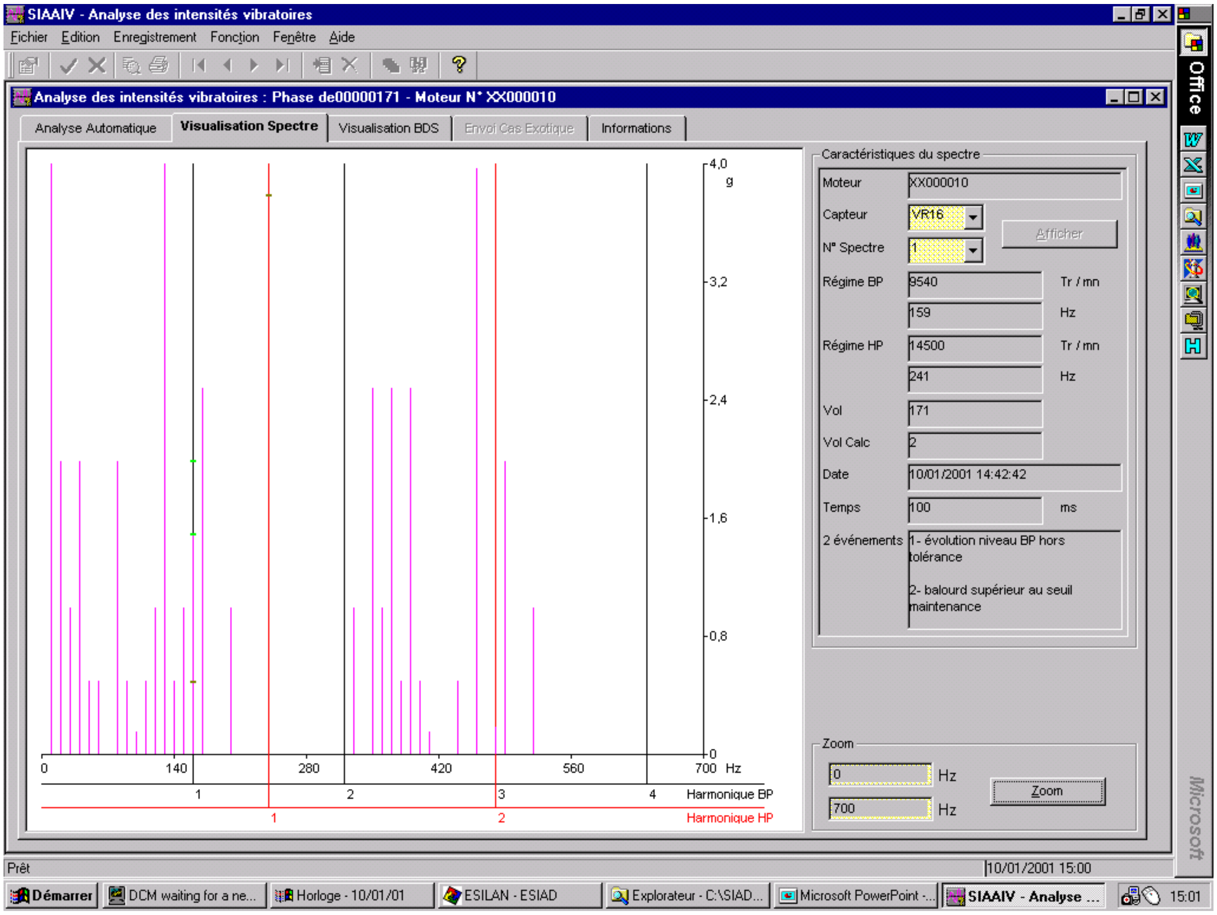


Figure 6-48: Example of Analytical Output from Dassault's HARPAGON, Showing Imbalance in the LP Rotor.

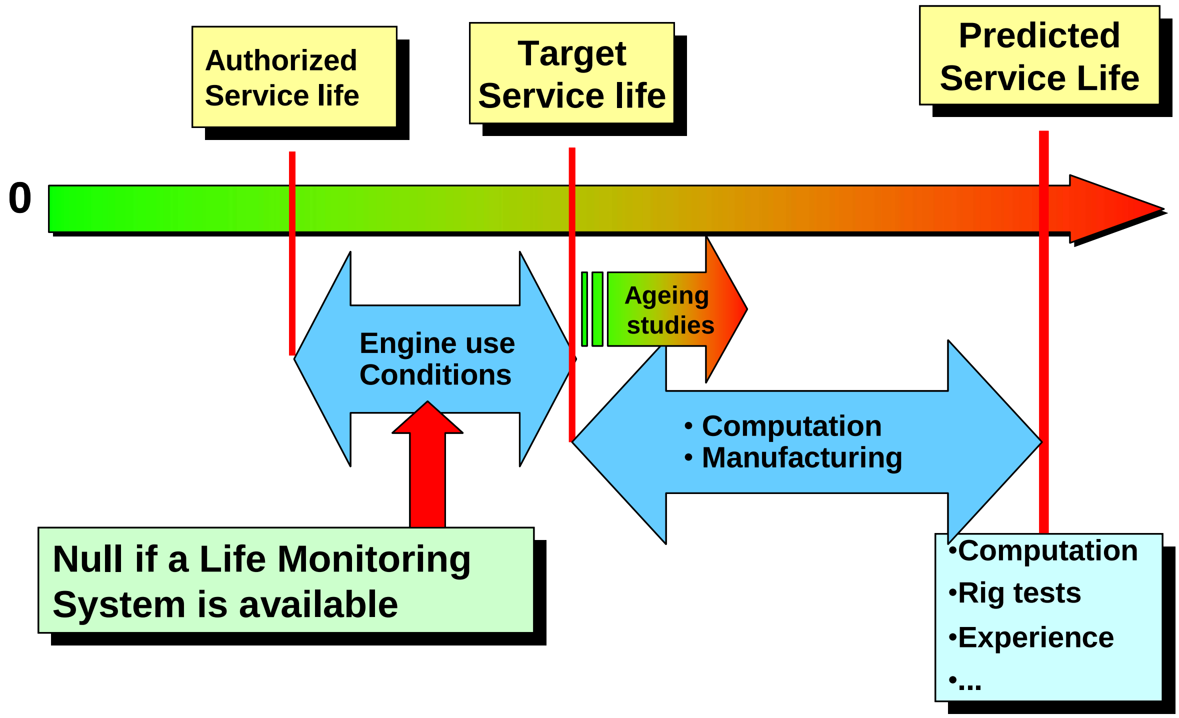


Figure 6-49: Downtime Reduction by Extending the Useful Lives of Engine Components.

It also allows the Time Between Overhaul (TBO) of components to be increased (Figure 6-50). This in turn provides the flexibility to increase the installed time of the engine and/or manage the maintenance of the engine and its modules so as to optimize aircraft availability and life-cycle cost.

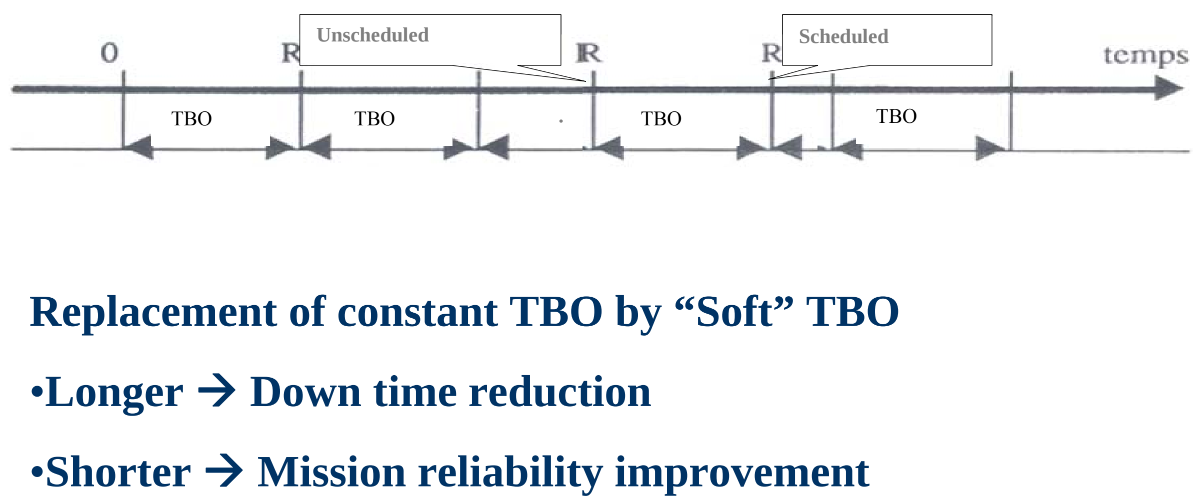


Figure 6-50: Reduction of Downtime and Improvement of Mission Reliability.

6.7.4 The Insertion of Advanced Diagnostic Technologies in an Ageing Fleet of Engines

6.7.4.1 Introduction

This section is based on Paper 4.4.2 by Wicks. It presents a case study of the way in which technology insertion into a legacy engine – the PW TF30 engine in the F-111 aircraft – together with an active program by the engine operator to benefit from the technology, can have a dramatic effect on engine support costs and availability.

6.7.4.2 Background

The Pratt & Whitney TF30 engine was the first turbofan engine to be installed in a supersonic bomber, and the first turbofan to be fitted with an augmented afterburner, with development occurring as early as 1958. The engine is a two spool low by-pass turbofan with a mixed flow exhaust. The fan and low pressure compressor are driven by a 3 stage low pressure turbine, while the high pressure compressor is driven by a single stage high pressure turbine.

The planned retirement date of the aircraft has varied over the last ten years. Current plans are to phase the aircraft out between 2010 and 2012. Although the main problems have centred on the airframe, rather than on the engine, studies were carried out to reduce the maintenance cost and to increase the reliability of the engine to a flexible withdrawal date that could extend to 2020.

Two Pratt and Whitney TF-30 turbofan engines are installed in the F-111 aircraft. Most engines have been upgraded to TF30-P109 RA standard. At basic engine power (non-afterburner) the engine will produce thrust of approximately 10,000 lbf. Conventional turbo-jet engines of this same thrust class require approximately 9,000 to 10,000 lb per hour fuel flow, but the TF30 consumes only about 6,500 lb per hour.

6.7.4.3 The Early History of F-111 and DSTO Involvement

Designed in the 1960s, the F-111 aircraft was manufactured by General Dynamics (now Lockheed Martin) in Fort Worth, Texas, throughout the late 1960s and early 1970s. Featuring variable sweep wings, the aircraft has the ability to operate low level, day or night, in all weather conditions, carrying a large payload over a long range, as well as being capable of speeds up to Mach 2.5. Some 562 aircraft were manufactured. Australia was the only country other than the USA to purchase the F-111, and when the USAF retired their last aircraft in 1998, this left the RAAF as the sole operator.

At this time the benefits of shared operation that the RAAF had enjoyed over the previous twenty four years disappeared and the sole responsibility for technical airworthiness of this weapon system fell upon the logistics system of the RAAF. The program that defined the way the platform was supported in this environment was dubbed the F-111 Aircraft Structural Integrity Sole Operator Program (FSOP).

The significance of USAF F-111 withdrawal must be fully appreciated with respect to RAAF structural integrity management of both the airframe and the engine. Sole responsibility for the F-111 ASIP and ESIP became the responsibility of the RAAF for what could be the next 22 years (almost half the life time of the aircraft). Up until then OEM support, shared responsibility with the USAF, and the relative low airframe hours (AFHRS) of the fleet enabled airworthiness of both airframe and engine to be held at an acceptable level without large investments structural integrity assessments. The objective of the FSOP was to develop a road map for the progression of the structural integrity in such way that ongoing technical airworthiness was assured.

For the TF30 engine, DSTO and industry developed the ability to analyse and assess the service life of gas turbine engine components, including those subject to low-cycle, high-cycle and thermo-mechanical fatigue, creep, and thermal distress. This in turn required the coordinated development of scientific capabilities and models for, mission profile analysis, engine gas paths analysis, thermal analysis, stress analysis, fracture mechanics and risk/reliability analysis. These were all complemented by appropriate experimental validation facilities. In addition there was a need to develop and support of life extension strategies for short-life components, with an emphasis on the engine hot section. In addition, an assessment was needed of retirement-for-cause methodologies for application to the management of critical components.

6.7.4.4 RAAF F-111 Fleet Sustainment

Since the mid 1990s the RAAF F-111 fleet time indicators in maintenance, availability and cost took a turn for the worse. There were many coincident contributors: fuel leaks, OH&S issues, block upgrades, fleet wing doubler failure and WOM development, support project activity, contracting out of maintenance, and finally the wing recovery program and the increasing cost of maintaining an ageing engine.

On the engines side, efforts to improve availability and reduce costs included developments like the maintenance interval extension of the RA engine and the improved software for the engine test-cells will likewise reduce support costs. The engine diagnostic software has, in part, resulted in engines staying on wing longer due to optimum trimming of the fuel controls, and also provides improved diagnostic information prior to maintenance, avoiding unnecessary repairs. These activities, together with the engine Reliability, Availability, Maintainability (RAM) program developed by the TF30 Engine Business Unit (EBU), have resulted in significant improvements in engine reliability and reduction in maintenance costs. As an example, in-flight shutdowns have decreased from 5 to 0.3 per year, while costs have decreased form A$30 million per year (prior to 1990), to A$20 million per year.

Upgrades to the engines over the years have included:

- Engine and fuels system modifications to extend the time between overhauls:
  - The use of a Thermal Barrier Coating (TBC) to reduce metal temperatures;
  - Structural modifications to the combustor liner; and
  - The use of a thermal additive in the fuel.
- The introduction of a TF30 Engine Monitoring System, primarily to analyse usage and provide some capability for condition assessment of individual engines.
- A reassessment of the durability of specific critical engine items through an Accelerated Mission Test (AMT) using a simulated RAAF mission.
- An increase the bay service life of TF30 hot section components from 800 hours to 1000 hours and the overhaul lives from 1500 hours to 2000 hours using durability enhancements such as thermal barrier coatings.
- A fleet leader program for the engine which will identify failure modes in the fleet leader engine before they occur in the fleet.

6.7.4.5 Introduction of On-Condition Maintenance in Place of Hard-Time Overhaul

In the early 1990s the RAAF started a concerted effort to shift TF30 engine maintenance from a hard-time overhaul philosophy to an on-condition policy named the “Condition Monitored Maintenance (CMM)” policy [163]. The CMM approach aimed to improve engine Reliability, Availability, and Maintainability (RAM). In support of this approach, and to facilitate its implementation, DSTO undertook the development of a number of diagnostic systems for the TF30 gas turbine engine. Different diagnostic systems were required as the gas turbine is a complex mechanical system and no single technology or methodology can provide all the answers.

Three diagnostic systems are described below. These are:

- The Engine Diagnostic and Acceptance System (EDAS) for troubleshooting and acceptance testing at the test-cell;
- A set of advanced Gas Path Analysis (GPA) methods for diagnosing faults to a modular level at the test-cell; and
- The Interactive Fault Diagnosis and Isolation System (IFDIS) for troubleshooting engine faults at the flight line.

6.7.4.6 Diagnostic Requirement

There is demonstrable benefit in terms of cost-efficiency of the repair and overhaul process in having a capability to correctly identify and isolate the faults in the TF30 engine to a modular level. The six TF30 modules are: the fan, the low and high pressure compressors, the low and high pressure turbines, and the nozzle. Correctly attributing the fault to the right module can bring about major cost savings and improved engine availability [164]-[165]. These benefits are demonstrated by the relative cost and time involved in repairing the TF30 modules. The typical cost and time impact of a compressor module repair is twelve times that of a fan module repair and a turbine module repair is four times that of a fan module repair. Clearly, for the TF30 engine, the major benefits arise from correctly attributing the fault to either the fan or a turbine module in preference to a compressor module; or in other words, from not falsely attributing the fault to a compressor module.

The correct diagnosis of TF30 faults requires the application of a number of different technologies and methodologies. These include the use of fibre-optic bore-scopes, oil debris and condition monitoring, vibration analysis, gas path analysis, and fault-tree troubleshooting of engine controls and accessories by artificial intelligence. Indeed, there is little overlap in the type of faults diagnosed by these techniques; each has its own niche. This is illustrated in Figure 6-51 where the causes of unscheduled maintenance are matched to appropriate diagnostic techniques. DSTO's program of work on-conditioning monitoring is addressing most of these techniques, including vibration analysis [166], but only the progress on diagnosing gas path faults and troubleshooting control and accessory faults is reported here.

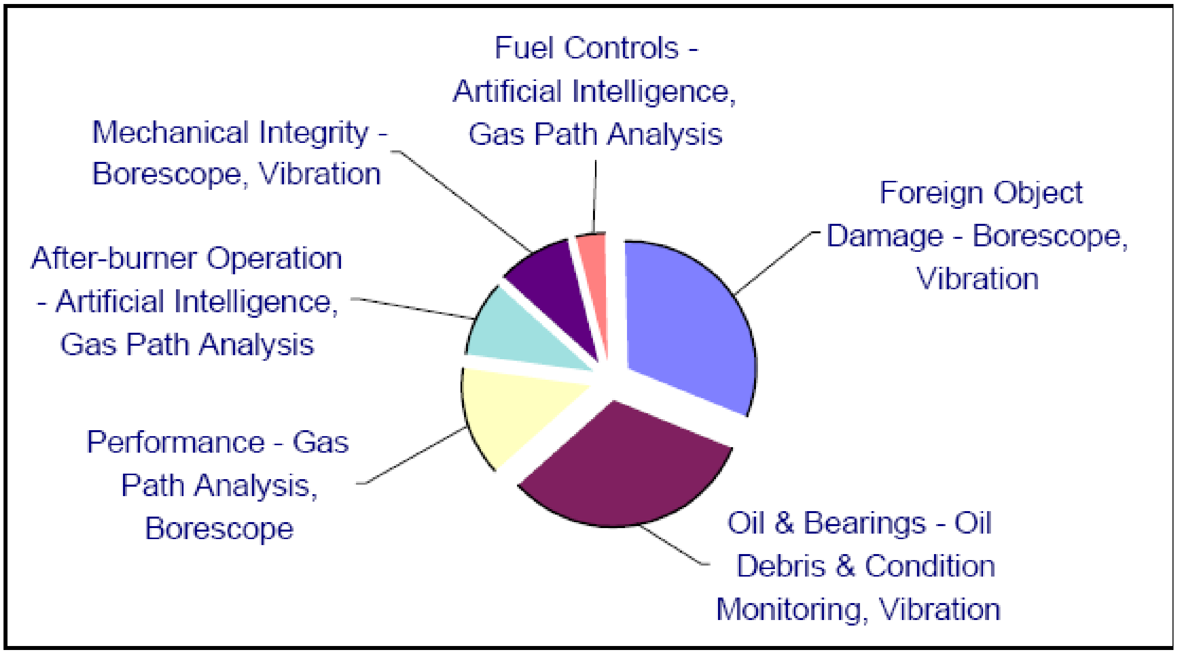


Figure 6-51: Causes of Unscheduled Maintenance and Appropriate Diagnostic Techniques.

6.7.4.7 Engine Acceptance Testing Using EDAS

In the mid-1990s, the RAAF sought to refurbish and modernise the engine test-cells at RAAF Amberley. In response to this requirement, DSTO developed an affordable PC-based system for the repair and overhaul testing of the TF30 engine. Called the 'Engine Diagnostic and Acceptance Test System (EDAS)' [167], it was installed in 1996. EDAS has since been in day-to-day operation with the RAAF, supported by industry. Overall, EDAS has improved the efficiency of the test acceptance process and produced major cost savings.

EDAS is a Windows-based program written in Microsoft Visual Basic [168]-[169]. It operates on two separate Personal Computers (PC), with one PC in Engine Operator mode and the other in Test Analyst mode. Both PC acquire a standard suite of 39 test parameters at 32 Hz. In the Engine Operator mode, EDAS ensures the safe operation of the TF30 engine by displaying to the operator all the test parameters on one PC Monitor. Hence, with this one PC screen, EDAS has replaced all the old gauges and eliminated the need to support them. In the Test Analyst mode, the EDAS menu guides the analyst through the acceptance test schedule with EDAS performing the required calculations, displaying the results on the PC screen and sending the accepted test values to an Excel Spreadsheet for reporting on and archiving the results of the test runs. This PC menu-based process has reduced the time to test engines by almost a half.

The current configuration of EDAS provides a basic diagnostic capability in terms of functional checks and troubleshooting. As well, EDAS has enabled the comparison of engine performance between different Engine Test Cells as a result of the improved accuracy of the recorded parameters. Previously, this comparison was not viable due to the uncertainty in the manually recorded data. In 1998, a program was undertaken to enhance the diagnostic capability of EDAS by developing a range of advanced gas path analysis techniques to address the problem of diagnosing engine condition to modular level. EDAS provides the major prerequisite for the use of such techniques – accurate measurements of the engine gas path parameters.

6.7.4.8 Modular Diagnostics Using Gas Path Analysis

Gas Path Analysis (GPA) serves a different role to the other main Health Monitoring Technologies of Vibration Analysis (VA) and Oil Condition Monitoring (OCM). VA and OCM attempt to diagnose events that lead to a catastrophic failure of an engine component, and so have a safety or airworthiness impact. On the other hand, GPA attempts to diagnose events that lead to graceful degradation in the function of the engine, and so have a performance or mission-worthiness (mission reliability) impact.

Gas Path Analysis (GPA) seeks to diagnose the loss of engine condition due to various causes, including:

- Eroded, corroded and fouled blades and vanes.
- Tip clearance changes.
- Turbine blade untwist and bowed vanes.
- Bleed and air-seal leaks.
- Mis-scheduled variable geometry.
- Control system failures.
- Sensor failures.

GPA seeks to infer the condition of components in the engine's gas path from the changes in the engine's thermodynamic parameters – pressures, temperatures, speeds, torque, air flow, and fuel flow – from their reference or healthy values [170]-[171]. Traditionally, GPA uses engine models to generate the reference values and influence coefficients. The influence coefficients provide the fault information, since they represent the effect of a change in a given component variable, such as a 1% decrease in fan efficiency, on the change in the measured engine parameters.

Pioneered in the early 1970s, the GPA methodology has found some limited success in the engine test facilities of civilian airline operators [172]-[174]. However, the typical aero-engine application presents a number of difficulties for GPA that must be overcome before it can become a more effective diagnostic tool. Indeed, the current methods still fall short of what can be achieved by a skilled analyst [175].

The first difficulty is that GPA must work with the very limited set of gas path instrumentation, both in terms of number and location, provided on production engines. The typical set is a long way from the ideal set of pressures and temperatures at the inlet and outlet to each component. Consequently, the problem of fault observability and uniqueness arises as a number of fault scenarios may fit the observed symptoms – the measured parameters.

The second difficulty is that GPA uses model-based influence coefficients that are deterministic whereas the actual process is stochastic. Consequently, the methodology needs to be modified so it can correctly isolate faults against the observed measurement and model uncertainty.

The third difficulty is that the influence coefficient approach assumes that the component variables such as efficiency and mass flow are independent whereas in reality they are coupled with the actual coupling being related to the type of fault, such as tip clearance changes. Incorporating this information within the methodology helps the diagnosis by restricting the domain of possible faults.

The fourth difficulty is that GPA must diagnose the occurrence of multiple component faults as the engine is likely to suffer some degradation through several modules. So far the success of the influence coefficient approach has been restricted to cases where single faults are present. Consequently, the methodology needs to be improved so it can recognise the occurrence and severity of multiple faults.

The fifth difficulty is the almost complete lack of specific and validated fault signatures for the engines – the problem that we are trying to diagnose. Whilst the general literature, model studies and fault implant tests provide some guide as to the likely fault signatures, they are not specific enough to be of practical use when diagnosing the faults of a given engine. Consequently, an important step is the development of a fault library that summarises the repairs that are performance related and their frequency of occurrence, and provides the link between the cause (the mechanical condition) and the symptoms (the gas path performance). However, as the process for collecting this information is not in place, it must be introduced.

In seeking to address the above weaknesses in the traditional GPA methodology and provide a more practical and robust diagnostic method, a number of different diagnostic tools have been developed. These are illustrated in the flow chart of Figure 6-52 and they are described in more detail in the following three sections.

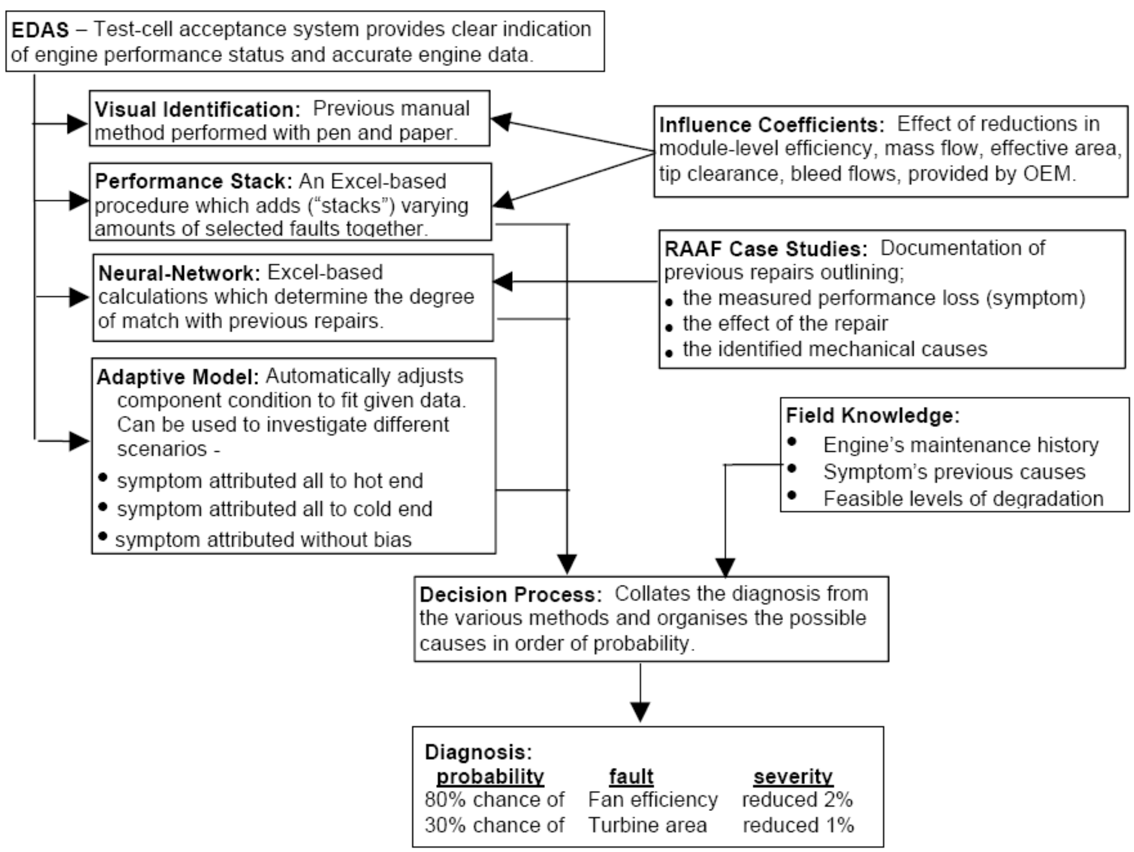


Figure 6-52: Gas-Path Diagnostic Methods and Process Developed by DSTO.

6.7.4.8.1 Performance "Stack" of Fault Signatures

The RAAF had attempted the diagnosis of gas path faults using the unofficial Pratt and Whitney TF30 test-cell troubleshooting guide. This guide provides a set of influence coefficients covering the impact of

32 separate component malfunctions or deficiencies on six measurable gas path parameters. Whilst these P&W fault signatures contain valuable information and help the identification of dominant faults, the manual process of trying to visually identify multiple faults of near equal severity using single fault patterns proved impractical.

Initially, DSTO tried a fully automated approach to recognising the P&W fault signatures using neural networks. Whilst it easily identified the occurrence of single faults and showed an ability to identify those multiple faults that affected different sets of parameters, it struggled to identify multiple faults when the fault signatures overlapped. As a result of the weaknesses of both the manual and fully automated approaches a semi-automatic method was developed.

This semi-automatic method allows the analyst to progressively stack up a fault scenario until the selected scenario accounts for the observed performance loss (symptom). The method uses the P&W influence coefficients to attribute the performance loss to specific faults as selected from a total set of 21 faults. The method is implemented as an Excel interface where the user selects and inputs a likely fault and its severity. The program then calculates the fault signature at the chosen severity, and subtracts this from the observed symptom, to give the portion of the symptom still to be accounted for. The user then selects another fault at a chosen severity and the process is repeated until the symptom has been accounted for. The method is illustrated in Figure 6-53. It allows the analyst to use past maintenance history and expert judgement to guide the diagnostic process whilst still producing a thermodynamically consistent set of faults. As well, the analyst can try various what-if scenarios to include or exclude other fault possibilities. Importantly, on trial against RAAF test-cell data, this method has demonstrated a capability to diagnose multiple faults.

Selected Fault:	*Severity,%*	*N1*	*N2*	*TIT*	*P3/P2*	*P4/P2*	*Wf*
Nozzle area	+ 1.7	1.67	0.77	1.55	0.34	0.57	1.45
HPC efficiency	- 1.3	-0.09	-1.05	0.18	0.49	0.00	0.00
LPC airflow	- 1.1	0.02	0.09	0.25	-0.25	-0.15	0.06
HPC airflow	- 1.0	-0.02	0.60	0.09	0.13	0.00	0.00
Burner pressure loss	+ 0.7	-0.04	-0.34	0.10	0.21	0.21	0.04
LPC efficiency	- 0.5	-0.09	0.08	0.18	-0.01	0.00	0.08
HPT area	+ 0.4	-0.04	-0.40	0.00	0.20	-0.04	0.04
1st turbine cooling leak	+ 0.4	-0.02	-0.15	-0.07	0.05	-0.12	0.00
Total effect of selected faults:		1.38	-0.39	2.27	1.15	0.47	1.65
Observed performance loss:		1.30	-0.37	2.41	1.15	0.40	0.50
Un-accounted for loss:		0.08	-0.02	-0.14	0.00	0.07	1.15

Influence coefficients, adjusted to show the effect of the selected fault at the selected severity.

Sum of the effects of all the faults.

Symptom of engine being diagnosed.

Remaining symptom.

Figure 6-53: Performance Stack Diagnosis of Engine P103-8841.

6.7.4.8.2 Probabilistic Neural Network with Case Studies of RAAF Repairs

In this second GPA method, an automated approach to fault diagnosis has been developed through the combination of a Probabilistic Neural Network (PNN) with the "case studies" of previous TF30 engine repairs. The fault diagnosis is based on how closely the engine being investigated matches previous repairs. This method has evolved from earlier DSTO studies into neural networks that demonstrated their ability to diagnose implanted faults in a single test-cell engine [176] and within the engine-to-engine build variations of a fleet of engines where the effect of a fault can be obscured by these variations [177]. The PNN presented here extends this work to diagnosing real-world faults within a fleet of military turbofan engines.

The PNN provides a mathematical method that is equivalent to the test-cell operator who can say "I know what is wrong with this engine because it has been seen before". In comparison, the traditional gas path approach using influence coefficients does not know anything about the frequency or appearance of common symptoms that represent combined faults. They cannot make use of this operational knowledge and known diagnostic information. With every repair, the neural network has another example of an observed fault added to its knowledge base. In comparison, the traditional influence coefficient approach starts every diagnosis as if it is the first; it has no knowledge of past experience.

Case studies, which document previous repairs, form the important database of operational-knowledge for the PNN's diagnosis. Whilst traditional scientific reports often provide a useful insight into the causes and effects of gas-path degradation, they usually do not provide measurements which are both practical and applicable to a specific engine. Hence, to establish a link between the cause and the symptom, a number of TF30 repairs were studied and a report format was developed to provide the RAAF with details of their own repairs. These case studies identify: the symptom using the parameters measured in the TF30 test-cells; the predicted degraded modules using the current diagnostic methods; the actual mechanical causes listed in the engine strip-down condition reports; the repair performed; and the performance recovered. Over time, these case studies will be built up into an invaluable fault database.

Each case study of a previous repair provides two links between the performance measurements and the mechanical condition (Figure 6-54). The first link is between the performance loss (symptom) and the defects found when the engine is stripped. This link is often an approximation, since not all modules are repaired during unscheduled maintenance, allowing some defects to remain undiscovered. In addition the symptom can be inaccurate, as reliable no-fault data for the particular engine can often be hard to establish due to the passage of time since its post-overhaul test. The second link is given between the performance recovery and the repair work performed. This link is more accurate because it is clearly known what repairs were done, and the performance they recovered. Since some modules remain unserviced, the performance recovery cannot be expected to be exactly equal and opposite to the performance loss.

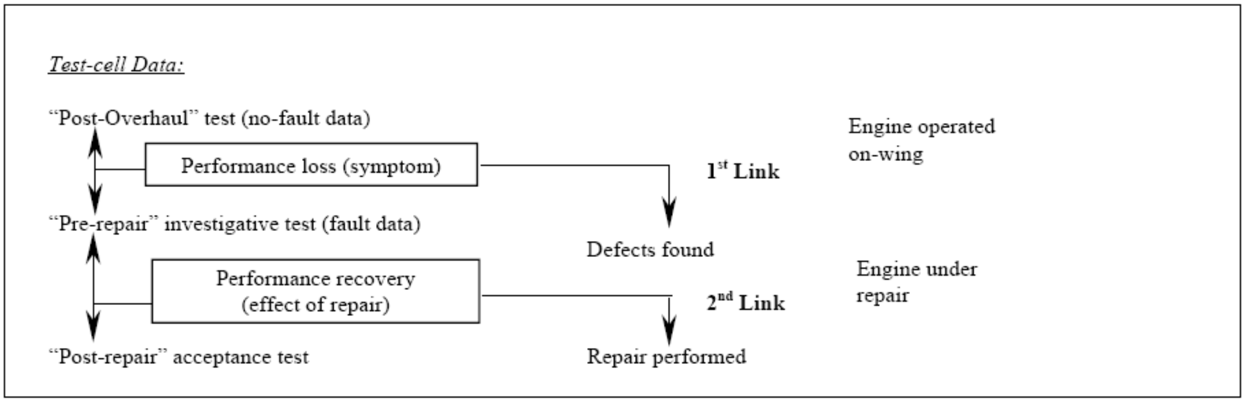


Figure 6-54: Links Between Observed Performance and Mechanical Condition.

Our only clues to the condition of the engine being investigated come from its loss in performance compared to its own earlier no-fault condition. The Probabilistic Neural Network (PNN) [178] calculates a statistical degree of match between this current symptom of the engine in-question and examples of previous repairs. This symptom being diagnosed is compared by the PNN with both previous symptoms and previous performance recoveries.

This first comparison is necessary, despite the inaccuracy of previous symptoms, because it is only fair to compare two like items with the same inherent process uncertainties. However, we also want to make use of the more accurate knowledge from the effects of previous repairs, so the second comparison is also performed.

The PNN is coded in Excel and its interface is shown in Figure 6-55. The symptom of the engine being diagnosed is entered in the top row. The symptom is measured between the pre-repair data and the engine's own post-overhaul data. The difference in seven parameters, at the same value of engine pressure ratio, is calculated. The symptoms and repair effects of the known case studies are contained vertically below the unknown symptom. For each case, the PNN calculates the degree of match, as shown graphically and by the % figure. The PNN can calculate the degree of match even if some of the seven input symptom-deltas are missing. This enables the effect that each parameter has on the degree of matching to be explored.

RAAF previous repairs		unknown	N1 rpm	N2 rpm	TIT deg F	P3/P2 ------ psia / psia -------	P4/P3	P4/P2	Wf lb/hr	match
case	serial	symptom:	10	300		-0.20	0.10	-0.35		%
1	5561	symptom	0	285	38	-0.16	0.04	-0.42	92	51
		repair	-41	-125	-44	0.00	-0.03	-0.13	95	0
2	5640	symptom	-19	190	8	-0.04	-0.21	-0.67	-133	0
		repair	19	-13	6	-0.03	0.08	0.26	120	0
3	8841	symptom	130	-45	53	0.19	-0.13	0.16	31	0
		repair	-143	20	-39	-0.26	0.16	-0.20	-35	0
4	4993	symptom	7	328	30	-0.29	0.20	-0.30	-221	13
		repair	-14	-96	8	0.07	-0.05	0.05	340	0

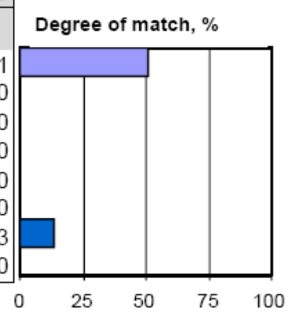


Figure 6-55: Diagnostic Comparison of a Symptom to 4 Previous Repairs.

This PNN approach closely follows the human identification process of using observed examples and it is capable of encapsulating information such as the frequency and appearance of symptoms observed in the test-cells. Such information is generally not used by traditional diagnostic approaches. The PNN is currently on trial with the RAAF.

6.7.4.8.3 Adaptive Model Approach

In this third GPA method, a robust adaptive approach to fault diagnosis has been developed based on the use of an adaptive component-based thermodynamic model of the TF30 engine [179]. Adaptive engine models [180] operate in reverse to a normal model. Typically, an engine model is run by selecting an input such as power lever angle and the model then computes engine speeds, pressures and temperatures. The adaptive model operates in the opposite direction. A schematic diagram of the adaptive modelling process is shown in Figure 6-56. The user inputs the engine measurements, and the model adjusts or 'adapts' its internal operation to achieve the requested values. If the engine measurements have been obtained from a degraded engine, then the way the model has had to adjust itself to obtain the degraded performance indicates how the real engine may also have degraded. Hence, the adjustments made by the adaptive model give a diagnosis of the engine's condition.

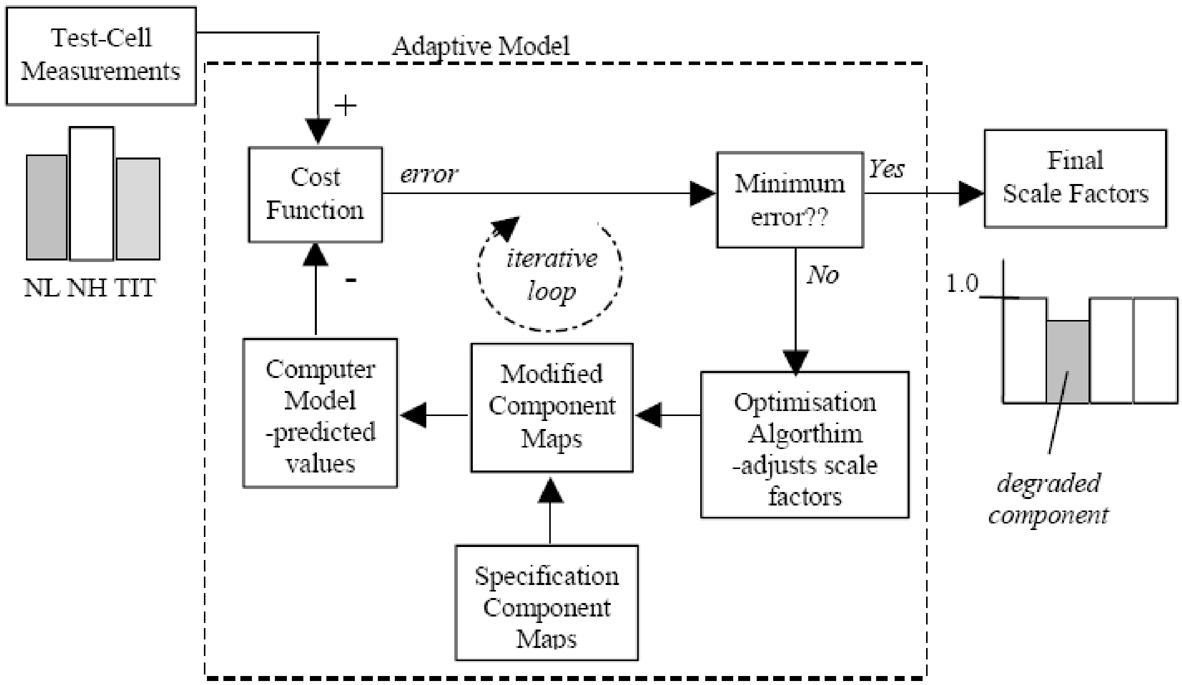


Figure 6-56: Procedure to Calculate Scale Factors in Adaptive Modelling.

The adjustments made in the adaptive model to fit the given data are indicated by Scale Factors. A Scale Factor is simply a modification factor that is applied to a performance parameter, such as efficiency, mass flow or effective area of the engine's major components, such as the fan, compressor, or turbine. The Scale Factors model the effective change (or degradation) in the performance of the gas path components. They represent the difference between the degraded engine's performance and the computer model's reference performance. In theory, the Scale Factors are unity in a healthy engine and both increases and decreases from unity indicate degradation. In practice however, Scale Factors will vary from unity even in engines that have not degraded, due to modelling error, measurement noise and/or the normal variations in engine build.

The adaptive procedure uses the Downhill Simplex Method of Nelder and Mead [181] to solve for the unknown set of Scale Factors by stepping around the multi-dimensional surface of a Cost Function in search of the minimum value. A number of other optimisation algorithms were investigated and the Downhill Simplex method proved to be the best with respect to identification, time and simplicity. In a series of deterministic model-based studies, the adaptive model demonstrated the ability to correctly identify the simulated degradation in 100% of the cases where a single Scale Factor was degraded reducing to 80% for the cases where two, three and four Scale Factors were degraded. The failure to correctly diagnose the degradation was primarily due to the adaptive model finding multiple solutions – different degradation scenarios – that all fitted the degraded data equally well. Furthermore, in many of these multiple Scale Factor cases the simulated degradation was not the solution with the lowest Cost Function value. For this reason, the overall process retains and considers all solutions with low or acceptable Cost Function values, often 50 to 100, rather than just the solution with the lowest value.

However, the above basic adaptive modelling process was not sufficient by itself to provide a robust and effective tool for diagnosing engine faults in the presence of real world uncertainties. These uncertainties can be classified as arising from either modelling errors or sensor errors. Consequently, to handle such uncertainties in the TF30 test-cells, the adaptive modelling process was modified as illustrated in Figure 6-57.

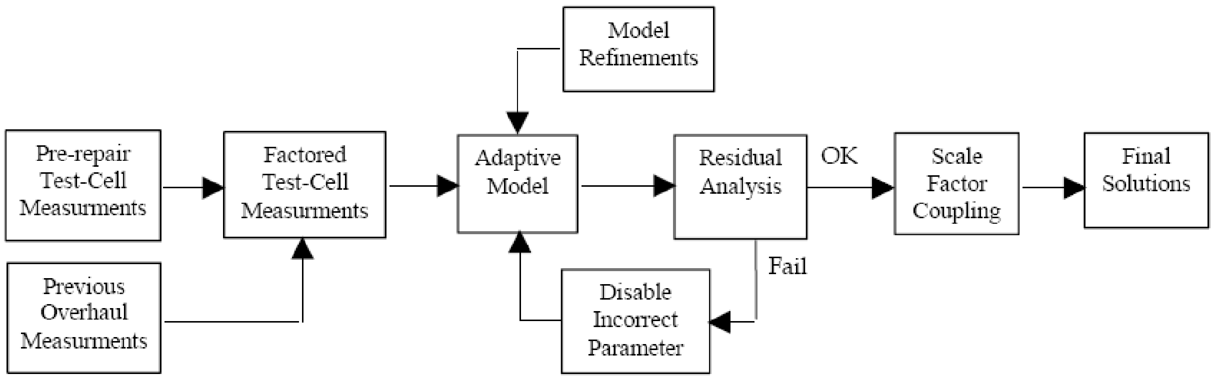


Figure 6-57: Adaptive Model Approach for Test-Cell Data.

The first step in this overall adaptive approach is the use of a "factoring" process to account for modelling error – the difference between the reference TF30 engine model and the no-fault "healthy" state of the engine under test. The "no-fault" or "baseline" value of each engine will vary across the fleet due to normal build differences and prior maintenance history. This engine to engine variation cannot be accounted for by a single "specification" reference model and if ignored would tend to hide the actual in-service degradation. This problem is partly addressed by using the post-overhaul data for each engine as the preferred baseline for determining in-service degradation. In the absence of post-overhaul data for a given engine, the average performance of post-overhauled engines must be used. The "specification" baseline is not used as this may indicate degradation that is unpractical or uneconomic to recover. The adjustment factors are calculated by dividing the model reference value by the engine's no-fault value. If the model and engine matched exactly, the factor would equal one. The engine's test data is then multiplied by these factors to provide the input to the adaptive model. Usually, the modelling error is removed after the adaptive process whereas here it is removed prior to the adaptive process.

The adaptive model was also modified to improve its performance. The changes included the following:

a) Specifying an appropriate domain for the Scale Factors to constrain the region of the Cost Function surface where a solution was allowed.

b) Introducing a weighting factor on the engine parameters in the Cost Function so as to reduce the impact of inaccurate sensors and to ensure that the optimisation algorithm continues to try and match the more accurate sensors down to a very small error.

c) Introducing a two stage optimisation strategy where the insensitive Scale Factors from the first stage are disabled making the second stage optimisation a much simpler task.

The next step after the adaptive model calculates the set of possible Scale Factor solutions is a residual analysis of the errors between the engine parameter values predicted by a given Scale Factor solution and the measured values. This is done in two parts. The first residual analysis looks for evidence of an individual sensor fault as indicated by a very high error in that sensor for all Scale Factor solutions. If this is the case, this sensor is rejected and the adaptive modelling is repeated but with out this sensor. The second residual analysis looks for evidence of bad Scale Factor solutions as indicated by the predicted values for a given parameter being outside the test-cell test to test variation of the measured parameters. If this is the case the solution is rejected. Neither of these methods is intended to detect small errors.

A key last step in the method is the use of a constraint on the plausible Scale Factor domain to reduce the 50 to 100 possible solutions generated by the adaptive model to a very small number of plausible scenarios of component degradation, say 2 or 3. In traditional GPA, the characteristic parameters of the component maps, such as efficiency and mass flow are treated as being independent of each other. However, most realistic gas path faults, such as eroded compressor blade tips, will affect both the efficiency and mass flow simultaneously. The allowable Scale Factor Coupling domain for the compressors is illustrated in Figure 6-58.

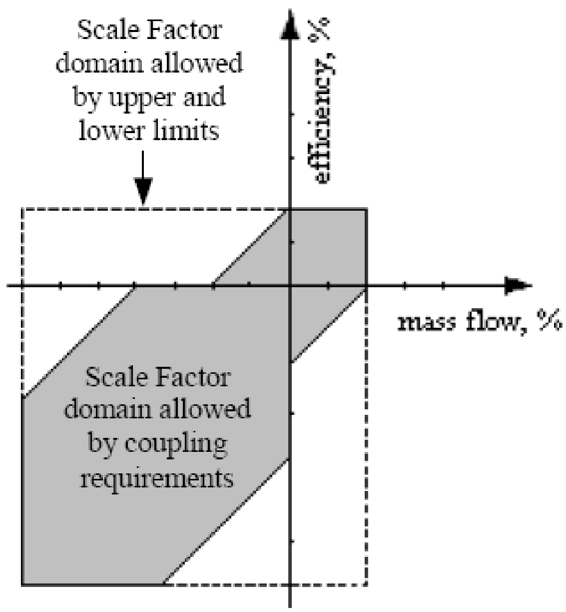


Figure 6-58: Scale Factor Domains Between Efficiency and Mass-Flow for Compressor Degradation.

6.7.4.9 Flight Line Troubleshooting Using Expert Systems

In the late 1980s, a joint RAAF, Pratt and Whitney and DSTO team was set up to develop a concept demonstrator for the use of expert systems in troubleshooting TF30 engine faults at the flight line. The concept demonstrator was called the Interactive Fault Diagnosis and Isolation System (IFDIS). The original requirement for IFDIS was the need to improve the on-wing troubleshooting of TF30 engine faults so as to reduce the excessive number of unnecessary engine removals arising from incorrect fault diagnosis. A demonstrator version was successfully developed and subjected to trials in 1989 [182]-[183]. Implementation of the system did not proceed at that time, but renewed interest in the concept led more recently to a requirement to redevelop IFDIS with the aim of maximising its long-term supportability across a number of modern computer platforms and over several cycles of system upgrades. This aim was met by redesigning IFDIS [184] as an advanced web-based expert system that used standard commercially available software packages to implement most of its functions, such as the database engine, the active web server, and the web browser. As a result, the specific software code (mainly in the active server pages and the inference engine) and the database of TF30 engine specific information (the data and the rules) make up less that one percent of the total system.

IFDIS performs the role of an intelligent assistant and so it was designed to help troubleshooting in an interactive fashion. Two essential features of troubleshooting a gas turbine are implicit to the design. These are: the ability to separate the problem domain into a finite number of discrete recognisable problems; and the ability to assign causal relationships as cascading fault trees. These features are implemented in the structure of the database and so inherent in it. Any other problem domain that showed these same features could use IFDIS with only a change to the information in the database. This would include a wide range of mechanical, pneumatic, hydraulic and electric/electrical systems.

The design of the new IFDIS inference engine and database was based on the troubleshooting expert system developed by Competitive Advantage Technology Pty Ltd called Diatron. Some significant changes were made to improve overall performance and supportability. The Diatron inference engine was recoded in eXtensible Markup Language (XML) to facilitate machine independent operation. For ease of verification, IFDIS was structured as a set of separate problems each with its own independent set of rules. This facilitated the use of the simplest type of expert system in the re-design, and improved the diagnostic response times, but came at the expense of a more complicated database. Importantly, for the gas turbine diagnostic problem, the inference engine was structured to handle multiple levels of nested rules by assigning a value to a symptom in the conclusion of one rule that is a condition of another rule.

An important feature of the inference engine is non-monotonic reasoning, this allows the user to engage in "what if" scenarios by stepping back and forth through the diagnostic session, changing the symptoms and re-assessing the answers as required. This feature is useful both in engine troubleshooting and in learning the troubleshooting process. The "undoing" process can continue back to the first question of the session. Naturally, changing an answer can lead to different questions being asked subsequently in the session since the diagnosis has moved to a different point in the answer-space. This reflects the fact that the diagnostic problem is structured as a multiple fault tree with many branches. In the inference engine, the symptoms for a selected problem are ranked in order and this controls the order the rules are passed to the inference engine. In responding to the interactive session, the user may supply "Don't Know" answers to the symptoms, resulting in "Known" or "Not Known" symptom states as well as "Not Answered", "Answered", or "Changed" symptom states. The rule and condition states can be "True", "False" or "Not Determined" and the resultant fault status can be "Indicated", "Possible", or "Not Indicated".

An important feature of the database is that it contains all the knowledge and causal relations acquired for the particular problem set. Consequently, the engine maintenance authority only needs to maintain the database to add additional problems or modify engine specific information due to some configuration change. The database comprises of a set of rules added in a particular problem order. The rules themselves are simply entries in a list of categories, problems, faults, rules, actions, reasons, symptom choices and symptoms. These lists simplify the database structure but it means all conditions are joined by "AND" rather than allowing "OR" connections. To reduce database access during operation and to speed up response in a served network, a generic program is used to automatically convert the database information into the XML code lists required by the inference engine.

Currently, IFDIS covers 18 observable faults (or symptoms) with an emphasis on after-burner operational problems. IFDIS and GPA diagnostics share some common symptoms, like high turbine inlet temperature, but they diagnose different causes. For example, GPA would look at causes such as reduced high pressure compressor mass flow, decreased low pressure compressor efficiency or eroded turbine nozzle guide vanes.

IFDIS would look at causes such as a faulty engine gas temperature probe, an un-trimmed fuel control, a mis-scheduled Mach number actuator, or a broken cockpit gauge. In diagnosing these 18 faults, IFDIS looks at 113 possible causes and uses 326 rules to do so. These faults, causes and rules are based on the TF30 troubleshooting manuals as well as RAAF and Pratt and Whitney operational experience, and they have been verified by the original IFDIS development team. Overall, IFDIS covers 30% of the possible faults, some 70% of the faults seen and 90% of the faults diagnosable on-wing.

6.7.4.10 Conclusions

A number of advanced diagnostic tools have been developed to support the RAAF in maintaining the TF30 engines in the F-111 through to the Life of Type. These involve: a modern engine acceptance test system for the TF30 test-cells, a suite of advanced gas path analysis methods for diagnosing faults to a modular level using test-cell data, and an expert system for troubleshooting engine faults at the flight line.

The retro-fitting of such modern engine health management systems to old engines poses a number of difficulties, in terms of lack of instrumentation, information, and policy that can lead to trade-offs that blunt their effectiveness. In the process of developing a practical and robust diagnostic system for the TF30 engine there have been a number of lessons learned. Firstly, no one single technology or methodology can provide all the answers. Each technique detects different faults, and even the three gas path methods presented here have different levels of fault coverage. Secondly, a robust gas path diagnostic system requires the simultaneous use of a number of complementary methods, so as to play to the strengths and overcome the weaknesses of the individual methods. For example, as discussed, both the performance stack and the adaptive model diagnose the exhaust nozzle fault and so add credibility to this diagnosis. Finally, the successful development of gas turbine diagnostics requires the early and active participation of the end-user in their development and evaluation. In particular, the end-user must be prepared to trial baseline versions of these techniques so they can be evolved over time.

6.8 INFORMATION ANALYSIS

6.8.1 Introduction

Information analysis technology, including data fusion and integrated reasoning, designed to exploit existing sensors and instrumentation for usage monitoring, inspection, and diagnostics is a key technology in on-board and ground-based maintenance systems. Information analysis technology is a highly specialised topic which is still in the early stages of development for aircraft and many other applications. This section provides some insight into information analysis technologies that are under development for aircraft maintenance.

6.8.2 The Use of Integrated Reasoning with Flight and Historical Maintenance Data to Diagnose Faults and Improve Prognosis

This section is based on Paper 4.5.3 by Létourneau and Halasz.

6.8.2.1 Introduction

Most aircraft operators collect huge amounts of information in central databases. Logistics data, flight data, reliability data, electronic manuals, and aircraft mission data are only a few examples of the information accumulated. Although this data can be effectively used in an isolated manner by staff from various departments, there are a clear lack of solutions that integrate and transform it into actionable knowledge to help organizations achieve their broader objectives. Major initiatives such as the JSF's Autonomic Logistics system [185] and the TATEM project[1] provide leadership in promoting the need for such an integrated

[1] http://www.tatemproject.com/.

solution. In all cases, the anticipated solution requires the development and integration of enabling Prognostics and Health Management (PHM) technologies. Established maintenance methodologies like Reliability Centred Maintenance (RCM) also call for continuous evaluation and integration of emerging PHM technologies to help improve diagnostics and prognostics.

Definitions of PHM as found in NAVAIR 00-25-403 and in Hess and al. [185] encompass all devices, analytical methods, and software that can be used for diagnostics, prognostics, health assessment, or health management. For practical reasons, the NRC's research follows a progressive integration of theses technologies. Guided by real-world PHM applications, the techniques that appear most promising were gradually integrated. A generic open software infrastructure was developed to support this incremental approach. This section introduces two PHM applications along with the technologies employed. The first application shows innovative use of artificial intelligence techniques to enhance diagnostic and improve maintenance efficiency on the 1st Line. The second application focuses on the use of data mining to build prognostic models. For brevity, the paper will only consider applications on commercial aircraft data. Wylie et al. [186] and Yang and Létourneau [187] generalize the concepts presented here and illustrate applications to other kinds of equipment such as mining and railway equipment. The section is structured as follows. The second part describes the context of this research and the data used. The third and fourth parts address the two PHM applications mentioned above. The fifth part overviews the open software infrastructure developed to support this research. The sixth part concludes the section.

6.8.2.2 Research Environment and Data

A key mandate of the National Research Council (NRC) of Canada is to help sustain competitiveness of Canadian companies through the development and integration of technology. In 1990, various industries were considered for the application of Artificial Intelligence (AI) techniques. The maintenance of complex equipment was selected as the preferred target application domain. The economic importance of the maintenance industry in Canada and the expertise of several team members in mechanical engineering warranted this choice. High level economic information available at that point suggested that for every dollar spent on new machinery, an additional 51 cents was also spent on the maintenance of existing equipment [Statistics Canada, 1990]. For 10 industrial sectors, total repair costs exceeded US$15 billion per year in Canada. Over the following six years, the proportion of the maintenance cost over the acquisition cost increased by 14%.

Initially focussing on the commercial aviation industry, NRC teamed with Air Canada, and GE to study and develop technologies to optimize the use of the available data. For research purposes, the scope was limited to data from Air Canada's fleet of 70 Airbus A319 and A320 aircraft. These aircraft have systems on board which transmit data to ground stations via Air Canada's datalink system. This allows monitoring of aircraft health status in a near real-time manner. The data consist of routine performance snapshots (e.g. altitude, temperature, pressures, engine temperatures, valve positions), pilot messages, aircraft generated fault messages, and special purpose reports generated when prescribed limits are exceeded such as on a hard landing. Maintenance data are also available in other systems. They contain descriptions of symptoms and associated maintenance actions in free form text. Some other sources of potentially relevant information could not be made available. These include: deferred problems, flight schedules (static and dynamic), weather, component reliability, check schedules, and parts location. Similarly, information held at the manufacturer, and by people and information systems in the engineering and maintenance control departments were not accessible. The two applications described in the following sections take advantage of different sub-sets of data.

6.8.2.3 Use of Artificial Intelligence to Improve Diagnostics

This section gives an overview of the Integrated Diagnostic System (IDS). Halasz et al [188] provides a more detailed description and discusses the commercialization of the IDS technology. The IDS system is a proof of concept software produced through an early research project on use of AI to optimize maintenance of complex equipment. The objective of the research project was to develop innovative software to improve the efficiency of 1st Line maintenance operations at Air Canada. Key functionalities of the proof of concept software developed include: reducing the ambiguity in fault isolation, providing advice on real-time repair action, providing clues on incipient failures, accessing and displaying relevant maintenance information, and facilitation of communication among maintenance staff.

Line technicians in commercial airlines are responsible for maintenance and certification between flights or between legs of a flight. Figure 6-59 illustrates the typical working environment of the line technician. Their work can be summarized as follows. As soon as an aircraft arrives at the gate, they typically examine pilot's input (snag messages) and information from the on-board systems for the presence of Minimum Equipment List (MEL) conditions that could affect aircraft availability. If such conditions exist, they proceed with prescribed troubleshooting procedures and perform repairs as required. Finally, they certify the aircraft for the following flight. This process can involve interaction with other departments of the airline which are either providing resources (e.g. parts and expertise) or waiting for certification of the aircraft in order to proceed with scheduled operations (e.g. system operations and control). Time constraints are typically very severe.

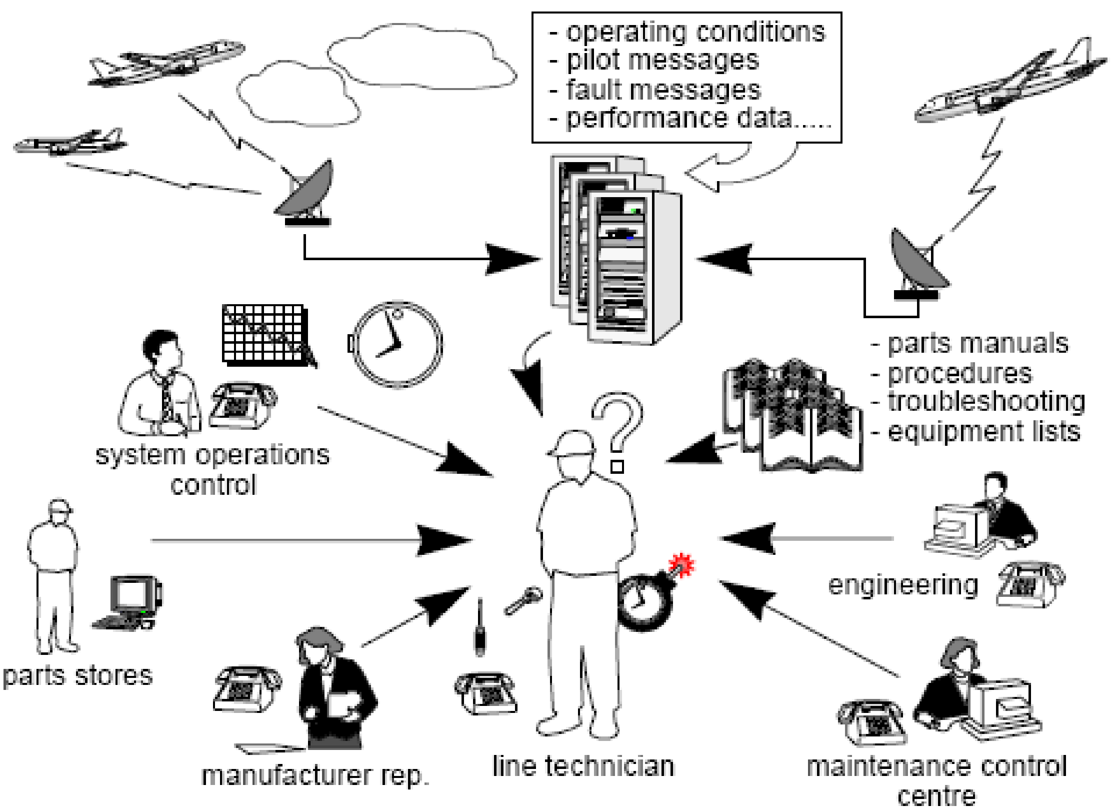


Figure 6-59: Operational Environment Around the Line Technician.

The IDS supports 1st Line activities by integrating and delivering key information in a timely manner to the various staff involved. It also automates some of the steps mentioned above. Specifically, it performs the following functions while the aircraft is still in the air:

- Clusters recent warning, failure, and snag (pilot) messages.
- Identifies probable causes by automatically searching the Trouble Shooting Manual (TSM).
- Provides links to the TSM pages as needed.
- Automatically assesses MEL conditions (GO, NOGO, GOIF).
- Retrieves relevant recent maintenance actions.

All the information is displayed in an effective user interface.

The reasoning in IDS relies on two core AI techniques. First, rule-bases are used to encode information contained in the TSM and MEL manuals. The highly structured format of these documents allowed us to develop innovative text processing tools that automatically extract information and generate corresponding rules ready to be implemented in a rule-based system. Rules were also developed to implement heuristics for linking in-flight messages (warning and failure messages) with the TSM, automatically assessing the MEL conditions, and aggregating information with temporal or textual proximity. The IDS also exploits case-based reasoning to retrieve relevant historical maintenance information and to suggest potential repairs for the current situation.

To facilitate the evaluation and distribution of the technology developed through this research project, the IDS functionalities were decoupled in a number of well-defined modules that can be distributed across an airline's network. Reasoning involved in data fusion, data abstraction, and state assessment is done in server modules. To increase robustness, these server modules can be duplicated as needed. Thin client modules tailored to the needs of the various types of users are deployed on desktops or mobile computers at various sites. Thanks to the reasoning performed by the server modules, only minimal processing is required at the user's device. Figure 6-60 presents the deployment diagram for the IDS trial. In this case, the server modules were running at the National Research Council in Ottawa while client modules were installed in Montreal and Toronto.

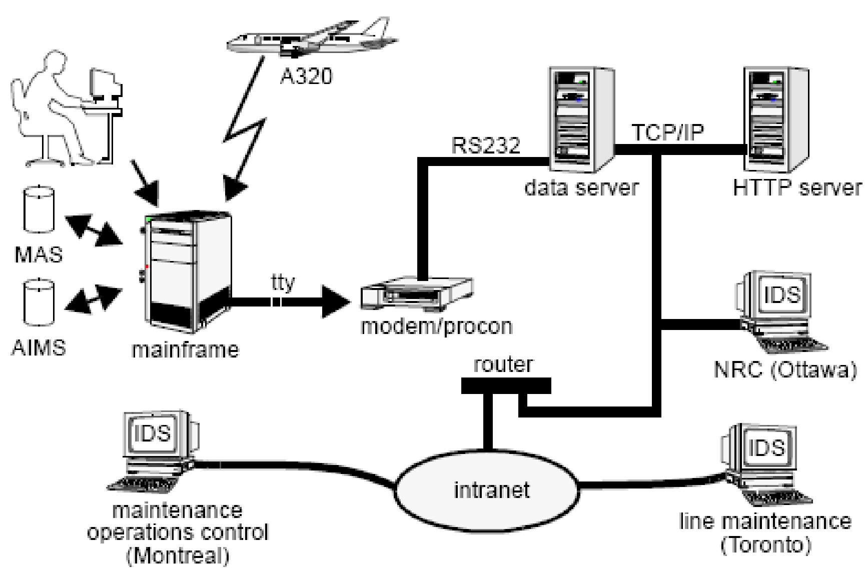


Figure 6-60: Deployment of the IDS Trial System.

Through data fusion and AI-based techniques, the IDS system provided the 1st Line technicians with all the information required as early as possible. This information helps technicians maximize their efficiency and it makes it easier to meet the time-constraints imposed for maintenance actions at the gates. This contributes to a reduction in down-time and less disruptions due to unexpected delays. By distributing up to date information on the status of the aircraft to the various staff involved, the IDS system streamlines communications between departments which, in turns, further contributes to increased efficiency. In terms of increased availability, the technology only provides a marginal benefit since it focuses on optimization of operations that happen during relatively short time-windows (turn around times). However, we note that in such time-critical operations even smallest increases in availability can lead to economic benefits.

6.8.2.4 Use of Data Mining to Improve Prognostics

Line technicians are only concerned by imminent maintenance actions. On the other hand, engineering, fleet management, and the parts departments would benefit from knowing ahead of time that certain component failures are gradually developing. To extend the IDS concept to these other groups of users, prognostic capabilities need to be integrated. This section briefly discusses a data mining methodology that the NRC is developing to help build the required prognostics models [189].

Figure 6-61 illustrates the proposed methodology. This methodology builds predictive models for a given component using readily available sensor and maintenance data. There are four steps: data gathering, data transformation, modelling/evaluation, and model fusion. The data gathering step starts by searching the maintenance database to retrieve information on previous replacements of the component of interest. For each case, we record the date of the replacement and the id of the system (e.g. the aircraft tail number or the engine serial number) on which the replacement occurred. In practice, this search may be difficult to automate due to inaccuracies or inconsistencies in the maintenance data. Although advanced text processing tools could help alleviate these difficulties, manual validation is generally required to ensure that only suitable data is used for modelling. Once the date and the system id for each component replacement have been validated, the data gathering step retrieves sensor data acquired prior to each replacement.

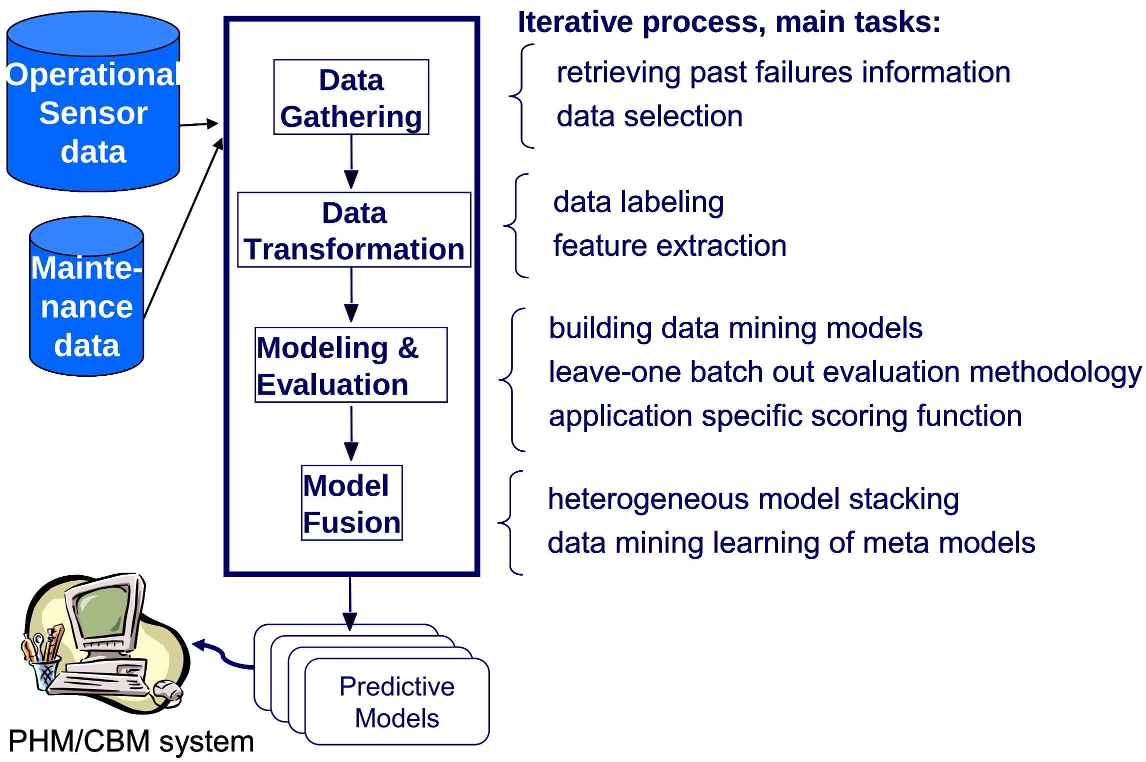


Figure 6-61: Data Mining Methodology to Build Prognostic Models.

The data transformation step modifies the obtained sensor dataset in two ways. First, it automatically adds the dependent variable, also named the class or the label. This new variable has two possible values: 1 or 0 for replace component or don't replace component, respectively. The algorithm sets the class to 1 for observations that fall in a pre-determined time interval prior to a replacement (e.g. between 1 to 20 days prior to the replacement) and sets the class to 0 otherwise. Second, several of the initial measurements are normalised to take into consideration the effects of the operating conditions and new time-series variables are included as needed (e.g. FFT, moving average).

In the modelling and evaluation step, data mining and machine learning algorithms are applied to build models that can predict the class as accurately as possible. Several models are created using different algorithms and parameter settings. These models are then evaluated using an evaluation method we have devised to take into account the timeliness of the predictions and the coverage of the models [189].

Finally, if performance improvements are deemed necessary, we complete the process by investigating model fusion approaches [190]. This allows combination of models developed in the previous step instead of selecting the single best one. In some cases, this final step has led to a significant improvement in the quality of the predictions [187].

NRC has applied the proposed data mining methodology in collaborative research projects in aerospace (commercial and military) and to help predict failures with railway equipment. Very promising results have been obtained for building predictive models for components such as starter motors, fuel controllers, and train wheels. On the other hand, research on the application of this methodology to components such as engine's bleed valves did not lead to positive results yet. To help understand the lack of successes with some components, a number of difficulties have been identified including: the lack of relevant measurements, the high level of noise, too many errors in the data, the lack of examples of failures (replacements), inadequate data transformation methods, and the need to integrate more domain information when performing data-driven modelling. Our current research tries to address the last two difficulties through the development of more powerful data transformation methods and the integration of engineering knowledge in the proposed data mining methodology. We are confident that advances in sensor development, signal processing, and an increased awareness of the importance of data quality within the maintenance organization will help resolve the first four difficulties.

Prognostics could help increase aircraft availability by reducing unscheduled down-time, helping to avoid major secondary damage that could ground an aircraft for a long period of time, and minimizing maintenance operations by changing components only when needed instead of at regular intervals. Also, like enhanced diagnostics, reliable prognostics can help reduce disruptions during operation and improve maintenance planning. On the other hand, prognostics usually require sophisticated data acquisition systems which also need maintenance, thus potentially reducing aircraft availability. Accordingly, it is essential to carefully select the candidate components for prognostics and ensure that the maintenance of the data acquisition devices and required software could be done efficiently.

6.8.2.5 PHM Software Architecture

The two applications presented above cover a small portion of PHM technologies. Practical PHM solutions often also integrate technologies from system engineering, materials, and sensors. These technologies are not at the same readiness level and new ones are continuously emerging. An incremental integration approach is therefore mandatory and the software development environment used should facilitate the process. Ideally, the software should also be generic enough to allow the study of PHM applications in various domains (e.g. aerospace, road transportation, railroads). Figure 6-62 presents a simplified high-level view of a proof of concept software infrastructure that NRC is developing to answer these needs.

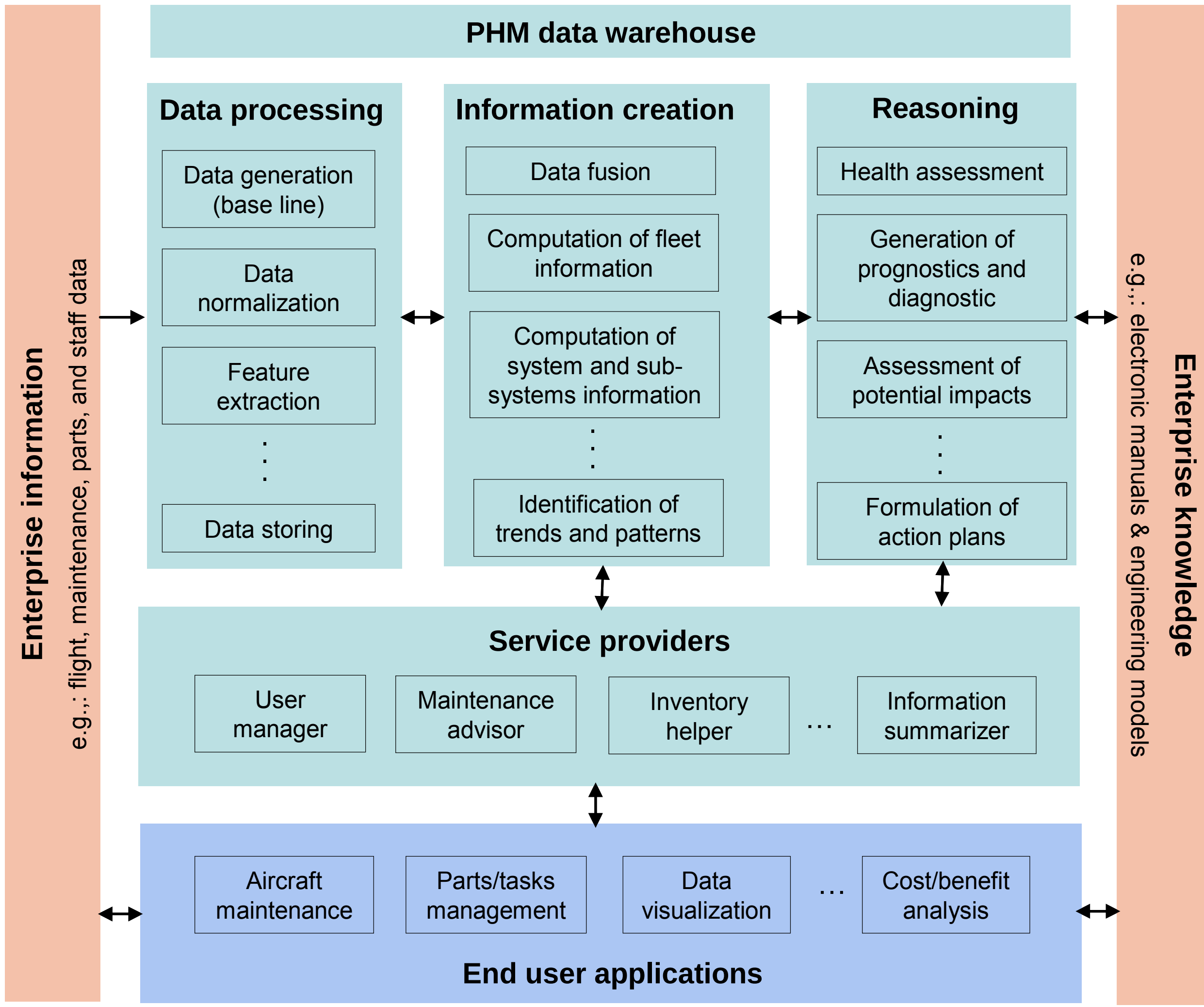


Figure 6-62: NRC PHM High Level Infrastructure.

The two modules on the sides represent the data and knowledge available in the organization. Some of the PHM modules can update the organization's information as shown by the bidirectional arrows connected to the side modules. At the top, the PHM data warehouse module captures the PHM data. All other modules have access to the information contained in the PHM data warehouse but, for simplicity, the diagram does not show the corresponding arrows. The three central modules deliver core PHM functionalities. These are responsible to transform raw information into useful and actionable knowledge. The service providers' module delivers this knowledge by providing appropriate information to end user applications shown in the module at the bottom. For simplicity, several utility modules have been omitted. These include modules to facilitate communications and data conversion between the various steps.

Each box in Figure 6-62 may be implemented by one or more algorithms. The system is designed to be robust to addition, modification, and deletion of functionalities. This allows us to gradually integrate new technologies as the R&D progresses. In terms of deployment, the various modules can be distributed over several computers to offer an adequate level of performance or simply installed on a single computer for demonstration purpose.

6.8.2.6 Conclusions

This section overviewed some of the research performed at the Institute for Information Technology of the National Research Council of Canada to illustrate the potential of artificial intelligence, data mining, and machine learning in the optimization of aircraft maintenance. In particular, it discussed the potential of these technologies to increase aircraft availability. In both real world applications described, the proposed solution integrates various reasoning methods. Moreover, in the case of data mining for prognostics, new methods needed to be developed and integrated in a comprehensive methodology (e.g. automatic labelling and evaluation methods). Since it is generally difficult to select in advanced the techniques to be used and the schema for integration, it is suitable to support the research with generic and open software tools that allow an incremental development of the final solution. The PHM deployment architecture discussed in this section partly answers this need. Current complementary work includes the development of software to support the model development process described in the paper.

6.8.3 Integrating Experience with BIT to Improve First-Time-Fix Performance (An Application of Case-Based Reasoning)

This section is based on Paper 4.5.2 by D’Eon and Hastings.

6.8.3.1 Introduction

“Field experience” is knowledge acquired by people during troubleshooting.

Although today’s state-of-the-art, machine-based prognostic and diagnostic systems can automatically identify a high percentage of faults and their causes, human expertise remains an essential part of the troubleshooting support system. When the machine-based diagnostics and the Fault Isolation Manuals (FIM) fail to resolve the problem, it is an expert person (or persons) that will solve the problem, ultimately – and new, valuable knowledge is generated in doing so.

But can that knowledge be re-used practically for the benefit of others in solving that problem? For that to happen, the knowledge must become part of the troubleshooting workflow such that it is used to identify the problem before expensive and ineffective repairs are attempted, no matter where or when, nor to whom that particular problem next appears.

Traditional attempts to get value from field experience have included strategies such as updating the FIM, creating searchable databases, publishing technical letters, and staffing a Technical Assistance Centre with the most experienced people. CaseBank’s analysis of first-time-fix performance on certain commercial aircraft (who use all the above to some extent) indicates that thirty to fifty percent of all troubleshooting attempts fail to resolve the problem.

SpotLight® is a guided diagnostic reasoning system that places field experience directly in the troubleshooting workflow, where it is integrated with BIT results, trend analysis results, electronic technical manuals, and help escalation channels. In applications with mature knowledgebases it sustains a “hit rate” in excess of 90%. The technology is being used to share field experience on aircraft old and new – from the C130 to the Joint Strike Fighter.

6.8.3.2 The Problem

There exists a “reliability-complexity conundrum” with modern aircraft. Aircraft are highly reliable, generally speaking. But aircraft are also very complex, with a great many parts. The conundrum is that failures are not uncommon occurrences, yet those failures tend to be distributed over a wide variety of causes, each of which happens infrequently. As a result, no single person can have complete knowledge of all failures, and the relative rarity of each fault makes it difficult to cost-justify an expensive engineering remediation for all those faults.

The weaknesses in a design, as implemented in an operating aircraft, become evident through operations, showing up as "the things that fail". Certain failure modes are exacerbated by factors such as operating environment (heat, cold, sand, humidity, salt), age, equipment configuration, maintenance error, coincidence, operator error, etc. Engineering analysis can predict many failure modes, but there are significant challenges. First, it is well recognized that unpredicted failure modes will happen, and second, not everything that is predicted to fail will fail exactly as predicted (Figure 6-63). The end result is that human intellect is called upon to solve very tricky problems, and in significant numbers. Accordingly, the people who troubleshoot those problems gain valuable experience.

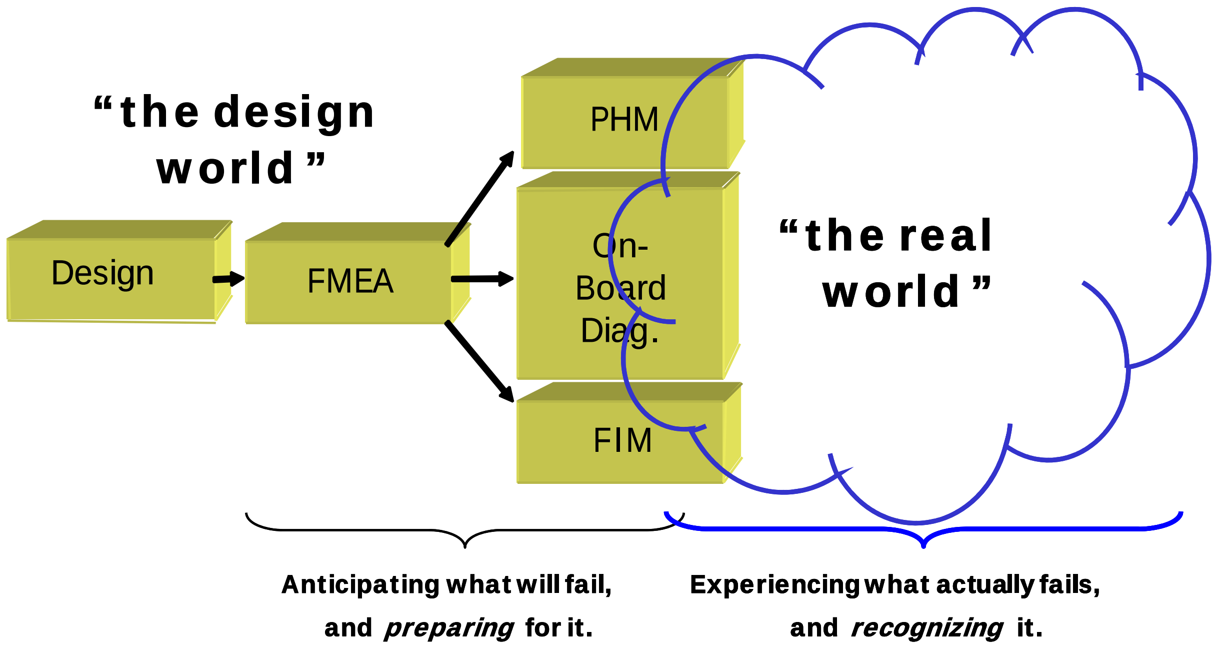


Figure 6-63: Anticipating and Recognizing Failures.

Where does this experience reside? The technician greeting the aircraft typically represents a very narrow slice of the entire body of available experience. In the user's organization, there is usually a "fleet specialist" who is familiar with his own fleet problems, and communicates frequently with his peers in other organizations. The manufacturer typically has experience reflecting the problems that are serious enough for operators to seek out their assistance. But every fault that has happened to that type of aircraft has been seen and resolved by somebody out there in the operator community. So, in fact, it is the "global fleet of aircraft operators" that has the greatest experience (Figure 6-64).

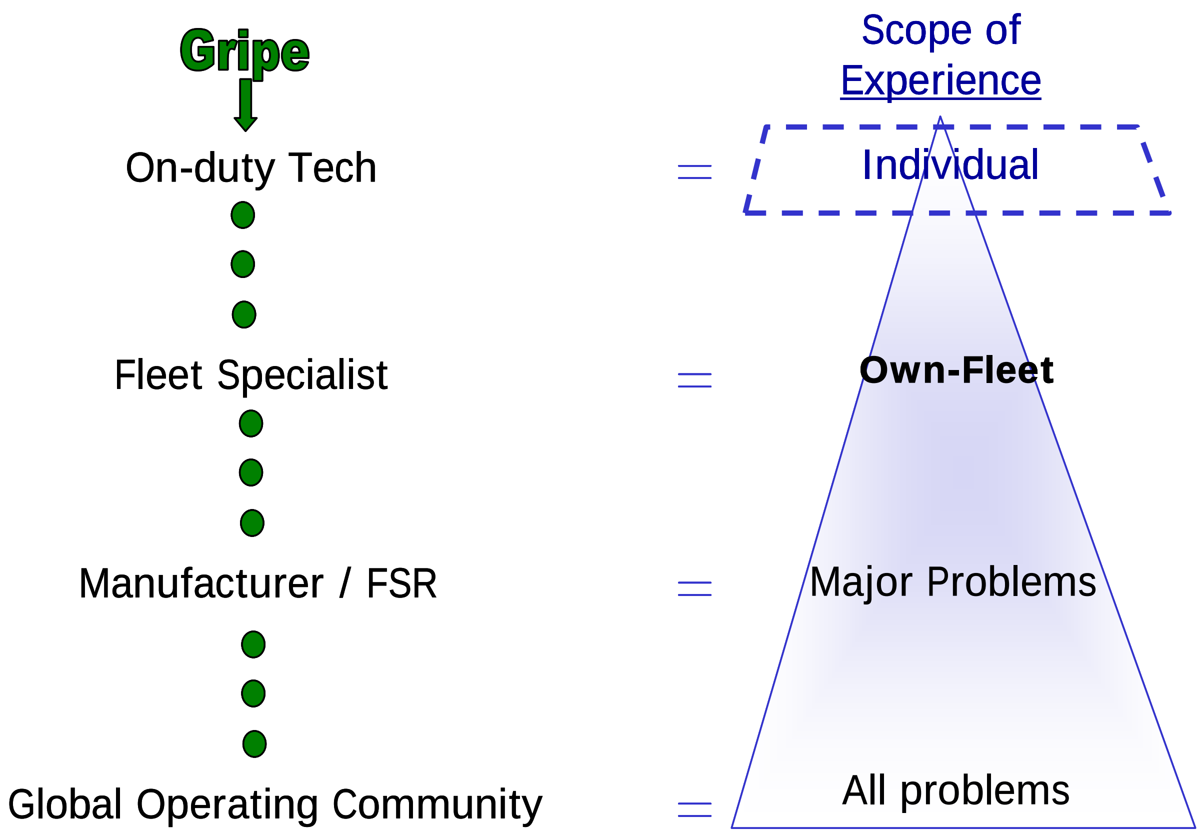


Figure 6-64: The Broad Distribution of Experience.

That experience needs to be integrated back into the diagnostic system efficiently and effectively. Unfortunately, because of the reliability-complexity conundrum, that "field experience" is spread broadly across the global community of operators of that aircraft type. The goal should be to put the benefit of global experience directly into the troubleshooting process of every technician (represented by the dashed trapezoid above).

After several years in service, the number of truly "new" failure modes that occur to an aircraft is greatly diminished. We start to see repeat instances of "the things that really fail". Most failure modes noted in any given aircraft maintenance log will have been seen and solved already by someone operating that aircraft type somewhere in the world.

Traditional approaches to collecting and re-using that knowledge are updates to databases, to troubleshooting procedures and to sensor-based fault detection methods. These approaches have their own well-recognized challenges, evident in the fact that we are still trying to solve the problem today.

In particular, the challenges faced by sensor-based diagnostic systems are well known. Notably, Built-In-Test ("BIT") is not always able to produce unambiguous results.

Here is an example of a failure mode that is known to exist, but the failure mechanism itself is not well understood. This type of aircraft experiences a failure mode which generates a STALL FAIL message.

There are many failure modes that could generate that message, but one of them is, in fact, a faulty boost pump! The boost pump itself performs flawlessly, except that it has a failure mode that generates electrical noise during start up. If one pilot happens to be running a Stall System pre-flight test while the other is starting the engines, the STALL FAIL message is generated. That is very valuable field experience, and it is very important to bring that knowledge into consideration during troubleshooting.

The following are situations in which field experience is invaluable as a diagnostic aid in conjunction with the machine-based diagnostics:

- The root cause of a fault code is a maintenance error, and not a valid component failure.
- A fault is indicated in one system, but the root cause is in a different system.
- A fault exists, but there are no codes.
- A code exists, but there is no fault.
- Multiple codes appearing simultaneously may indicate a cause other than the intended meaning of each code individually.
- Trend alert is ambiguous regarding the cause – some external causes can create indications of deterioration that are very similar to internal causes.

What is needed is a system that catches the problems that BIT and prognostics fail to identify correctly, and it needs to be invoked before good parts are needlessly changed.

6.8.3.3 The Solution

Field experience must be:

a) Captured.

b) Integrated with existing diagnostic resources.

c) Delivered as "guided diagnostics".

6.8.3.3.1 Knowledge Capture

Field experience is stored in a knowledgebase. The seed knowledgebase is created by capturing documented experience. Typically aircraft logs are mined to discover "the things that really happen" (Figure 6-65). There is overlap with BIT and FIM (Fault Isolation Manual) results where those resources are correct in identifying the cause of the failure. That knowledge becomes a better interpretation of what the fault codes really mean – multiple possibilities, depending on code combinations, fault modes, etc.

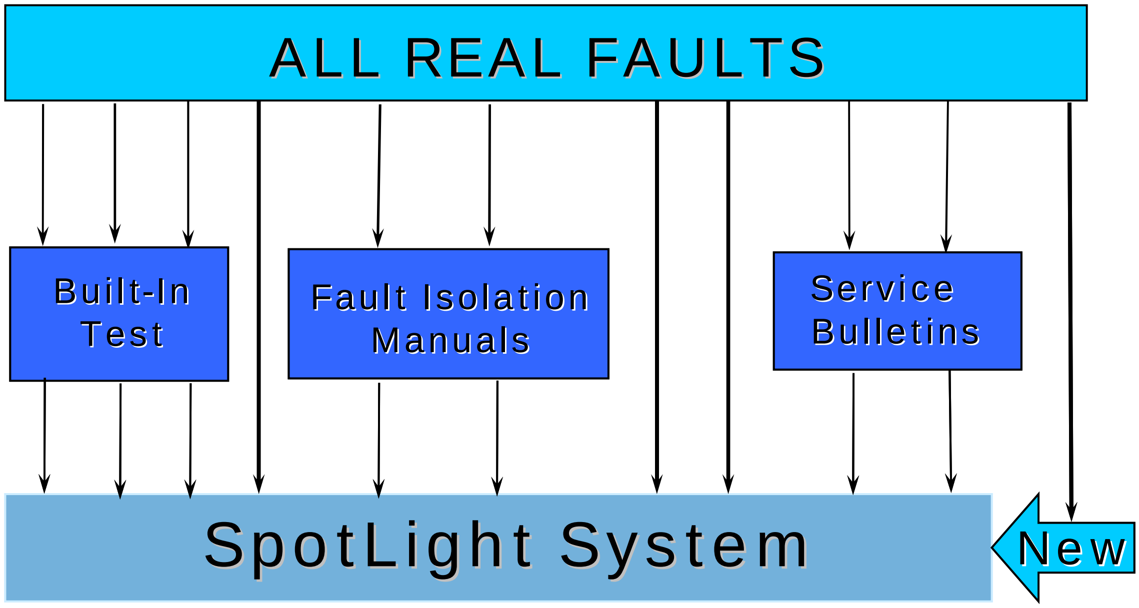


Figure 6-65: Knowledge Capture.

Each failure mode (not each failure event) is represented as a "Solution" in the knowledgebase. Each failure is researched, confirmed, described with discriminating symptoms, sanitized of user-identifying information, and enriched with helpful content such as references to maintenance instructions, tips, and explanations. BIT codes, cockpit messages, and trend alerts become "symptoms of the problem", as opposed to conclusions.

A technician consulting the system creates a "Session" that stores the details, and that session is shared only within the user's own organization – no operator can see another operator's troubleshooting sessions. Troubleshooting Sessions for which there is no solution in the knowledgebase are captured, investigated, and the results used to prepare a new solution, sanitized of user-identifying information. It is added to the knowledgebase after a quality approval process. In that way, the knowledgebase content grows as new problems are discovered across the community of users.

Thus each operator organization can benefit from the totality of experience among participating operators, with complete confidentiality. The system handles vehicle configuration differences, user access controls, privacy issues, and security issues.

To recap: One unified knowledgebase of "sanitized" knowledge is shared by many operators; Troubleshooting "sessions" are not shared – they are private to each operator's own organization; the Sessions will identify gaps in the knowledgebase while at the same time providing most of the information for the new solution. The maintainer of the knowledgebase (e.g. CaseBank, or Lockheed Martin, or whomever) identifies "new" problems and updates the knowledgebase with quality-controlled new solutions.

6.8.3.3.2 Integration with Diagnostic Resources

BIT – The SpotLight reasoning engine can interact automatically with downloaded data such as fault codes. If a connection to an automated download is not available for some reason, the user will be prompted to provide the information via a diagnostic question. In this sense, the system helps evolve the interpretation of

BIT codes and trend results. If a BIT code has never been wrong, the system will not get in the way. But if other causes for a BIT code have been discovered, they will be brought into the reasoning process.

FIM (Fault Isolation Manual) – With respect to FIM integration, options are available. Once the available field experience solutions are ruled out, the system can link to relevant FIM procedures, or the content of FIM procedures can be integrated with field experience. The system is, in fact, replacing the FIM in some developing aircraft applications because it eliminates the need for separate FIM creation and maintenance.

IETM (Interactive Electronic Technical Manual) – The system integrates with Interactive Electronic Technical Manuals for task support and authorized maintenance instructions through embedded hyperlinks.

HELP ESCALATION – The system has built-in asynchronous help-escalation facilities. This provides fault-centric communication that follows the aircraft, and allows collaboration not only within the user's own organization but also with authorized experts from outside the organization, with appropriate controls and security.

6.8.3.3.3 Guided Diagnostics

SpotLight delivers this integrated field experience as "guided diagnostics" that is comparable to the line of questioning that a human expert would follow. This is generated automatically by the system's reasoning algorithm and is updated with every new bit of information provided.

The algorithm takes into account:

- The degree of match between the problem conditions identified so far and the attributes of each of the candidate solutions;
- The cost and time of candidate solutions;
- The cost and time of the relevant tests to gather more information (observations, wiring checks, tests, etc.);
- The relative frequency of occurrence of the candidate solutions;
- The operating environment;
- Sounds and smells; and
- Recent maintenance activity.

The user is presented with an ordered list of the best diagnostic question to answer next. This provides flexibility, in that the user is permitted to answer only the questions that can be answered in the user's particular situation. As more questions are answered, relevant solutions will become more prominent and less relevant solutions will fade from prominence on the user interface screen. A decision tree can be extracted from the knowledgebase if paper copy is required.

6.8.3.3.4 Performance

A key measure of diagnostic performance is SpotLight's "hit rate", where a hit means the correct solution is identified. Current aircraft applications are achieving a hit rate in the 90% range after 2 – 3 years of knowledge capture through use.

The system is applicable to aircraft of any vintage – old and new. The key difference is in the source of the knowledge. For old aircraft, field experience can be captured by mining records. For new aircraft, the knowledgebase can be created from a FMEA database. For example, SpotLight is currently being used on both the C130E and JSF. It is also applicable to whole aircraft and/or to major sub-systems.

For aircraft manufacturers and operators, the system's knowledgebase represents their specific aircraft type with all systems integrated. For major sub-system manufacturers, the knowledgebase will represent that sub-system as used on many different applications. For example, one engine application supports over 55 different variants installed on over 20 aircraft types.

6.8.3.4 Conclusions

Field experience must be considered an integral element in the diagnostic methodology. The field experience of a global fleet of operators can be shared through controlled knowledge bases. New knowledge can be captured through diagnostic activities. SpotLight® is a proven system that does this.

6.9 INTEGRATED MAINTENANCE (HEALTH MANAGEMENT) SYSTEMS FOR USAGE MONITORING, INSPECTION, DIAGNOSTICS, AND PROGNOSTICS

6.9.1 General

Earlier sections in this chapter and Chapter 5 have dealt individually with the functions known as usage monitoring, NDE inspection, automated on-board inspection, diagnostics, prognostics, and decision support. This section deals with the integration of these functions in an embedded aircraft maintenance system or "health management" system. As explained in Chapter 2, such systems are referred to by several generic names: SHM, HUMS, PHM, DPHM, and IVHM. Aircraft manufacturers also have their own proprietary names for embedded maintenance systems, such as the Integrated Monitoring and Recording System (IMRS) on the Eurofighter Typhoon, which was described in Chapter 5. Not all real-time or near-real-time functions need to be embedded. In some cases it may be operationally acceptable and more effective to perform some functions in ground-based equipment that is networked with the aircraft via some form of data-link.

The maintenance and mission functions that may be included in an embedded maintenance system include the following:

- Perform on-condition tasks – i.e. inspections for potential failure. Included in "Condition-Based Maintenance (CBM).
- Enable on-condition inspections in place of discard or restoration tasks at a safe life. Included in CBM.
- Facilitate the application of a Predictive Maintenance Window (PMW), subject to approval by the regulatory authority. Included in CBM.
- Perform failure-finding tasks – i.e. inspections for failures not evident to the aircrew.
- Provide automated updates of Remaining Useful Life (RUL) during flight – known as prognostics.
- Facilitate more accurate usage monitoring (for estimation of RUL) through the integration of multiple in-flight data sources.
- Facilitate age exploration – i.e. the monitoring of parameters for a limited period to help improve the efficiency and effectiveness of the maintenance program.
- Perform diagnostics (fault recognition, fault localization and cause identification) during flight to provide the maintenance/support system with advance warning.

- Facilitate diagnostics by monitoring systems while they are operating in flight.
- Provide decision support for maintenance management.
- Facilitate corrective action by aircrew during flight to maintain or restore full or partial functionality of safety-critical and mission-critical components.
- Enable automatic reconfiguration in flight of safety-critical and mission-critical components to maintain or restore full or partial functionality of safety-critical and mission-critical components.

As discussed in Chapter 2, the term CBM is not well defined, but is often used in connection with the automation of preventive maintenance. The first three functions above have been highlighted as functions normally included in CBM by users of the term.

The term Predictive Maintenance Window (PMW) was used by J. Cook in Paper 4.6, and was mentioned in the description of MOD UK's model of maintenance/support in Chapter 4. If a potential failure can be detected early enough, it may feasible to defer corrective maintenance for a limited period – the PMW – without undue risk to the aircraft. The PMW would have to be some safe fraction of what is known in RCM as the "Potential Failure (PF) interval". A PMW can provide operational and logistical flexibility. However, the deferment of corrective action may be subject to regulatory approval. The Discussion and Conclusions for Chapter 4 include more detailed comments on the concept of a PMW.

The option to use embedded maintenance systems for preventive maintenance and decision support on specific components should be considered as part of the iterative RCM analysis process that starts during concept design. This process was described in Chapters 2 and 5. Embedded maintenance systems add weight, complexity, and cost, and so they are only used when they offer an adequate return on investment via improvements in aircraft availability and mission reliability. A greater degree of integration of these systems with other aircraft systems would help justify their use.

The remainder of this section is based on Paper 4.7 by Dunsdon. It illustrates in some detail the current philosophy and state of the art in integrated maintenance (health management) systems for aircraft. It also mentions efforts to develop an industry-wide standard for an open architecture, which is intended to encourage innovation and R&D by small and medium enterprises.

6.9.2 The TATEM and AEPHM Programs

6.9.2.1 Background to TATEM and AEPHM

GE Aviation Systems (formerly Smiths Aerospace Electronic Systems) is working on a number of research programmes to extend and improve the existing monitoring functions on aircraft into truly *Integrated Vehicle Health Management* (IVHM). Chief amongst these are:

- TATEM (Techniques and Technologies for New Maintenance Concepts), a €40 million European Commission project involving 60 companies from a wide spectrum of aerospace organisations, including airlines, airframe companies, suppliers, and research institutes; and
- AEPHM (Advanced Electrical Power Prognostics and Health Management), a joint USAF AFRL project with Boeing Phantom Work, St Louis.

These projects show the increasing awareness and interest in IVHM and the role that it has to play in increasing aircraft safety whilst also reducing the operating costs.

There is no doubt that improvements in the maintenance process can contribute to both improved operability and increased aircraft safety. With ongoing force size reduction programmes and ever increasing operational demands aircraft availability and mission reliability have become increasingly important over recent years, these two factors when combined with maintenance related costs give the overall measure termed “Operability”. Experience has shown that it is simple to keep any two of these three parameters under control but the true challenge for the future is to optimise all three to ensure that the correct numbers of mission reliable aircraft are available at the minimum cost.

Recent civil aerospace studies have shown that maintenance activities can account for as much as 20% of an operator’s direct operating costs and have remained at this level for many years. Detailed analysis of operating costs shows that there is clear scope for increasing the efficiency of the maintenance process. For example, it is estimated that line mechanics spend 30% of their time trying to access information to diagnose and rectify failures. Additionally, the occurrence of the need for unscheduled maintenance can introduce costly delays and cancellations if the problem cannot be rectified in a timely manner.

In a recent survey the incidence of human error in the maintenance task was estimated as being a contributing factor in 15% of aircraft incidents.

Existing aircraft systems tend to be limited in both their collection of data and the integration of the available data sources. This has tended to lead to a situation where the operator can become overwhelmed by the variety and disjointed nature of data sources and “not see the forest for the trees”. Modern IVHM systems are working to overcome this problem by integrating all the condition monitoring, health assessment and prognostics into an open modular architecture and then further supporting the operator by adding intelligent decision support tools.

There have been two major enabling technologies that have allowed IVHM to become a real system and provide these clear safety and costs benefits for operators.

The first is the evolution of modern integrated aircraft architectures. In older systems all data produced needed to be communicated by dedicated connections, to dedicated on-board data storage media for post-flight analysis using independent ground-based systems. This leads to additional weight and complexity on the aircraft, and then slow and unconnected analysis of the data on the ground.

Modern systems, such as the GE Aviation Systems Modular Processing System (MPS), selected for the Boeing 787, Lockheed C-130 AMP, and Northrop Grumman X-47, provide a modular computing hardware platform and partitioned operating system that will host the software applications of the airplanes avionics and utilities functions. The system replaces the traditional, unique, standalone, computers that are fitted to current aircraft. This Modular Processing System enables the evolution of a truly integrated data management system which will enable data to be communicated in a common format in a common physical and logical maintenance infrastructure. The system will include on-board communication media, air-ground communications media, air and ground computing resources, and data storage and access devices.

The second major evolution is the publication of open standards for IVHM systems, the leading standard, which is being used on both TATEM and AEPHM, is the Open Systems Architecture for Condition-Based Maintenance (OSA-CBM). This was developed under a NAVAIR Dual Use Science and Technology programme that completed in 2002. This published standard allows multiple companies to work together to produce the software components for an optimised IVHM system and ensures that all of the data is available in a single location, and format, for the operator.

In this section, the AEPHM programme is used as an example of an IVHM system, where microprocessors embedded in digitally controlled power distribution systems, as well as in the digital controllers within these systems, provide an unprecedented, affordable and inherent opportunity to monitor an electrically powered vehicle's systems health. Data transmitted to, and from, these controllers can be used to characterize the system and component operating signatures, thereby enabling advanced diagnostic and prognostic capabilities, through diagnostics, prognostics and decision aiding algorithms.

The AEPHM architecture supports system level fusion of evidence and state information from multiple sources to improve estimates of degradation. Phase I of the program was completed with an end to end, hardware-in-the-loop (electric actuator, fuel pump, fuel valve, arc fault, and power distribution unit) demonstration with on-line data generation to show the integration of the technology into a realistic setting.

6.9.2.2 Basic Concepts

The concept of modern Integrated Vehicle Health Management (IVHM) Systems can be directly traced back the original Health and Usage Monitoring Systems (HUMS) developed for helicopter during the 1980s and 1990s.

The concept of Prognostic Health Management (PHM) for engines has been widely embraced but the remainder of the aircraft still lags some way behind. This section looks at how IVHM could help improve availability and how systems such as the GE Aviation Systems Common Core System (CCS) will allow this to happen.

Figure 6-66, shows how early warnings of failed components allow the ground crew to prepare for the arrival of the aircraft and hence reduce the time required for turn-around. It also shows how, if the fault can be detected at an early stage, the need to perform maintenance at the turn-around might be eliminated. Whilst these potential benefits are well understood and have been written about for many years [191], no comprehensive health management systems are yet in service, this paper will look at the reasons for this and showcase recent work which demonstrates that the technology is now finally ready for such a system to work in practice.

IVHM: Changing Maintenance

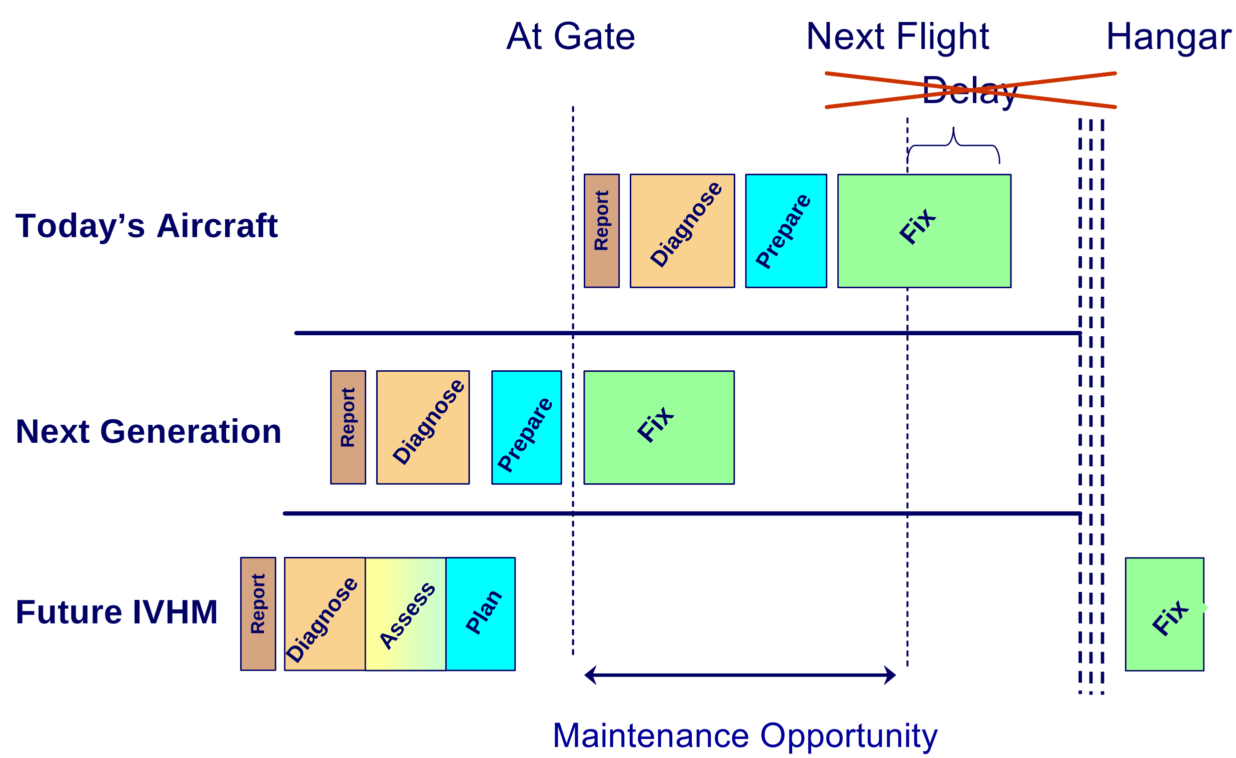


Figure 6-66: The Effect of IVHM on TAT.

6.9.2.3 Problems of System by System PHM Approach

Historically Health Monitoring Systems have been implemented on "where necessary for safety" basis. This has created a situation where an aircraft may have several separate Health Monitoring Systems for specific parts, classically the engines on fixed wing aircraft and the drive train on helicopters.

This approach has led to several significant problems when attempting to scale this up to the whole aircraft, namely:

- Weight – For most PHM systems most of the weight is classically in the wiring, so scales as a factor of both aircraft size and the number of systems monitored.
- Cost – Buying and installing *separate* monitoring systems for each aircraft system would be an enormous investment and undertaking. Any such installation would undoubtedly require the aircraft to be out of service for sometime, hence further increasing the costs. As a baseline it currently costs up to £100,000 (US$180,000) to buy and fit a helicopter HUMS to cover the drive-train.
- Complexity – By purchasing independent monitoring systems for each aircraft system the operator could have to deal with multiple ground stations and interfaces and train their personnel to use all of these separate systems. Also, it is highly probable that these systems could, and at times would, provide contradictory results.

These have often been cited as the reasons why there has not been more widespread uptake of Health Monitoring Equipment. One of the first programmes to invest in a comprehensive IVHM system was the Joint Strike Fighter (JSF), where mission readiness and availability requirements have driven the need for IVHM.

6.9.2.4 Modern Aircraft Systems

One of the biggest changes in the design of modern aircraft systems has been the development of Integrated Modular Avionics systems. These systems such as the Common Core System (CCS) selected for the Boeing 787 provide a common avionics platform on which multiple applications can be run in parallel. This has provided a major breakthrough in terms of both hardware and especially software with these common systems providing a suitable platform for running numerous applications with different requirements and criticality levels without needing a separate "box" for each system.

As part of this seed change in the design of systems, aircraft have implemented high speed digital buses such as IEEE-1394B, on JSF, and AFDX, on 787 and A380. The GE Aviation Systems Remote Interface Unit (RIU) shown in Figure 6-67, variants of which have been selected for both JSF and 787, allows up to 200 signals to be collated near the point of generation and streamed onto these buses, thereby reducing the wire count by up to 2 orders of magnitude.

Figure 6-67: Smith's Remote Interface Unit (RIU).

Once these signals have been collected by the RIU they can be made available in the central CCS in a standard format making any storage, processing and further distribution much simpler.

6.9.2.5 Concept of IVHM

These modern systems have finally allowed the realisation of IVHM, since the combination of RIU/RDC and CCS has tackled the major challenges identified above.

- **Weight** – The RIU/RDC has greatly reduced the wiring that would have been required for multiple individual systems. Also the CCS allows the IVHM software and algorithms to be run alongside the other airborne software, thereby avoiding the need for dedicated IVHM hardware. The aircraft's normal communication methods can also be used – a major breakthrough compared to the dedicated PCMCIA card readers classically required in the cockpit for helicopter HUMS.
- **Cost** – By utilising the existing aircraft hardware for both data processing and networking, the cost of installation now reduces to the cost of the sensor systems and software. Virtual sensor systems can reduce the cost of sensors, and software can be installed without significant aircraft downtime.
- **Complexity** – By transmitting all data over common buses to a common core, complexity is greatly reduced. Complexity can be reduced even further by developments such as the Open Systems Architecture for Condition-Based Maintenance (OSA-CBM) initiative [192]. The maintenance technician can now expect one coherent interface to the entire maintenance system. Attempts are being made to develop a "Process-Oriented" structure for the data displayed at the point of need [195].

The combination of RIU/RDC and CCS has also placed all of the data in one place. This centralisation opens up more possibilities for aircraft health management, because "the whole is greater than the sum of the parts".

However, the realisation of a workable system still requires an open software architecture, to allow airframe companies, equipment suppliers, and specialist PHM companies to provide the tools to turn this data into information, knowledge, and finally actions. Developments such as OSA-CBM are playing an important role in this regard.

The goal of OSA-CBM is "to facilitate the integration of PHM components from a variety of sources. OSA-CBM is striving to build a de-facto standard that encompasses the entire range of functions from data collection through the recommendation of specific maintenance actions".

OSA-CBM has now been published as a Machinery Information Management Open Systems Alliance (MIMOSA) standard, defining an open architecture for implementing IVHM systems. It is a cross-industry standard. In the aerospace industry it has been implemented in developmental systems by Boeing Phantom Works, GE Aviation Systems, and the TATEM project. The OSA-CBM framework is shown in Figure 6-68, and full documentation, UML models and XML schemas may be downloaded from the MIMOSA and OSA-CBM websites [192].

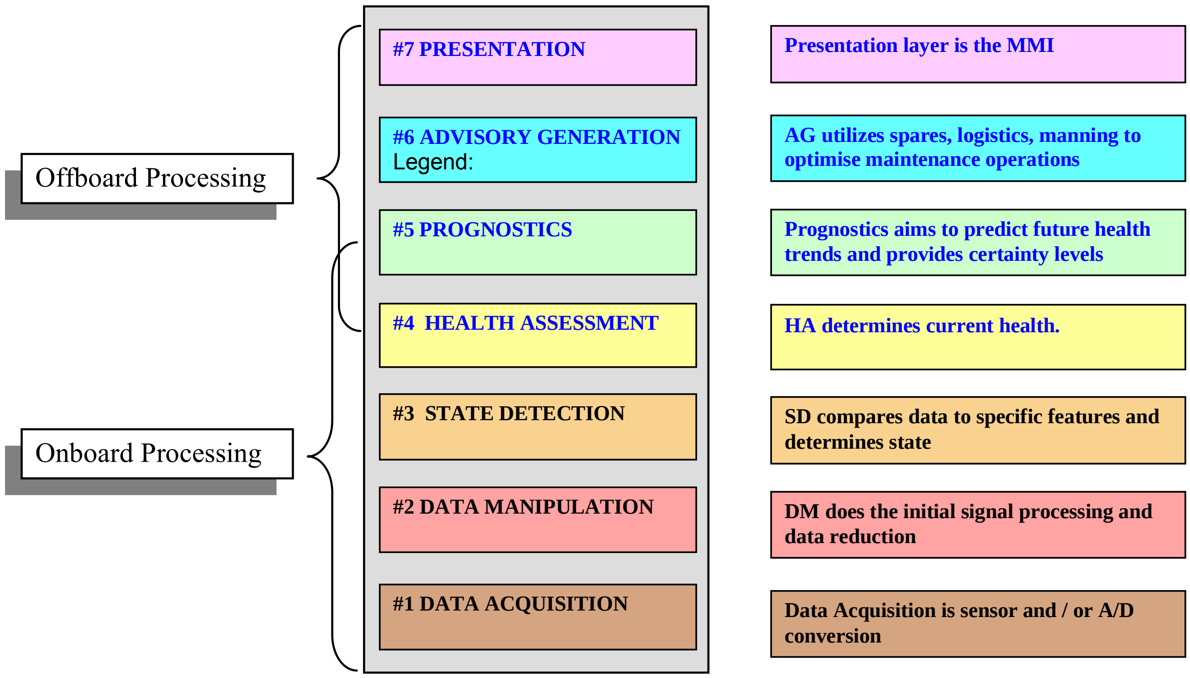


Figure 6-68: OSA-CBM.

The combination of the RDC to obviate the need for dedicated sensor wiring, common computing platforms such as the CCS, and maintenance software architectures such as OSA-CBM have now made it possible to have the benefits of PHM without the pain. This is the true concept of IVHM.

6.9.2.6 Advanced Electrical Power Prognostics and Health Management (AEPHM) Programme

6.9.2.6.1 Introduction

As an example of a future IVHM system application for a military aircraft and the use of the generic approaches described above, this section will look at the Advanced Electrical power Prognostics and Health Management (AEPHM) programme.

The Aircraft AEPHM program was a Dual Use Science and Technology (DUS&T) program being sponsored by the Air Force Research Laboratory Power Division (AFRL-PRPE). Boeing Phantom Works in St. Louis was the prime contractor for the AEPHM program with GE Aviation Systems as the principal sub-contractor.

The objective of the program was to demonstrate health management technologies which will enable condition-based maintenance and thereby improve the availability of military aircraft and the dispatch reliability of commercial aircraft. Aircraft electrical power distribution systems are of increasing concern from a safety perspective in both civilian and military aircraft. The trend toward more electric aircraft is accelerating the incorporation of flight-critical electrical components such as actuators, fuel/hydraulic pumps, valves, and fans. An ability reliably to detect impending failures of electrical loads and impending arcing in aircraft wiring well in advance of their occurrence can improve flight safety and allow more predictable aircraft operation.

The outline of the AEPHM programme can be seen in Figure 6-69.

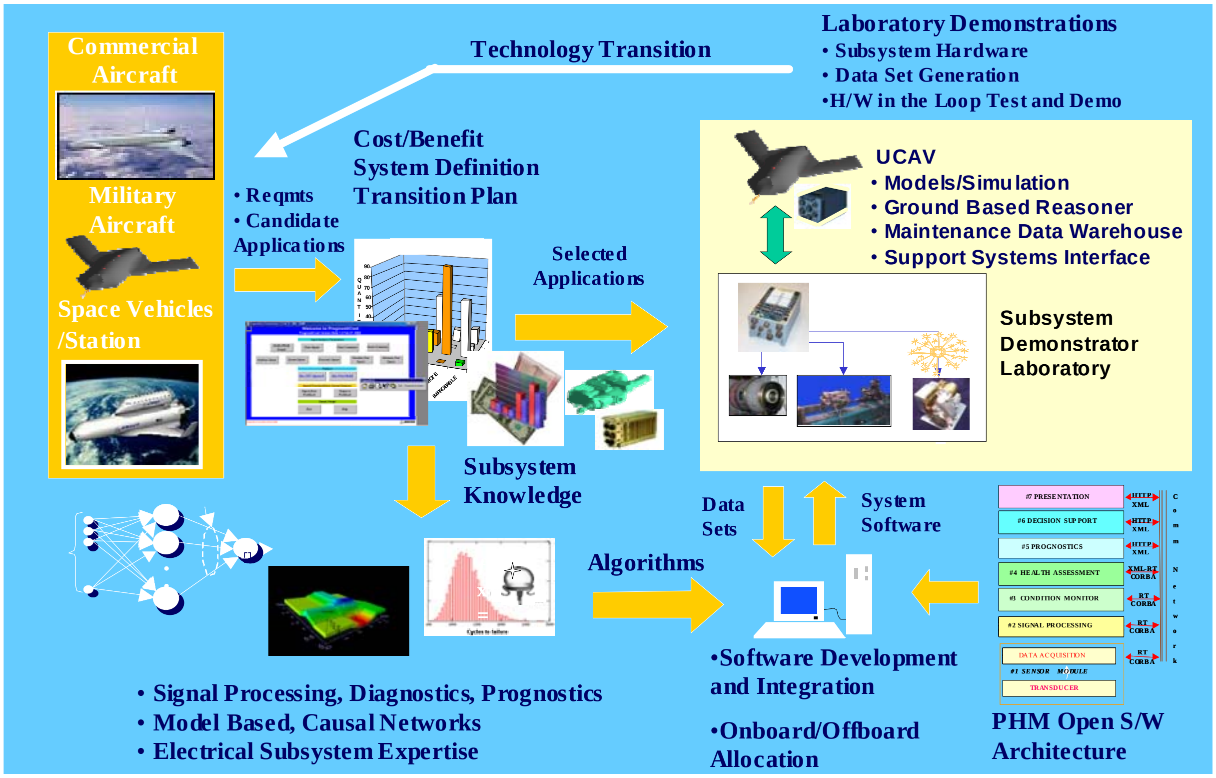


Figure 6-69: Advanced Electrical Power Prognostics and Health Management (AEPHM) Programme – Overview.

An important goal of the AEPHM program was to find an economic way of accessing the data needed to achieve the desired level of health management. The goal was achieved by modifying an existing GE Aviation Systems Power Distribution Unit (PDU) (Figure 6-70). This unit provided access to data on electrical loads, and was also used to perform health management processing.

Figure 6-70: GE Aviation Systems Power Distribution Unit (PDU).

Prognostics and Health Management (PHM) applications for electrical sub-systems were identified, and algorithms were developed and integrated into a PHM system that would assist an operator/commander and support logistics and maintenance functions. To facilitate the integration of multiple components, an open software architecture was used. The primary focus for the demonstration of AEPHM technology was electrical systems similar to those now being implemented on advanced Unmanned Air Vehicles (UAV). Failure modes and degraded operation were studied with the help of seeded faults and accelerated wear tests so that realistic diagnostic and prognostic models could be developed.

The first phase of the AEPHM program was completed in July of 2005 with a demonstration of health management for actuators, fuel pumps, and valves, and a demonstration of Arc Fault Protection (AFP). The second phase of the program is addressing generator health management.

Special test fixtures were used to emulate realistic operating conditions and collect data. Electro-Mechanical Actuators (EMA), fuel pumps, and fuel valves were tested in the Boeing Sub-system Demonstration Laboratory. Arc and wire fault testing and data collection were performed in GE Aviation Systems' laboratory in Cheltenham, UK [193].

Electrical actuation was a key area of interest because of its extensive use on UAV. The actuator selected for experiments and demonstration was a 135 VDC brushless motor unit, as shown in Figure 6-71. This model had previously been used for flight control applications on UAV and has dual motors powering a drive train that includes bearings, a gear drive, and a ball screw.

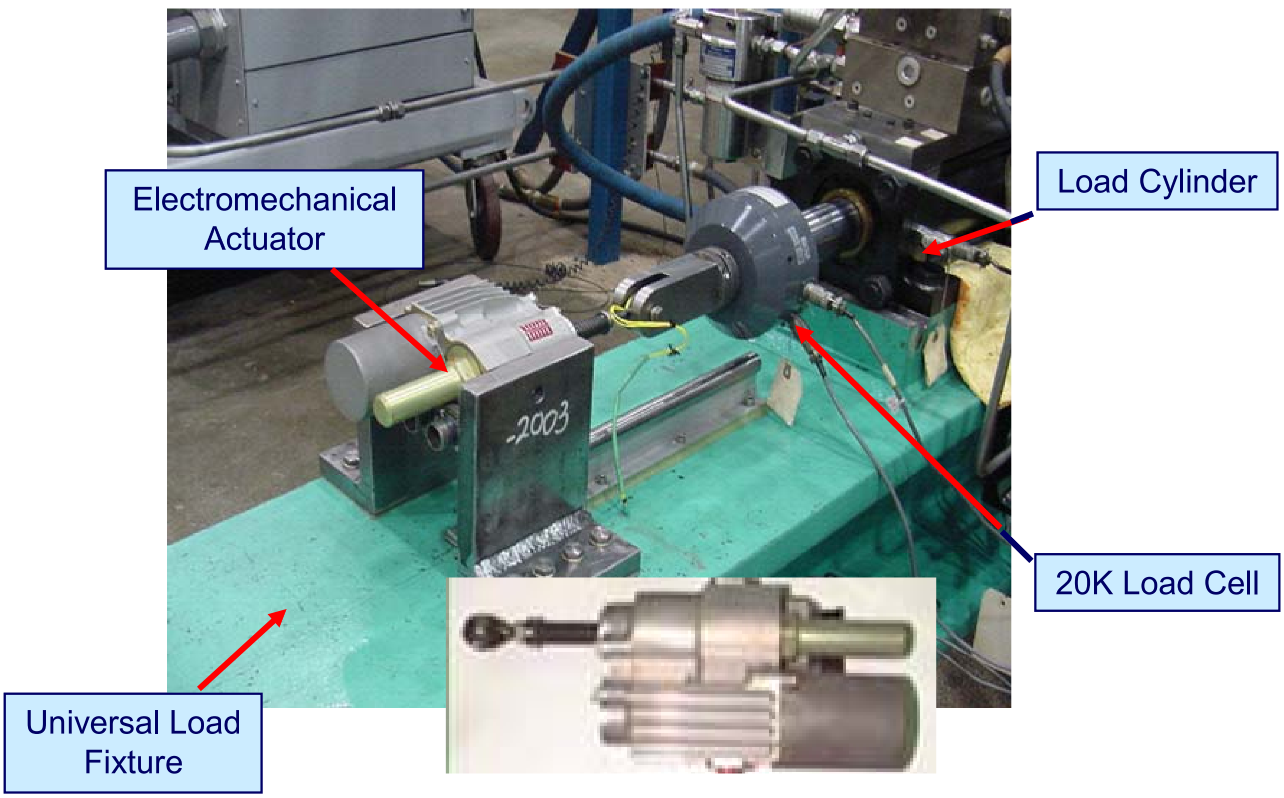


Figure 6-71: AEPHM Actuator Test Rig.

In developing PHM for the electrical actuator, the aim was to detect potential failures in the motor and mechanical drive and characterise their progression to functional failure. In practice, this meant detecting gear, bearing, and ball screw failures before they resulted in mechanical jamming of the actuator, and characterising the failure modes such that diagnostic and prognostic algorithms could be developed.

Data collection to characterize actuator failure modes consisted of performing accelerated wear tests in the actuator test fixture with defined load scenarios or profiles. Four actuators with various levels of wear were seeded with faults and subjected to accelerated life tests. Failure analyses were performed after the tests.

Based on the extensive data collected from these tests, four actuator PHM health indicator algorithms were developed: torque efficiency, free play, motor performance, and vibration analysis. The results of the motor performance algorithms are illustrated in Figure 6-72, which plots the relative motor performance (health) for 5 levels of degradation of the motor coils at two different loads. The graph illustrates how the effects of the degradation of the motor coils could be measured and calculated independently of the load on the actuator from data available from the PDU.

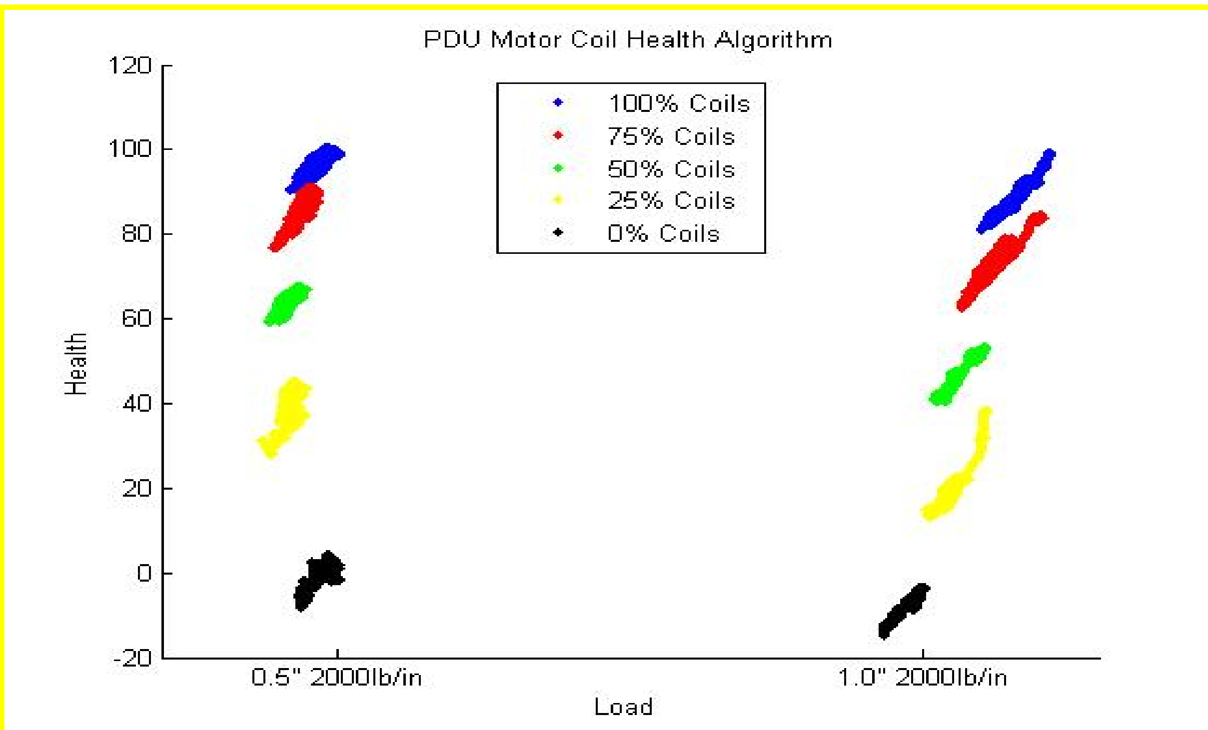


Figure 6-72: Load-Independent Motor Performance Algorithms – Results.

The objective of the fuel system PHM study was also to avoid in-flight failures and improve availability by reducing downtime. A 270 VDC transfer pump (Figure 6-73) was used in the tests. In consultation with the manufacturer of the fuel pump, several catastrophic failure modes were studied, including bearing failure, dry running, and foreign object damage. The load on the pump was adjusted by means of an output valve.

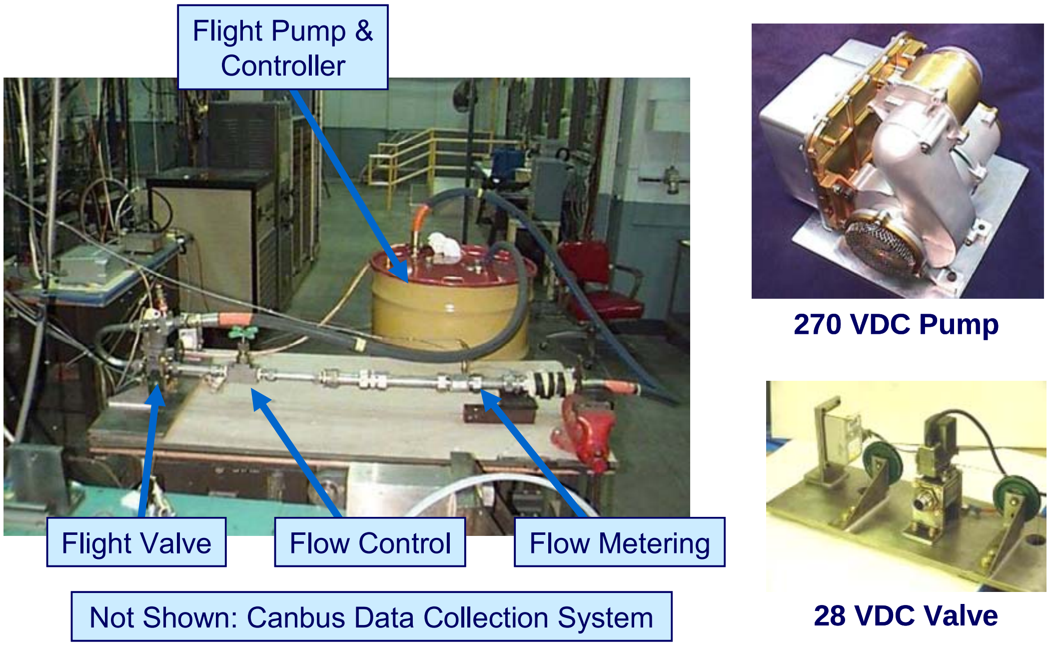


Figure 6-73: AEPHM Fuel System Test Rig.

Data to characterize the pump failure modes were collected using the capabilities of the PDU. It was found that potential failure of the pump could be detected by means of a shift in frequency, as illustrated in Figure 6-74. Since pump control is based on constant power, it is not possible to detect this reduction in motor speed from the control signal interface with the pump.

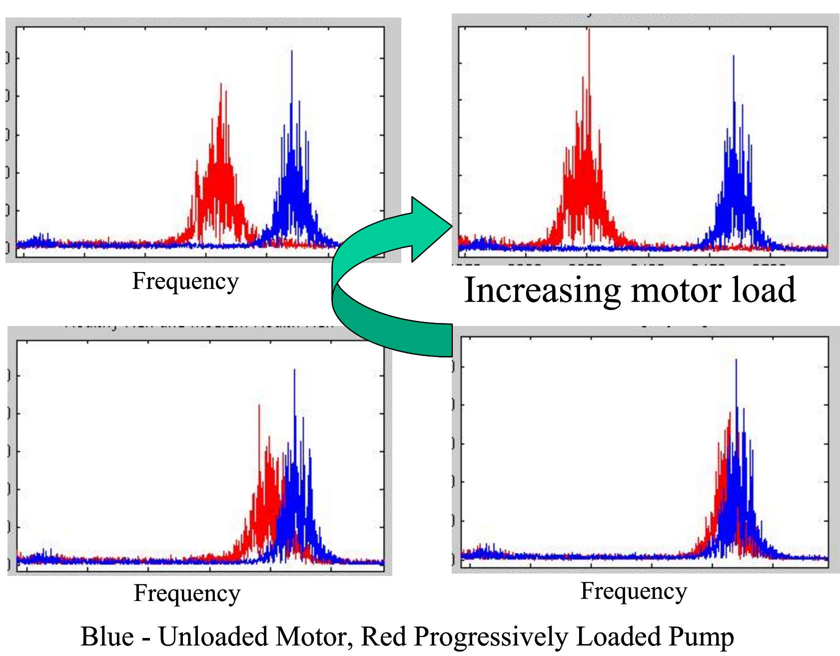


Figure 6-74: AEPHM Fuel Pump Results – Pump Frequency Change Indicates Potential Failure.

In the case of the electrically actuated fuel valve, it was found that progressive binding of the valve could be detected by monitoring the actuation time and the actuating current. The change in the slope of the time/current characteristic curve indicated the degree of binding. For the tests, different levels of binding were simulated by mechanically loading the valve. Two algorithms were developed to detect binding conditions from changes in the slope of the actuation time/current characteristic curve. One used data from the PDU, while the other used data from the vehicle management system. Both algorithms were effective.

The studies on the fuel pump and fuel valve showed that PHM concepts could be implemented for these components without the need to add sensor systems to the aircraft.

6.9.2.6.2 System Integration and Demonstration

The diagnostic and prognostic algorithms for the fuel system components were integrated into an end-to-end sensor to decision-support demonstration system, as shown in Figure 6-75. The system was configured to run using hardware inputs or stored scenario data.

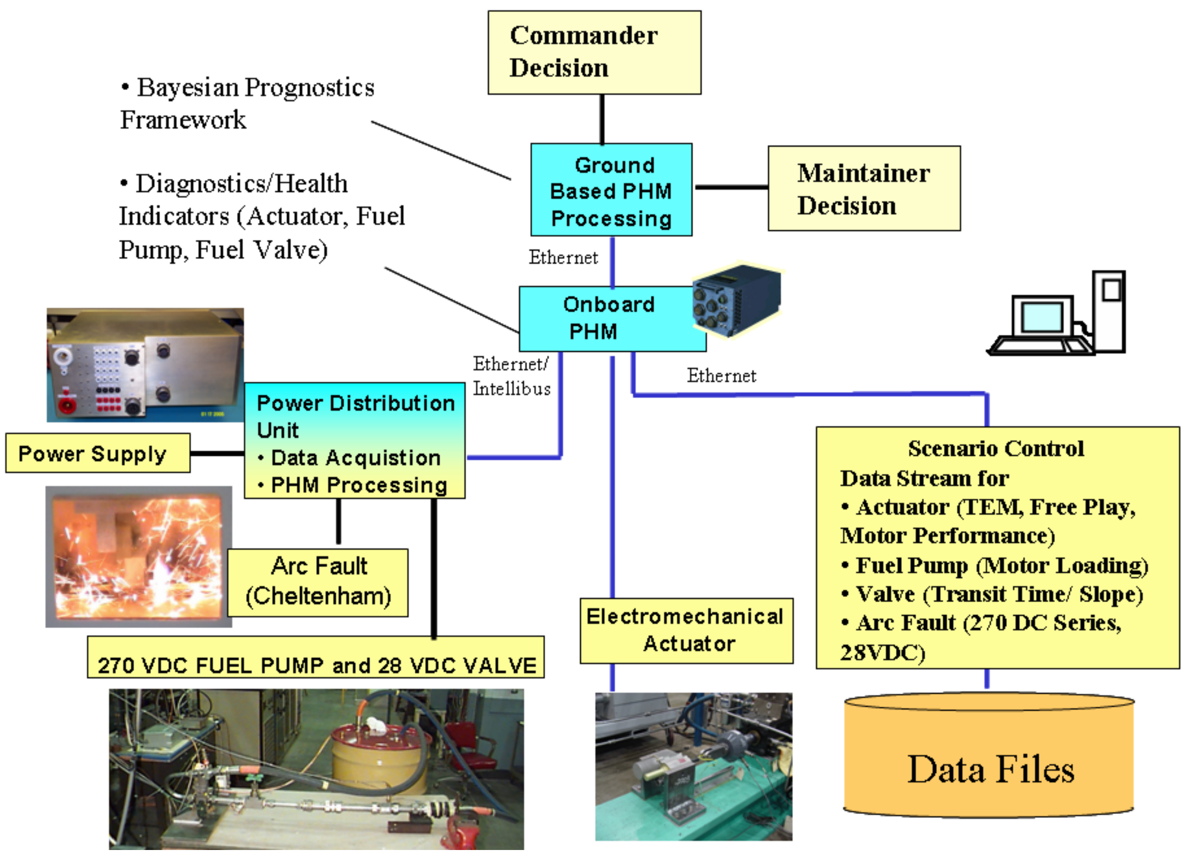


Figure 6-75: AEPHM System Integration.

System modules were configured in accordance with the Open System Architecture for Condition-Based Maintenance (OSA-CBM) standard. The demonstration system included grey scale health indicators for the actuator, pump, and valve. It also generated trending and prognostics (remaining useful life) for actuator bearing failure and fuel pump failure as the load on these components were progressively increased.

It was envisioned that the health indicators for the various sub-systems would be generated on-board but that trending, prognostics, decision support, and other maintenance/support management functions would be performed on a ground-based system using data downloaded from the aircraft.

Full test facilities for arc fault existed only at GE Aviation Systems laboratory in Cheltenham, UK, while facilities for actuator and fuel system hardware-in-the-loop testing existed only in the Boeing sub-system laboratory. However, data streams from all systems were available for "integrated" demonstrations.

The AEPHM program established the feasibility of detecting and trending actuator and fuel system degradation. It also established the feasibility of using the GE Aviation Systems Power Distribution Unit (PDU) as an effective means of implementing arc fault protection, data acquisition, and data processing for electrical system Prognostics and Health Management (PHM).

The actuator and fuel system health indicators and trending/prognostics were based on only a few test cases. Nevertheless, these were sufficient to identify failure modes with progressive degradation that could be detected early enough to avoid functional failure. Further R&D is needed to develop a flight-worthy PHM capability for electrical actuators. In particular, ways must be found to differentiate reliably between failure modes. Additional sensors (e.g. accelerometers) may be needed for this purpose.

6.9.2.6.3 Reasoning with Design Data

A Failure Modes and Effects Analysis (FMEA) can serve many purposes, but is commonly used in the design of a new system to identify possible failure modes and their effects on system functionality. It is a useful source of information for developing diagnostics and verifying testability. This design data may contain thousands of propositions describing the causal associations between components and failure modes.

The knowledge captured by a FMEA and testability analysis can be utilized in the early construction of a diagnostic reasoning engine. This reasoner will have to deal with uncertainties in interpreting the available data. Causal networks incorporating a Bayesian approach to diagnostic inference are virtually unrivalled as a theoretically sound, generic approach to reasoning with multiple, potentially conflicting pieces of evidence [194].

A Boeing fuel system is shown in Figure 6-76. The major components include transfer tanks, wing tanks, engine feed tanks, pumps, valves, plumbing with t-connections, power distribution units, and remote interface units. The components can be grouped into major sub-assemblies: left and right transfer tanks, left and right wing tanks, left and right engine feed tanks, transfer plumbing, interconnect and cross-feed, and right and left engine feeds. The structure of the causal network for Bayesian analysis of this fuel system is relatively simple. The failures causally connect to detecting tests and their probability of occurrence can be determined from the failure rate information in the FMEA. The failures also connect directly to their parent component, which in turn can be connected to other components through the component hierarchy. The causal network allows the modelling of the probability of a test being triggered given multiple failure combinations. The statistics for such a model are not contained in the design data, and it is hard to imagine how sufficient data could be collected from field experience to allow such combinations to be reliably modelled. Therefore, Noisy-OR gates are used to constrain the causal network's model to those probability estimates contained in the FMEA.

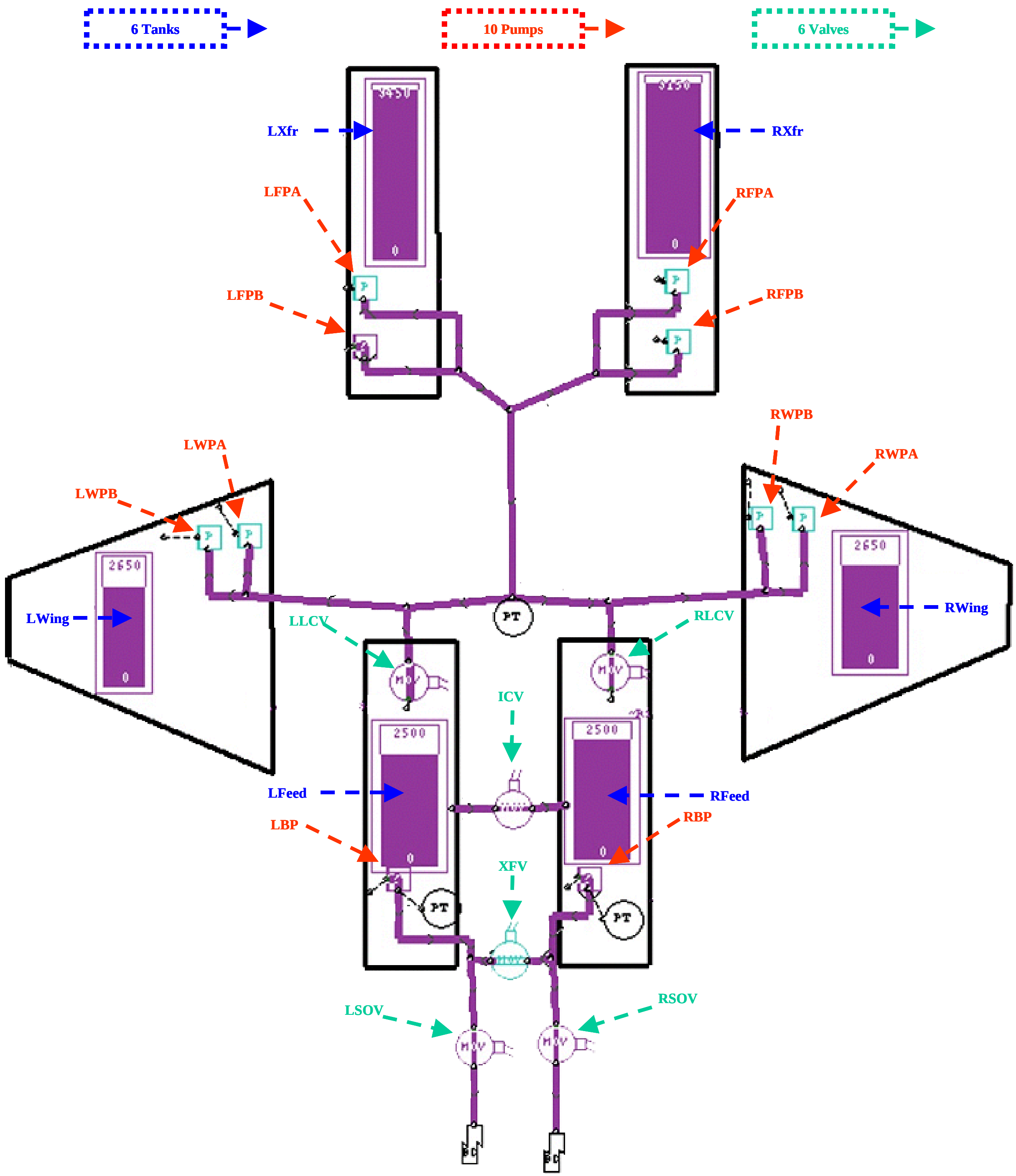


Figure 6-76: AEPHM Fuel System for Diagnostic Reasoning.

In this case, the large size of the fuel system network required the development of some novel techniques in dynamic restructuring to identify network sub-structures that could compile and infer independently while reaching the same conclusions as if the network had been kept complete.

Causal networks have fundamental benefits over logic type reasoning systems. Firstly, they can perform non-monotonic reasoning, which is fundamental for correct diagnosis. Secondly, partial evidence of state can be entered. For example, a valve might have states open, closed and partially open. When entering evidence for this valve it might not be possible to define its true state but it may be known for example that the valve is definitely not closed. Thirdly, causal networks can be updated with probability distributions based on more recent data. Finally, they can detect when evidence may not be consistent.

From a practical standpoint, it is also useful that diagnostic knowledge contained in a FMEA and other design data can be automatically mapped into a causal network. This approach avoids the need for the manual development of aircraft and system diagnostic fault-trees.

6.9.2.7 Where Next for IVHM?

Projects such as TATEM [195] and AEPHM have shown that operators could gain substantial benefits from a truly Integrated Vehicle Health Management solution. These benefits include:

- Optimisation of maintenance intervals;
- Leaner maintenance regimes / reduced activity and shop-time;
- Reduction in spares inventory;
- Fewer unscheduled activities;
- More technically advanced and integrated aircraft and systems;
- Support for the increased use of electrical systems; and
- Less technical *data* – more technical *information*.

In the future, IVHM could even help organisations achieve greater internal flexibility, integration, and collaboration.

To achieve all these benefits, the IVHM systems must be based on the needs of the end users. A key goal for an IVHM system designer is to ensure that *"the right qualified person is at the right place at the right time with the right tools, the right parts, and the right information, doing the right economically opportunistic maintenance, seamlessly integrated throughout the organization as well as the external value chain network."*

The following is relevant advice to IVHM system designers:

a) Understand the operator's need for an integrated "end to end" solution.

b) Use and support open system architectures for IVHM solutions:
   - Accept that no one organisation can expect to provide the whole solution.
   - Use an architecture that allows for future developments and changes.

c) Ensure the architecture is simple to use for the other solution providers.

d) Respect that 3rd party organisations need to be able to retain their intellectual property rights.

e) Ensure support for the integration of 3rd party, and operator-developed enhancements.

GE Aviation Systems and Boeing Phantom Works are continuing their close working relationship beyond the AEPHM programme to develop extensions to the OSA-CBM standard [196].

6.10 MAINTENANCE CONCEPTS AND TECHNOLOGIES FOR ACHIEVING A MAINTENANCE-FREE OPERATING PERIOD (MFOP)

6.10.1 Challenging Traditional Reliability Thinking

As mentioned in Chapter 2, the trend to more expeditionary operations by NATO forces makes it important to have the ability for limited periods to enhance the availability of deployed aircraft while simultaneously minimising their logistics footprint. The term "Maintenance-Free Operating Period (MFOP)" is sometimes used idealistically to describe this maintenance concept. One of the purposes of IVHM systems, discussed earlier, is the deferment of corrective maintenance without undue risk. Thus IVHM systems could help in the achievement of an MFOP capability.

The remainder of this section is based on the discussion of the MFOP concept in Paper 4.8 by Hockley. Hockley observes that the implementation of the MFOP concept challenges traditional reliability thinking and the way that R&M specifications have been written. In designing new equipment there is a need to get back to the designer's basic aim of designing for success, and away from the traditional philosophy of having an acceptable level of failures.

6.10.2 What are the *Real* Customer Needs?

The Royal Air Force concluded in the 1990s that the move to an uncertain expeditionary posture required guaranteed periods of aircraft availability. It was realised that changes in design and maintenance philosophy would both be needed to achieve these. From a design perspective, the Mean Time Between Failure (MTBF) had been the primary metric of reliability. This metric remains useful to this day, but is based on an assumption that failures will occur. It had become necessary also to design for success in the form of substantial periods without failures [197]. This modified view of aircraft reliability is consistent with standard definitions of reliability:

- The ability of an item to perform a required function under stated conditions for a specified period of time [198].
- The duration of failure free performance under stated conditions [199].

On the other hand, the traditional metric of reliability in acquisition contracts has been the Mean Time Between Failures (MTBF). For example, the reliability specification for the Tornado GR1 is an MTBF of 1.25 hours. This has always been translated as 800 faults per 1000 flying hours. MTBF have always been converted this way. This metric of reliability is not necessarily consistent with the above definitions of reliability and the RAF's need for guaranteed periods of aircraft availability.

While the traditional process of using MTBF might *account* for reliability, it fails to "engineer-in" the right solution. What must be done is to get rid of the idea of "random failures" and their inevitability.

6.10.3 New Ways

The concept of Maintenance-Free Operating Periods (MFOP) would help to engineer the right solution. Such periods would be interspersed with a defined period of recovery when maintenance could be planned to restore the system to full operation; this was defined as a Maintenance Recovery Period (MRP). MFOP are applicable at the system and sub-system level, and it is believed eventually, at the major platform level. Neither successive MFOP nor successive MRP lengths would be an equal length; flexibility of management and planning was in fact the key. The following are provisional definitions of MFOP and MRP:

- A Maintenance-Free Operating Period (MFOP) is defined as a period during which the equipment shall operate without failure and without the need for any maintenance; however, faults and minor planned contractually agreed maintenance are permissible [200].
- A Maintenance Recovery Period (MRP) is defined as the time spent carrying out maintenance after an MFOP has elapsed. The maintenance done should be enough to ensure that the equipment can start another MFOP cycle [200].

In other words a pure MFOP is about doing nothing between MRP except operating the equipment, replenishing consumables, fuel, oil, tyres, etc., and pre-positioning the spares and manpower that will be required for the next MRP.

In the UK, availability-based contracting is now being used in the procurement of aircraft and maintenance/ support. In the future, contracts with requirements based on capability might be used. The MFOP concept could be adapted as a performance requirement – a measure of effectiveness – in such contracts.

6.10.3.1 Design Approach

In designing for a MFOP capability, a bottom up approach is needed to reliability assessment, rather than a top-down allocation of failures and failure rates. To achieve a specified aircraft MFOP, all components would have to be designed and maintained to have an MFOP greater than the specification. A key aspect is to understand the equipment's operating parameters, usage (and "abusage") and the operating environment. There is a surprising lack of knowledge on the part of both designers and operators on these issues. A database of actual service usage would be useful in this regard. The designer must, also pay more attention to understanding all potential failure mechanisms. That means that he must understand the true physics of failure of *all* aspects of the design in all environments. Finally, there must be an understanding of the relative value of predictions versus test data in the earlier stages.

The real challenge of course is how to apply MFOP at the overall platform level. There are many options that need to be designed in at the earliest stages. Designing inherent reliability into the platform is the first solution and is perhaps self-evident, as is deciding effective lifing policies where required. Some designs will be able to employ redundancy better than others; some will not be able to employ it because of weight restrictions. However, reconfigurability might be possible as a design solution, as it usually would not involve additional weight. Another solution might be to use sophisticated multi-tasking and shared use of systems. Some of the other design options available are:

- Smart structures which possibly indicate faults.
- The various forms of condition monitoring, self-test, self-diagnosis and self-correction systems.
- Early warning and indication of faults perhaps with sophisticated avionics and software measures such as neural networks.
- Fault tolerance and other the capabilities obtained from integrated modular avionics.
- Reconfigurability of avionic systems.
- System redundancy in all its forms, some of which might not involve additional weight.
- Knowledge of the life of the equipment.
- Graceful degradation of a system as long as it does not involve loss of the mission.
- New and emerging technologies that might give improvements.

- Improved processes for manufacture and repair which will enable an improvement in the inherent reliability.
- Sacrificial elements that give a warning of problems.
- Health and Usage Monitoring Systems (HUMS) which will enable improved knowledge of the health of the system and eventually will be developed into a prognostic ability.

The implementation of an MFOP is likely to require the deferment of some corrective maintenance. This is already an accepted practice, but only to a very limited degree. At present most if not all failures on military aircraft require immediate corrective action. In some cases, usually because there is a lack of manpower or spares, the fault may have its rectification deferred. In RAF terminology this requires a “red or green line” to be raised which identifies the fault either as an acceptable one to be deferred (green line) or one that gives a limitation on the operation of the aircraft (red line).

6.10.3.2 Using Health Management Systems to Enhance MFOP Capability

On-board maintenance systems, such as the HUM, PHM, and IVHM systems described earlier in this chapter provide knowledge of the state of individual aircraft in a formation, and can thereby facilitate the selection of aircraft for deployments requiring a MFOP. Such systems can also help minimise the logistics footprint by ensuring the most effective use of maintenance/support resources. However, the most important potential contribution of health management systems to MFOP capability is in increasing the numbers of mission critical components to which on-condition maintenance can be applied and in maximising the associated potential failure intervals – i.e. the estimated remaining useful lives after the detection of potential failure. If the risk of functional failure would remain low for a long period after the detection of potential failure, corrective action could be deferred. This ability to defer corrective action could be used to avoid or mitigate any effect on aircraft availability during the MFOP. The strategy is illustrated in Figure 6-77. The time between the end of the MFOP and the predicted failure point can be regarded as a safety period. The operator must determine the minimum acceptable safety period, taking into account any regulatory constraints.

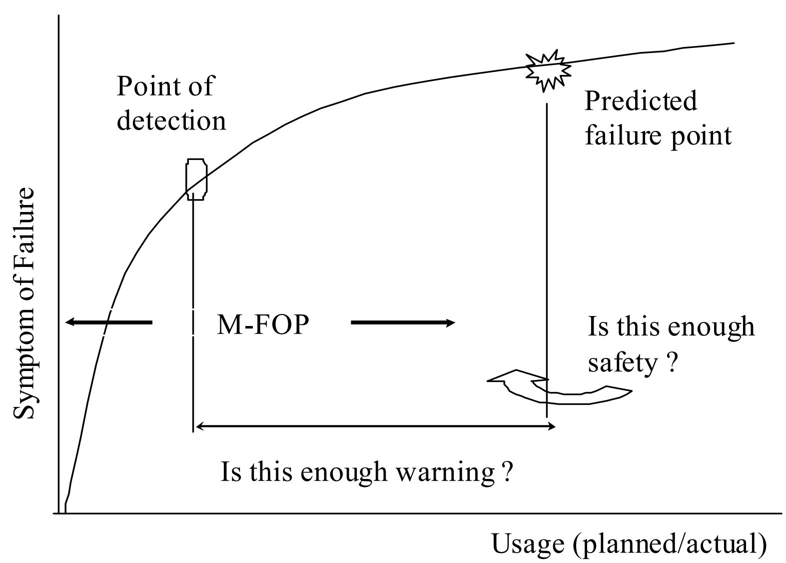


Figure 6-77: Failure Life Characteristics.

The probability that an aircraft will require corrective maintenance during an MFOP depends on the reliability and mission reliability of every mission-critical component, taking into account any redundancy and fault tolerance. These reliabilities will normally diminish with cumulative operating time. The MFOP capability of the aircraft or a component can be assessed by plotting the reliability from time zero and overlaying the required probability of completion (Figure 6-78).

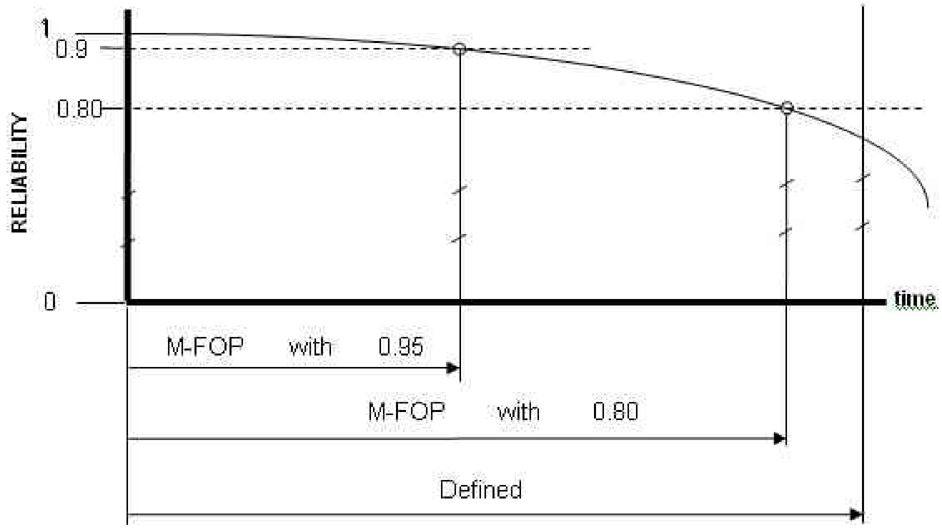


Figure 6-78: Reliability vs. Time and Probability of Maintenance-Free Operating Period (MFOP) Completion.

Generally a higher requirement for success results in a smaller MFOP, and vice-versa. Knowing the probability of completion of the individual MFOP for each separate piece of equipment gives the user the ability and confidence to determine the number of aircraft required for a given task.

Working strictly to a system MFOP may necessitate the replacement of components more often than needed. Also, it is possible that a contractor will design equipment with a specific MFOP that is supplied to more than one customer. Each customer will have different usage and will require a different MFOP capability. The concept of a Management MFOP was developed in some excellent work presented by Burdaky to the 10th MIRCE Symposium [201]. It showed how MFOP could be managed effectively to utilise much of the sub-system life that might be thrown away by strict system MFOP application.

As indicated earlier, the primary enabler of an MFOP is high reliability. This depends primarily on the inherent (design) reliability. It also depends on the extent to which inherent reliability is degraded by shortcomings in manufacture and maintenance. It also depends on the extent to which the maintenance support system can compensate for a shortfall in reliability from any cause. The relevant issues are discussed in Chapters 2 and 5.

While design is the ultimate enabler, the maintenance/support system must also contribute to the achievement of an MFOP capability. For example, the preventive maintenance of helicopters in theatre in Iraq has been minimised, to improve availability and reduce the logistics footprint. This has involved rotating helicopters back to home base in a C-130 transport aircraft.

6.10.4 Industry and Contractual Perspectives on the MFOP Concept

The RAF and industry have debated the issues involved in MFOP since 1998. The achievement of a useful MFOP on some legacy aircraft presents a challenge. The RAF Tornado was analysed using the Ultra Reliable Aircraft Software Model (URAM) [202]. The predicted MFOP was less than one hour! The conclusions were:

- This was hardly surprising but makes the point that legacy aircraft simply do not have sufficient (if any) redundancy or re-configuration to allow a “pure” MFOP to be applied.
- Military operators are not happy with the concept of a Minimum Equipment List (MEL) that allows flight with unserviceable equipments or systems.
- The cost of modifying major in-service platforms would far exceed the benefits of “converting” to MFOP.
- It is only worth considering a MFOP requirement in the acquisition of completely new aircraft types.

The MFOP debate has served to focus attention on the need for aircraft specifications that more closely reflect actual operational needs with respect to availability, reliability, and maintainability. Some changes have been noted in recent contracts to indicate that aircraft must have high availability when required and that recovery periods are expected. When Industry accepts an availability-based contract, the Customer is probably (and properly) only interested in the operational window: Maintenance is now “no longer his problem” The attitude of “…get me another one – this one is broken…” is becoming clear (quite correctly, given the contractual conditions).

As mentioned earlier, properly applied RCM processes can help to move unscheduled maintenance to a more convenient, i.e. scheduled time. However, in doing so, the following concerns may have to be answered by a contractor:

- Is this an MFOP by “stealth”?
- Substantial component life could be lost (at high cost) by anticipating failure too early – this has already been experienced in Contractor or Augmented Logistic Support (CLS/ALS) type contracts.
- Has the accuracy/validity of in-service data used in the analysis been checked?

With availability-based contracting, in-service data capture, storage, analysis and distribution are already starting to suffer, and this may have consequences later. Contractors have observed that:

- The majority of data is being seen as “not required” by the Customer if Industry is managing the fleet for him.
- Key Performance Indicators (KPI) and associate contract compliance will become increasingly difficult to monitor.

Some other issues with contracting are relevant. Firstly, it is not easy to monitor average aircraft availability for contract performance purposes. It will be even harder to hold a contractor accountable for MFOP performance. Secondly, in a difficult situation, a company might accept penalties rather than correct performance deficiencies. Finally, while industry can be “incentivised”, there is a risk that extreme and urgent measures to correct availability or MFOP problems will not be forthcoming when really needed.

6.10.5 Conclusions

- A substantial MFOP might be achievable on new aircraft.

- A useful MFOP can be achieved on some legacy aircraft by careful management of maintenance/support.
- Wider use by Air Forces of "Minimum Equipment Lists" would be useful in avoiding unnecessary delays in aircraft turnaround at 1st Line.
- The debate over the MFOP concept has focussed attention on the need for improvements in aircraft specifications and contract terms with respect to aircraft platform availability and mission reliability.

6.11 RAPID REPAIR OF AIRCRAFT DAMAGED IN ACTION

6.11.1 Introduction

Wars and battles can be won or lost through attrition, and so there is a critical need for rapid salvage and repair strategies and technologies for aircraft disabled or damaged in action. This is particularly so in view of the trend to greater concentration of capability in fewer aircraft, the need for expeditionary operations, and the long lead times for the manufacture of new aircraft and components. The salvage and repair strategies need to cover structure, engines, mechanical systems, and wiring. They should include temporary battle damage repairs. While many of the concepts and technologies addressed in developing the general maintenance/ support system will help in the rapid repair of aircraft, it is necessary also to consider the specific additional measures needed to succeed in a prolonged combat scenario.

The scope of this topic is broad. It includes strategies and technologies for retrieving and/or transporting aircraft to repair centres in theatre. It includes maintenance/support concepts and technologies that will allow major component replacements and repairs to be performed quickly in theatre, at forward bases if possible. It includes the design criteria and concepts needed to enable these maintenance/support concepts. Finally, it includes concepts and technologies for rapid "battle damage repairs" to components that cannot be replaced in theatre. These are defined in MOD UK Def-Stan 00-49 [203] as "essential repairs, which may be improvised, carried out in a battle environment in order to return damaged or disabled equipment to temporary service". The aspects of the topic dealing with assessment and repair were addressed by Absi and Lemaignen in Paper 4.9. The remainder of this section is taken from their paper.

6.11.2 The Need for a Global Vision of Aircraft Repair

The whole subject of this report, "enhanced aircraft availability through advanced maintenance concepts and technologies", applies to the topic of aircraft repair. Even in war, all proper "peacetime" measures for the repair and restoration of an aircraft will be used. The subject is too broad to be completely covered by this section, and so we do not try here to make an inventory of these measures (it is obvious that, when needed and possible, aircraft might be flown back or transported to a maintenance centre). Instead, we concentrate on specific rapid salvage and repair solutions which can be used in wartime, where mission accomplishment becomes an absolute priority, and some increase in risk may be tolerated.

The recent deployed war operations by NATO and coalition forces have highlighted the need for fast repairs to maintain the tempo of operations. Deployment can be far from home base and logistic resupply times can be incompatible with operational needs, creating the need for a fast local repair. Therefore the "repairability" of aircraft is an important quality in deployed operations.

The French definition of battle damage in [204] is similar to the definition in Def-Stan 00-49 [203]. The aim in both cases is to bring the aircraft to a given temporary serviceability condition (with reduced safety margin) and to avoid compromising the ability to make a proper repair later. These documents try to answer the questions of Figure 6-79, below.

I have to repair this aircraft.

- ***4 constraints :***
  - ***Temporal*** — ***I have xx hours.***
  - ***Material*** — ***I have these means (tools, spares, personnel)***
  - ***Operational*** — ***I have to do this mission.***
  - ***Flight safety*** — ***I accept the risk to do this flight.***
- ***2 questions :***
  - ***Assessment*** — ***Is it possible ?***
  - ***Repair*** — ***How to do it ?***

Figure 6-79: The Aircraft Battle Damage Assessment and Repair (BDAR) Context.

The answer to the assessment and repair questions raise the subject of repairability. In the French Air Force, repairability is a specific part of maintainability. This view is consistent with the DoD Supportability Guide which defines maintainability as: "The ability of a system to be repaired and restored to service when maintenance is conducted by personnel using specified skill levels and prescribed procedures and resources". Some public papers have cited the famous B-2 bomber as an example of an aircraft difficult to operate in deployment. Its size, range and low observability characteristics allow it to perform very impressive missions, but a 1997 GAO report said it could not be deployed overseas without special climate-controlled shelters. In operations from the island of Diego Garcia, it was equipped with large climatically controlled temporary shelters [205].

The aptitude to fast "Assessment and Repair" clearly depends on the aircraft specification, and is obviously better on a deployable aircraft. Figure 6-80 shows an example of some actual combat damage, and illustrates that aircraft repair requires a **global vision** of the different damage that can occur to structure and systems, and the measures needed to assess and repair such complex damage.

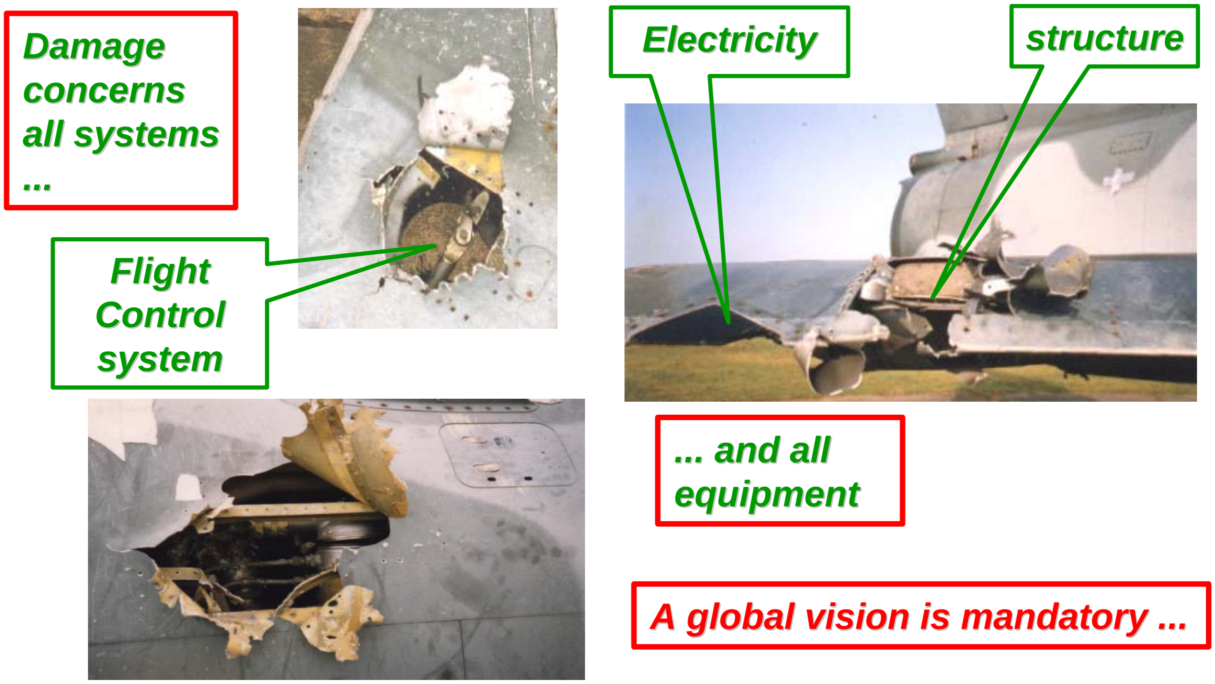


Figure 6-80: Global Vision Needed for Aircraft Repair.

This aptitude to fast repair exists on the aircraft only if these qualities have been incorporated into the design through an Integrated Logistic Support approach as shown in Figure 6-81. It is the case for the Rafale fighter which is presented in this document as **a good example** of deployable and repairable aircraft (but Dassault does not pretend that it is the only one).

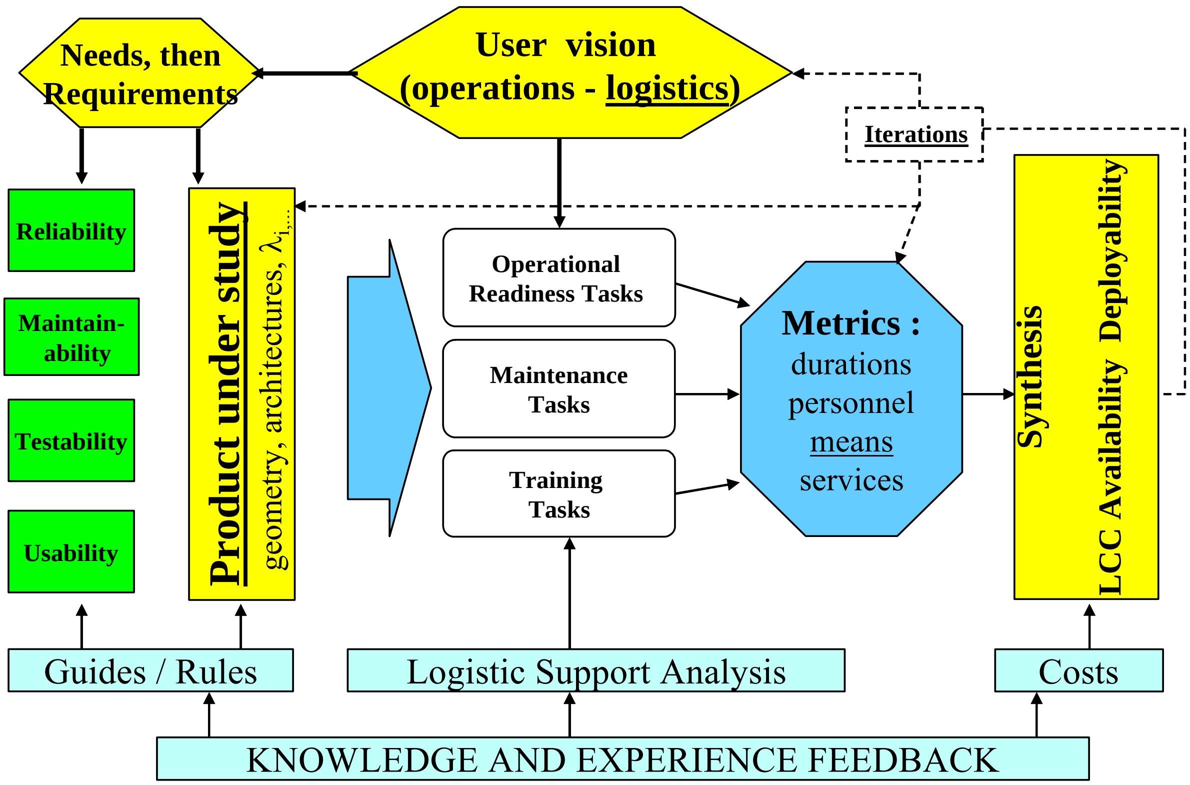


Figure 6-81: The Integrated Logistic Support (ILS) Approach.

Therefore, this section will explain the French operational background (operational feedback and lessons learnt) which has led to the concept of a deployable aircraft. It will then show specific fast repair technologies applicable to the aircraft. Finally, it will discuss the key questions in "assessment and safety", which are:

- What is the acceptable safety level (knowing that the acceptable remaining risk level is a *political choice* between the value of the objective and the cost of the effort which can reasonably be made)?
- How can it be demonstrated (*technical aspect* of the question)?

6.11.3 The French Air Force and Navy Operational Feedback on Deployability and Repairability

Reference [206], which was published in August 1994, presents the results of a NATO Working Group study on the ways to improve aircraft mobility and deployability by reducing their dependency on specialized infrastructure and support. It recognized that the "French Armed Forces have been involved overseas almost without pause" and that their "long-standing requirements of operations in Africa had led to a greater emphasis on the mobility and deployability issues"….. "Routinely, French forces have operated from isolated and extremely austere airfields lacking adequate runways …maintenance facilities, and other basic support services". From this experience, many lessons have been learnt and implemented in the requirements and the design of "compact, robust, and easily deployable support assets and combat aircraft".

Among the key deployability features, you will find the On-Board Oxygen Generation System (OBOGS) and the Auxiliary Power Unit (APU); French Air Force pilots who operated the Jaguar and the Mirage F1 in Chad reported they were sometimes obliged to fly at low altitude with their mask partially disengaged because they had no more liquid oxygen on the base. Of course, the installation of an OBOGS was one of the first requirements for Rafale. The APU, which provides autonomous power and allows comfortable operations in hot countries, was another basic choice for the Rafale (contrary to Annex E of [206]).

The French Navy, for similar reasons and by tradition, has always been very proud of its autonomy and has put robustness and repairability atop its mandatory requirements. The need to operate for months from a carrier (which is one of the most powerful ways to deploy) is a strong incentive for such a position.

As the only supplier of French fighter aircraft, Dassault Aviation has used its best engineering efforts to put into the design all these “abilities”. This knowledge has been reinforced also by the operational feedback from about 40 different foreign countries all over the world which operate or have operated Dassault military aircraft. Some of these customers have raised specific needs like simple repair solutions. Therefore, the aircraft and support system have been designed together using a true ILS approach (Figure 6-81) [207], to provide products easily usable and repairable in deployment. Recent operations in coalition or in training deployments (such as Red Flag or Maple Flag) have demonstrated the successful operation of the aircraft with very limited personnel and very few means (very small logistic footprint) compared to other participants.

The aptitudes of ILS, brought together, are one of the keys to rapid salvage of damaged aircraft in deployment:

- Reliability (simplicity, robustness);
- Maintainability (size and replaceability of components, modularity, repairability);
- Testability (self contained diagnostics, very few GSE); and
- Usability (ease of use/repair/training).

The other key to rapid salvage in deployment is repair techniques as shown hereafter; some are generic but others can apply only to specific design features. This is why deployability and repairability have strong links.

6.11.4 The Lessons Learnt About Battle Damage Repair

In 1986, Dassault Aviation delivered the documentation to perform the BDR for the Mirage III and for the Mirage F1. This documentation consisted of:

- Black and white figures showing the damage tolerance examples for the structural parts.
- Description of structural repairs and of the restoration of the functional chains (electric cables, mechanical linkages, tubing, etc.).

In 1990, Dassault Aviation delivered the BDR documentation for the Mirage 2000. Basically, it had the same content but the figures illustrating the tolerances to structural damage were coloured and associated to tables giving a much better readability. The electrical wiring repair chapter was introduced later by the customer (EET-RDC which is part of the French Air Force). Figure 6-82 shows an example of the Mirage 2000 BDR documentation. Though well accepted and considered better than the previous BDR booklet, Dassault considered a few improvements which led to a new repair vision as will be explained later.

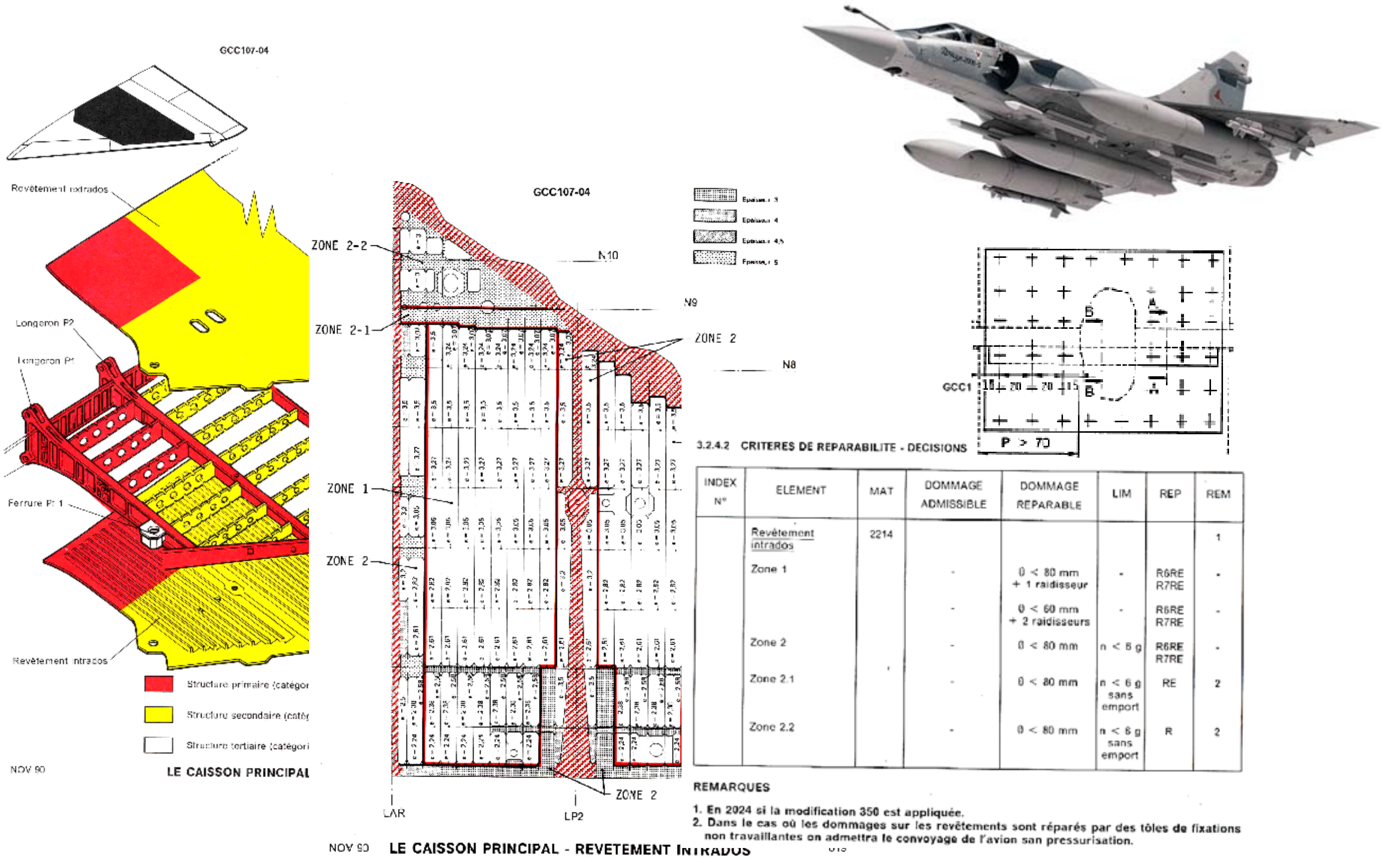


Figure 6-82: Example of Mirage 2000 Battle Damage Repair (BDR) Booklet Content.

The following improvements deal with the document (procedures description), the damage tolerance knowledge, and the nature of the repair itself:

- *Document* – There was a representation difficulty for the coherency of the information (concept of "non-repairable damage", link between damage and repair, etc.). Also the operational impact was not discussed adequately (flight envelope limitations), and the system aspect was not treated (considered, by defect, as being maintained "serviceable" by the user). Finally, it was considered that the BDR documentation should be a complement to the normal "peacetime" maintenance documentation and, therefore, that the descriptive parts were not needed (digital documentation now).

- *Damage Tolerance* – It was considered that theoretical studies could be performed using design calculation models and that the safety margins should not be changed. Also, the structural limit coefficients should be kept the same as for peacetime design.

- *The Repair* – It was recognized that, in several cases, the repair was not reversible (peacetime proper "normal" repair performed later). It was considered that existing repair principles could be kept subject to a proper optimisation and a qualification by tests. Finally, simple rules were established allowing "typical repairs" to any real case (concept of "repair features" in CATIA as we have "design features").

6.11.5 The Rafale Repair Vision

6.11.5.1 Short Description of Rafale

As said before, an aircraft can be repaired easily only if it has been designed as a repairable item (size and number of the parts – even if it is a trade-off with manufacturing cost – interchangeability, modularity, etc.). Therefore, the repair vision presented hereafter really fits the Rafale, but most techniques or solutions could be also used in other aircraft using similar technologies. In order to better understand them, the basic design features of the Rafale are shown below:

- Structure using composites for 75% of the wet surface and 25% of the weight, new self-reinforced structural elements (co-cured ribs inside the composites, titanium SPF-DB elements) and new low observability features.
- Twin-engine aircraft with increased redundancies, strong integration of all sub-systems, full integrated testability (structure, aircraft sub-systems, WDNS) with centralized failure management (including visual and voice warnings), new wiring (buses and hyper frequencies), and high pressure hydraulics (5,000 psi).

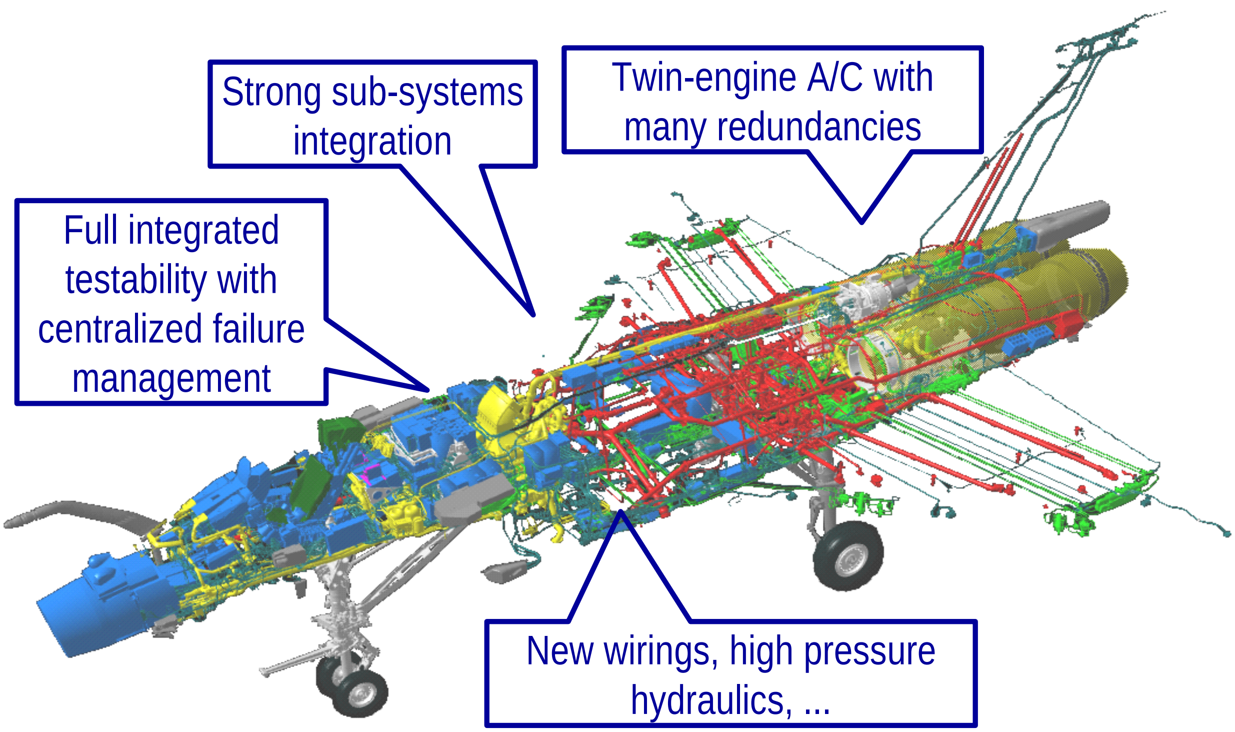


Figure 6-83: Rafale Basic Sub-Systems Definition and Integration.

6.11.5.2 Principles of the Structure Maintenance Study

The Battle Damage Assessment and Repair (BDAR) for the structure remains in line and follows the principles of the initial maintenance study of the structure, but with specific requirements. Its principles are listed below. There is a clear separation between the maximum **allowable** damage and the maximum **repairable** damage:

- For maximum allowable damage, visual checks or NDI tests are defined with a detection threshold compatible with the safe use without repair;
- For maximum repairable damage, the functional role (structural, electrical continuity, aerodynamics, Radar Cross-Section (RCS), etc.) is analysed and the repair is defined to satisfy both the structural strength and the functional performance; and
- For both categories of damage, the design criteria are simplicity, ease of use and minimum need of Ground Support Equipment (GSE).

6.11.5.3 The Battle Damage Assessment and Repair (BDAR) Concept Evolution

Though the abbreviation RDC (which translates as Battle Damage Repair) is still in the title of [204], its application is **not limited to war time** but includes **particular circumstances** where repairs have to be performed under constraints of time or of lack of means and where standard maintenance procedures cannot be applied. This has three consequences:

- A degraded level of safety must be accepted;
- The operational capabilities of the aircraft must be known precisely; and
- The behaviour in time and the reversibility of the repair must be insured.

During the years 2001 and 2002, a Working Group including Dassault Aviation, representatives of the Ministry of Defence and of the French Air Force and Navy (basically an Integrated Product Team – IPT) conducted studies to:

- Translate the “particular circumstances” concept into Rafale needs;
- Define a methodology to assist the “assessment” or “expertise aspect” (see Figure 6-84 below); and
- Validate the methodology on a number of examples.

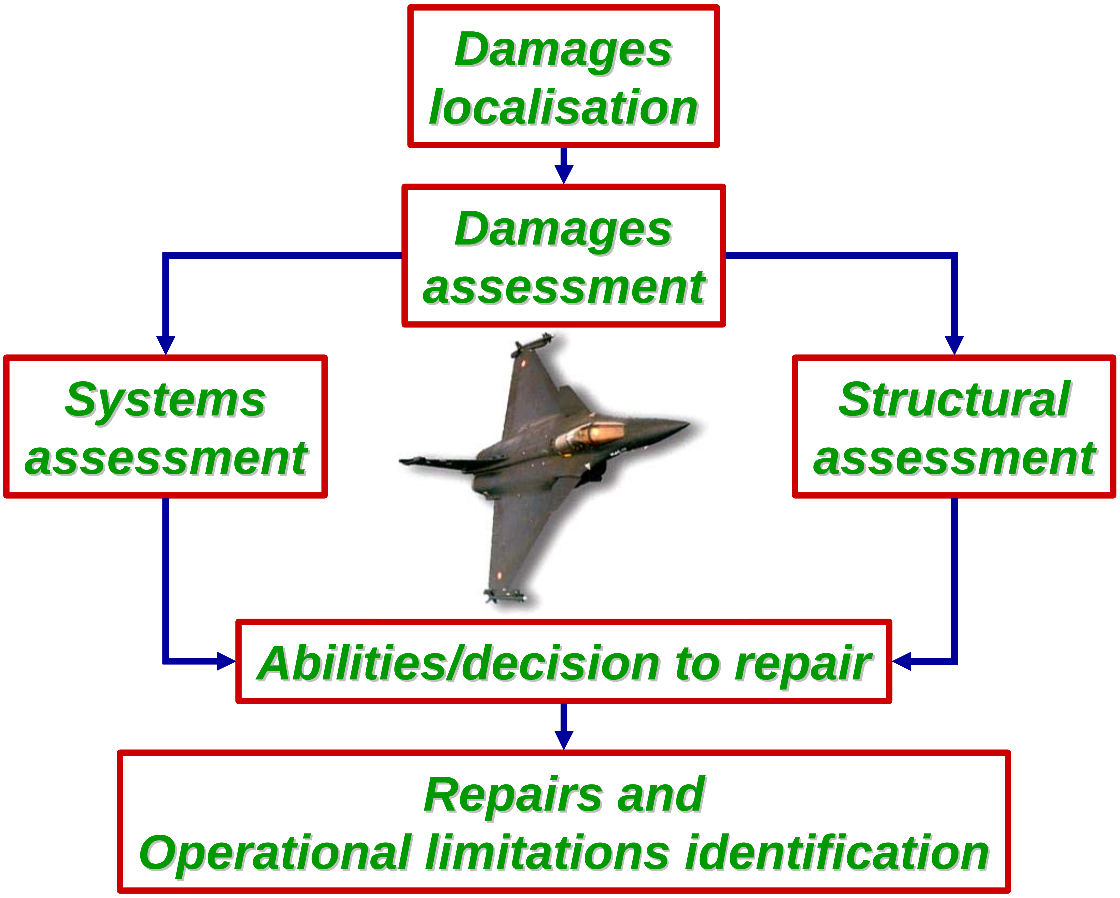


Figure 6-84: French BDAR Methodology as Applied to Rafale.

6.11.5.4 Damage Assessment of the Aircraft

6.11.5.4.1 Structural Assessment of the Airframe

The first task is to detect the damage by visual inspection or with the use of available NDI standard means. The second task is then to identify the structural elements which are concerned. The third task is to analyse whether the damage is in the allowable limits for "no repair" (allowable damage) or whether it is repairable (dimensions of the damage within the repairable limits). The fourth task is to identify the impact of the potential repair on the structural strength and on other aircraft functional performances in order to define the operational limitations which would apply to the repaired aircraft.

Some significant structural items are **not repairable in a BDR context**. It is the case for the main structural components, as a general rule, for all integrally machined parts and for some secondary structure components which are subjected to particularly high stress levels (see Figure 6-85 below for criticality). For those elements, in case of damage, two options exist depending on the "damage tolerance tables" (or, better, on calculation results of the structural strength) and of the acceptable degradation in mission capability:

- A certain level of damage will be accepted to perform specific missions (for example air/ground mission without external tank under the fuselage).

- A certain level of damage may be permissible by load factor limitation for instance for a ferry flight.

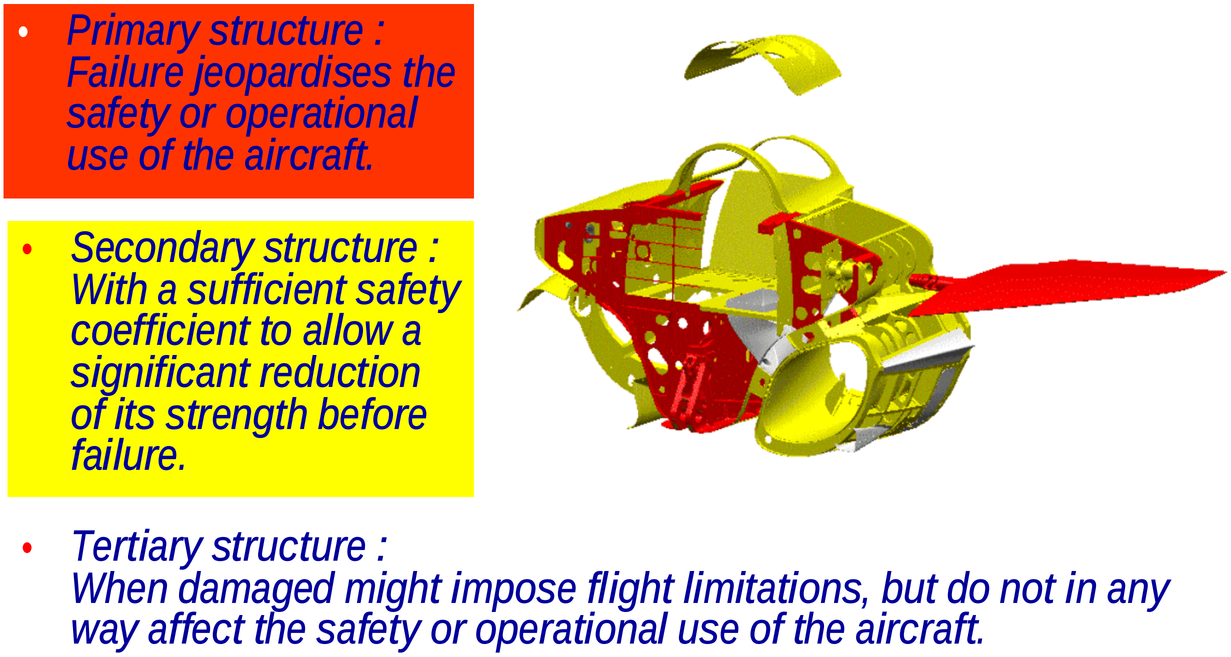


Figure 6-85: Criticality of Structural Members.

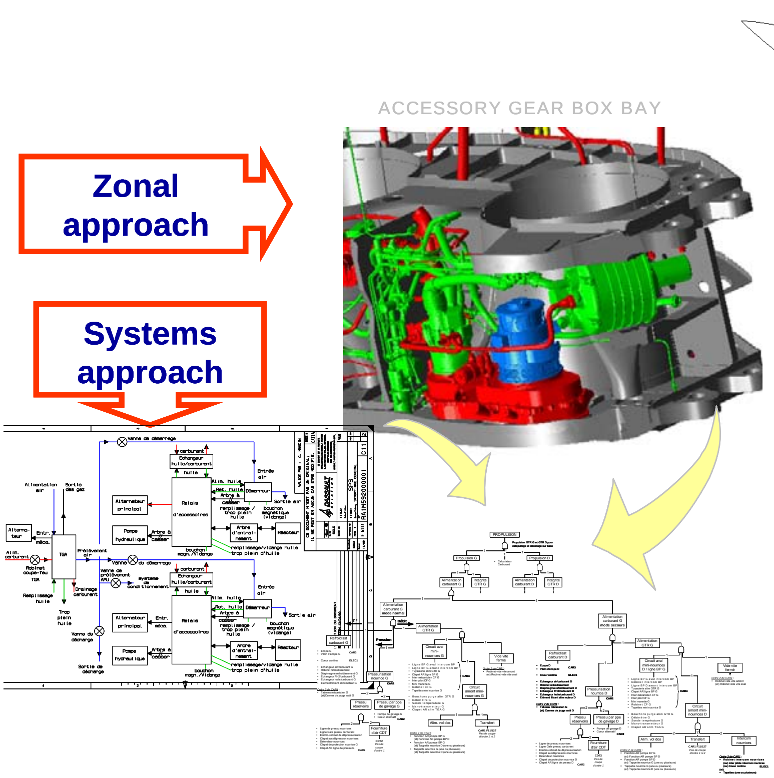
6.11.5.4.2 Systems Assessment

With complex modern weapon systems, this task is the **most complex task** and could justify a full presentation of its own. The principles used are summarised in the following paragraphs.

Among the different systems, the propulsion system is the most important one. The M-88, developed by SNECMA for Rafale, has a sophisticated diagnostics/prognostics capability, called SIAD (which translates into Digital Engine Diagnostics System) which gives the required engines assessment and exchanges its main information with the aircraft on-board integrated testability (both ways because obviously all aircraft sub-systems receive their renewable energy from the propulsion but the aircraft only knows whether it is airborne or on the ground) and keeps specific additional information for treatment by the engine manufacturer itself. As it uses the same principles as the aircraft on-board Integrated Testability, it is not described more in detail.

In most cases, aircraft inspection and pilot report allow a first immediate localisation of "apparent" damage to the systems, and the on-board integrated testability can go deeper in the investigation (direct reporting of faults and integrated complementary ground maintenance, which can generate solicitation of functions and check their response), identification and localisation of the damage. But the Integrated Testability depends on the wiring itself, and so, in the most difficult cases where this wiring is damaged, the exact identification and localisation of faults can require long investigations and real expertise. So, a proper assessment of the aircraft condition remains a challenge, and there is still a range of improvements to explore for the future.

Once the damage is identified, the system assessment follows a similar logic as the structural one: the impact of the damage on the aircraft functions is analysed and, depending on the mission requirements, the minimum repair can be decided. The Figure 6-86 shows an example of the system analysis made to take the repair decision. It includes the use of functional schematic diagrams which are part of the digital maintenance documentation (and dysfunction models in the future) and failure trees. The results can be presented under the shape of decision tables.



SYMBOLS	SAFETY STATUS	OPERATIONAL CONSEQUENCES
~	SAFETY LEVEL IS PRESERVED	ALL MISSIONS CAN BE PERFOMED
↘	SAFETY LEVEL IS NOT PRESERVED	LOSS OF OPERATIONAL CAPACITIES OR DEGRADATION OF MISSION SUCCESS PROBABILITY
↘↘	IMMOBILISATION RECOMMENDED	ONLY FERRY FLIGHT

Figure 6-86: Example of System Analysis Used for Repair Decision Tables.

As an extreme example, if the hydraulic reservoir of Circuit 1 is lost, several nominal functions are lost because it is the circuit which performs the auxiliary functions, but the aircraft can still fly with the following limitations: some loss in manoeuvrability, no retraction of the landing gear (only emergency descent), no possibility of “two points only” braking (emergency braking is still there due to park brake), loss of front wheel steering but driveability achieved through differential braking.

Of course, structural and systems assessment must have homogeneous goals and flight performance limitations to decide to put the aircraft back to a flight worthy condition.

6.11.5.4.3 Operational Assessment and Limitations

The logic presented in 6.11.5.4.1 and 2 gives the answer to the operational commander for **one specific aircraft**. But, in a prolonged deployment or in surge operations, the situation of multiple damages to several aircraft may occur and make necessary the **selection** of which aircraft have to be repaired. Though the answer to this question might be given better with the assistance of modelling tools envisaged for the future (see 6.11.6), the question itself has to be placed here because, even if it is debated today by the officers in charge of the operations and those in charge of the maintenance, the answer will be the repair decision. It will be based on the operational mission, cost of the repair, and the minimum maintenance and repair tasks which can be performed (personnel and means) to satisfy the need in time (including "cannibalisation" of another damaged aircraft). Depending on the nature of the repair, the remaining safety level might be reduced even with flight envelope limitations. This short discussion shows the difficulty of the overall system and operational assessment, what is called the **"expertise side" of the problem**, and which justifies future efforts to allow a true "full assets management" (see Section 6.11.6).

6.11.5.5 Repair of the Damaged Aircraft

6.11.5.5.1 Example of Structural Repairs

Their goals are three-fold:

- To reinforce a damaged structure to allow at least 50 more flights;
- To perform the sealing of all volumes containing gases or liquids; and
- To restore the operational functions if necessary (like low observability, which cannot be presented here).

All materials used in the aircraft are covered (metallic, composites, honeycomb, canopy glass, etc.) and common means or tools are used. Most battle damage repairs are derived from the standard peace-time repairs. Some others are specific but are designed to allow their rectification during peace-time to fully restore the structural characteristics. A "Combat Damage repair" lot is defined to complement the standard tools and ingredients. Figure 6-87 below gives a few structural repair examples.

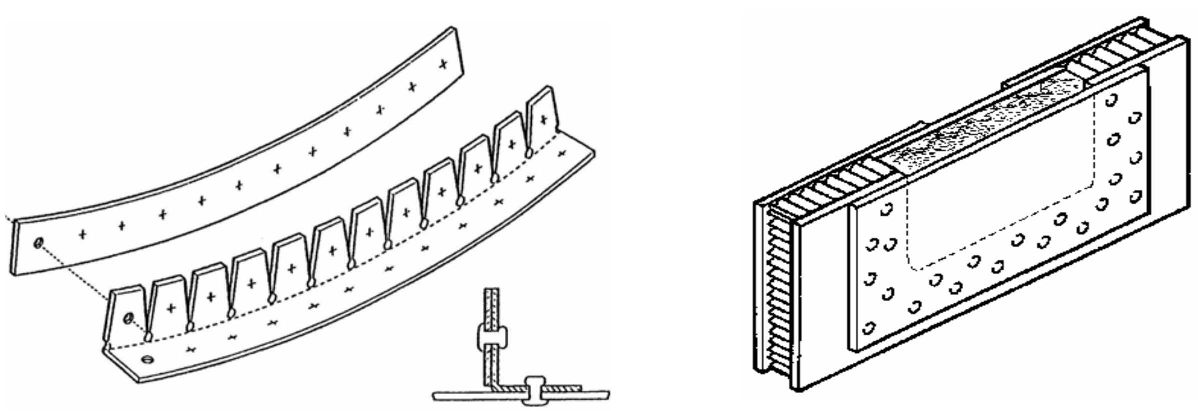


Figure 6-87: Basic Structural Repair Examples.

6.11.5.5.2 Engine Repairs

The M-88 modular design allows the replacement of any LRU and engine module and the return to flight condition without complete bench tests (even if the Charles de Gaulle aircraft carrier has an engine test bench). This basic repairability, applicable in deployment, should cover most damage cases, but other specific repairs are envisaged by the engine manufacturer. They will not be presented here.

6.11.5.5.3 Examples of System Repairs

As a general rule, equipment is not considered as repairable. It is replaced by a spare (including cannibalisation of another damaged aircraft) or by a shunt. In fact, some minor repairs may be feasible. The purpose of the repair is to restore the nominal or sometimes degraded function of the considered system (the question being the acceptability of the degraded mode – see system assessment above). Pipes can be repaired with Permaswage or ArsAéro/SM fittings and wirings can be repaired (except UHF cables). Figure 6-88 below shows examples of pipes repairs.

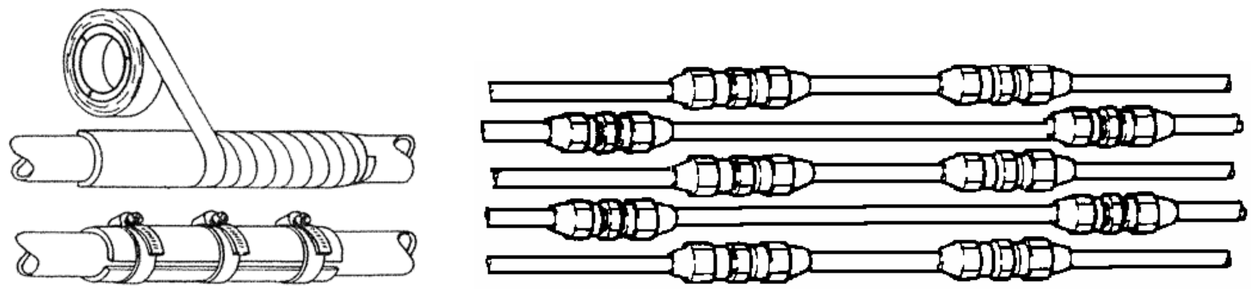


Figure 6-88: Example of Basic Pipe Repairs.

6.11.5.6 Strong Points of Rafale Maintenance and Documentation

To perform his assessment and repair tasks, the maintainer receives a strong assistance, which did not exist for older generation aircraft, from the digital documentation, the integrated testability and new technologies:

- The digital documentation provides maximum information in minimum volume. In deployment, the whole Organizational and Intermediate Levels (O/L & I/L) documentation is available and we have developed and tested encrypted Tele Maintenance (used during the first campaign of Charles de Gaulle aircraft carrier). Many improvements remain possible for the future, using numerical models (see Section 6.11.6) and more generally the New Technologies of Information and Communication (NTIC).
- The on-board integrated testability is clearly one of the key tools to assist the maintainer for the systems assessment, as explained before. It can be completed by already existing tools like the Interactive Trouble-shooter Assistant System (ITAS) which uses the “failure words” of the Integrated Testability to guide the diagnostic task of the maintainer.
- New technologies facilitate the repair itself. It is the case for the wiring identification by bar-codes and portable readers, and for titanium tubing and Permaswage junctions which can be cold-crimped for hydraulic circuits. Both are represented on the Figure 6-89 below.

Figure 6-89: Examples of Technologies Making Identification and Repair Easier.

6.11.6 Future Foreseen Improvements: Assistance to the Aircraft Assessment and Repair Decision

As seen before, the overall aircraft assessment and the decision to repair or not is the **central problem of the BDAR context**; it is the most difficult question to answer, especially in a prolonged deployment situation where multiple damage can occur while the critical need to perform missions persists, awaiting for resupply of spares. New tools can assist the operational and maintenance officers to make a decision. The first one can assist the overall system assessment of **each** damaged aircraft. The second one can assist with the choice between **several** damaged aircraft. Though already tested, they are not yet integrated in an operational usable decision making tool; however, for interest they are presented hereafter.

As part of Dassault's engineering design process and for aircraft certification, a "dependability" suite of tools is used. This was initially developed in-house with research institutes, but is now commercially available under the name CECILIA. Its failure trees have been used for many years, but new functionalities have been developed for flight controls. One of them is the dysfunctional model of sub-systems. Each system can be represented with different operable or dysfunctional states (failure or damage). Once **all** sub-systems have been described with such a tool, it becomes possible to visualize the combined effect of several failures (or multiple damage); this is equivalent to a FMECA analysis, as it gathers all the information leading to a "warning" condition or to a red "NO GO" condition. Connected to the failure trees, it can also give the resulting probability of occurrence of a number of "feared events", and give the decision maker the indication of the "remaining safety". This is for the "technical assessment" of the systems on one specific aircraft. Figure 6-90 below shows an example of a rather simple page of the tool.

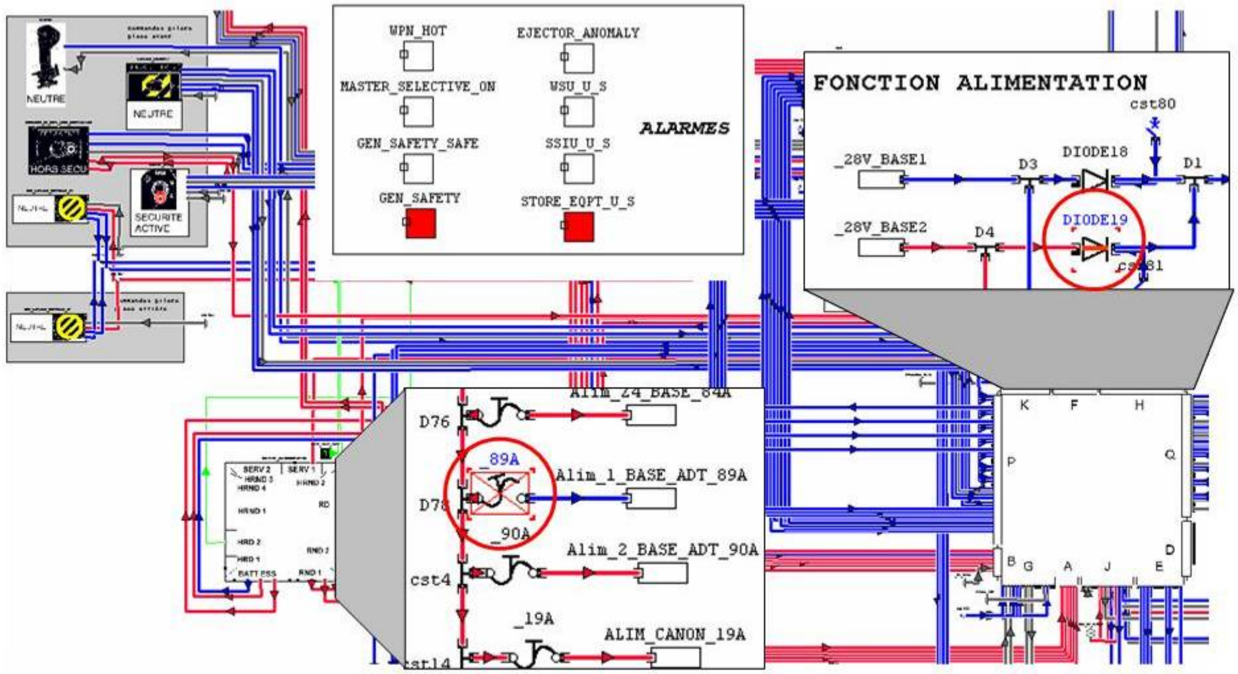
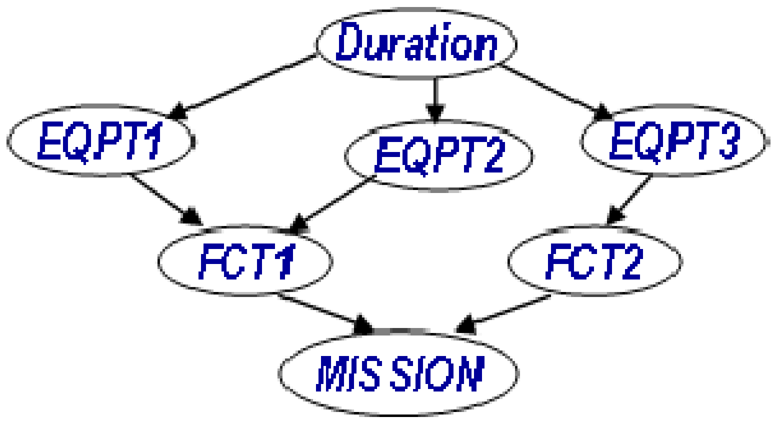


Figure 6-90: Use of CECILIA Workshop to Assess a Combined Damage (or Failure) Criticality.

Bayesian networks can be used as decision support tools. Dassault has used such a tool for repair decision making in a BDAR context (simple prototype tool but which gave the expected results on simple cases). The principle is the following. The operations officer selects an aircraft tail number and a mission to perform. A list of repairs and of their foreseen durations is associated to the aircraft tail number (automatic extraction from the on-board integrated testability system completed, if necessary, by further complementary investigation, as seen before) and a minimum equipment list is associated with the mission. A Bayesian network of the functional equipment needed for the mission is built, and the tool evaluates the different combinations of repair options (represented by different shapes and colours on Figure 6-91 below). The calculation report gives a graph indicating the mission success probability as a function of the potential repair duration. The example represented below shows that the repair of one specific critical equipment can give a major increase in mission success probability. Similar graphs would be generated for each envisaged tail number, allowing the operations officer to select the best aircraft for the priority mission. This simple example shows the value of decision support tools when the number of damage cases increases.



Repair decision graph

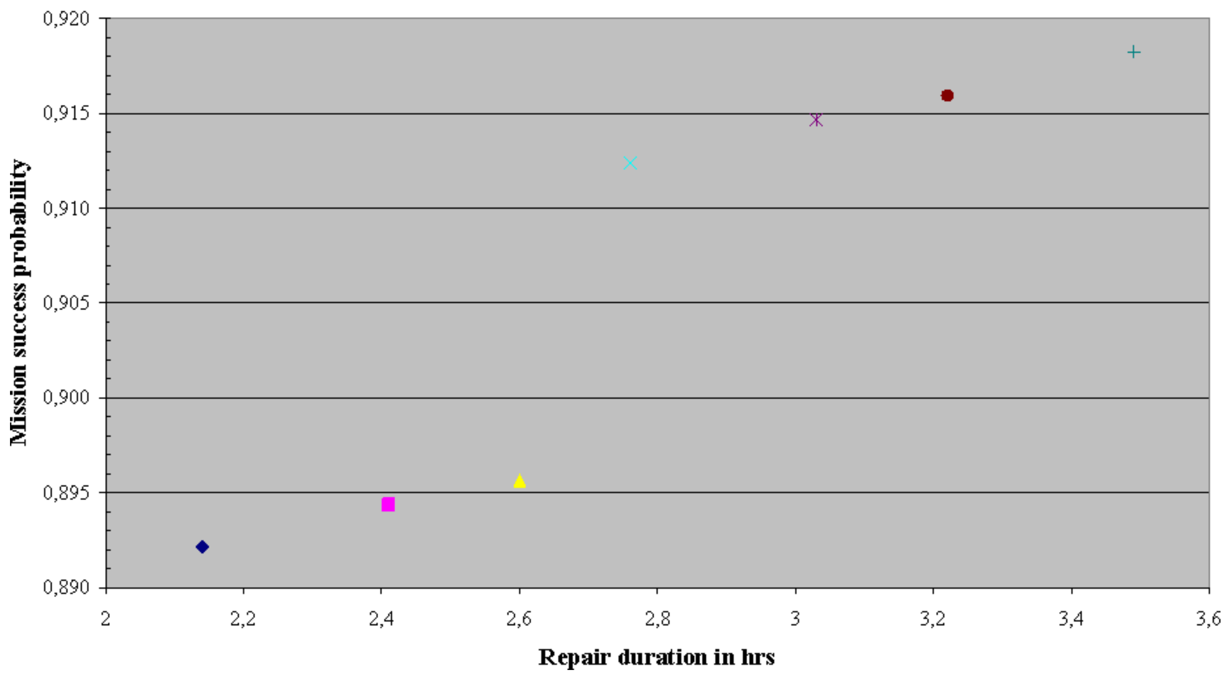


Figure 6-91: Bayesian Network Used as a Repair Decision Assistance Tool.

Finally, the INDET European research program, in which Dassault participated, tries to associate 2D structural representation to NDI results and, in conjunction with a finite element analysis of strength, to allow a very rapid assessment of a structural damage in composites. 3D versions are presently in development. This kind of tool could be very useful to assist the structural repair decision.

The above examples show a few potential tools developed and proven by Dassault Aviation engineers but some essential questions have to be answered:

- Will these tools be available and usable by the operational people in deployment?

- As they contain the very knowledge of the designer, how are the intellectual property rights satisfied contractually?

There are probably different answers to these questions depending on the customer. Some will like full decision autonomy, having their own experts. Others may prefer simplified decision tables (as is the case in present BDAR brochures), or simplified executable models, or even Tele Maintenance assistance from the aircraft manufacturer.

6.11.7 Conclusions

This section has concentrated on repairability and on the functional assessment of a damaged aircraft.

While the section focuses on the Rafale aircraft, the subjects raised are universal and apply to many aircraft facing the same context of Battle Damage Assessment and Repair. Through the example used, it looks clear that the **major challenge** in a BDAR context is the "**system assessment**" (expertise), and that this will be the case for any new modern weapon system. It is obvious that Integrated Testability is a powerful tool to assist the sub-systems assessment and that modularity and structural repairability (size and removability of parts) are strong enablers to put the aircraft back to a flight worthy condition. Both are available if they have been incorporated to the design through an ILS approach; it is what Dassault Aviation has tried to do on Rafale to make it a deployable and easily repairable aircraft.

NTIC and computer models can still offer a significant improvement potential to assist the repair decision. We are clearly in favour of interactive computer tools which bring a considerable improvement over static charts or data bases or manuals which cannot fit as closely the real damage to assess. It would be a subject by itself to review them in detail due to their fast progress … and it is also probable that several of them will have been presented in other sessions of this Workshop. As a simple example of further improvements, we have demonstrated solutions to keep **on the hardware** (aircraft part or equipment) the description or the indication of the repair which has been performed (4 Kbytes RFID tags or memory buttons – both have been tested successfully in the aircraft environment) and, thus, to facilitate further proper repair in peace-time with simple update of the repair information which is also automatically transferred to the Maintenance Management System. The major advantage is that the "source information" is on the hardware itself where the work has been performed and that it avoids the very well-known loss of accompanying documents.

6.12 CORROSION PREVENTION AND REPAIR

6.12.1 Introduction

Corrosion of airframe structure and systems, engine structure, and electrical/electronic systems accounts for a large part of the inspection and component replacement/restoration needed at 3rd and 4th Line. In an effort to reduce this maintenance effort, routine washing, corrosion protection, and dehumidification is performed at 1st Line, and extra ground handling is required to move aircraft into hangars and other shelters. Thus, preventive and corrective maintenance related to corrosion is a major drag on average aircraft availability. The following quotation from a report in 2003 by the USA General Accounting Office (GAO) [208] illustrates the situation in the US Armed Forces and reflects the situation in other NATO forces:

> "Although the full impact of corrosion cannot be quantified due to the limited amount of reliable data captured by DoD and the military services, data on current cost estimates, readiness, and safety indicate that corrosion has a substantial impact on military equipment and infrastructure. For example,

in 2001, a 2-year, government-sponsored study estimated the direct costs of corrosion for military systems and infrastructure at approximately US$20 billion annually and found corrosion to be one of the largest components of life-cycle costs for military weapon systems. Another study puts the cost at closer to US$10 billion. Corrosion has also been shown to substantially increase equipment downtime, thereby reducing readiness. For example, a 2001 study concluded that corrective maintenance of corrosion-related faults has degraded the readiness of all of the Army's approximately 2,450 force modernization helicopters; the Army estimated in 1998 that approximately US$4 billion was spent on corrosion repair of helicopters alone. In 2001, DoD also reported that more than two thirds of its military facilities have serious deficiencies and are in such poor condition that they are unable to meet certain mission requirements; corrosion was identified as a major contributor to much of this deterioration. Finally, a number of safety concerns have also been associated with corrosion. During the 1980s, the crashes of several F-16 aircraft were traced to corroded electrical contacts that caused uncommanded fuel valve closures. More recently, Navy F-14 and F-18 aircraft have experienced landing gear failures (collapses) during carrier operations that were attributed to corrosion-related cracking."

The downtime and cost of 3rd and 4th Line maintenance for preventative or corrective maintenance related to corrosion can be reduced in several ways:

a) Firstly several technologies are available for reducing corrosion arisings and damage. These include aircraft shelters, dehumidification, washing/cleaning, corrosion preventive compounds, improved paints, improved sealants, the addition of drainage, and the use of alternative materials or rework by Retrogression and Re-Aging (RRA) heat treatment to reduce corrosion susceptibility.

b) Secondly, improved NDI technologies are becoming available for wide area and multi-layer inspection for corrosion and related fatigue damage. These NDI technologies can reduce costs and provide added flexibility in the response to a corrosion arising. (An in depth review of NDI is provided earlier in Chapter 6.)

c) Thirdly, methods are becoming available for modelling the stress distribution and fatigue characteristics of corroded structure, for modelling the interaction of corrosion and fatigue, and for modelling the rate of deterioration of protective paints and coatings. Experimental techniques are being developed to validate these models. These modelling technologies can be used to perform durability and damage tolerance assessments to determine whether costly and time-consuming repairs can be deferred or avoided subject to some interim, less costly maintenance action.

d) Finally, new sensor technologies are becoming available that will help in assessing the actual environment or the actual rate of corrosion of a given component. These will enable PHM systems for corrosion and the use of an automated CBM approach.

The remainder of this section will review concepts and technologies for reducing the overall maintenance burden due to corrosion in more detail. The content is based on Paper 4.10.a by Agarwala except for the final sub-section dealing with dehumidification of aircraft (Section 6.12.8), which is based on Paper 4.10.c by Schweitz.

6.12.2 Types (Forms) of Corrosion Identified – Applies to All Aircraft Platforms (Types)

- Exfoliation and Intergranular – ribs, spars, skins, fastener joints.
- Pitting and Crevice – localized corrosion under skins and coatings, fastener joints, overlaps, under sealant.

- Galvanic Corrosion – dissimilar metal joints – fastener holes, electronics, cable connectors, etc.
- Composite (Resin) Degradation – galvanic effects at metal joints, resin swelling or loss of fibre adhesion.
- General and Filiform Corrosion – under thin coatings.
- Corrosion Fatigue – load bearing structures such as landing gear, fastener holes.
- Stress Corrosion Cracking and Hydrogen Embrittlement.
- Microbially Induced Corrosion (MIC).

All forms of corrosion lead to:

Initiation → Growth → Fatigue / SCC Failure

6.12.3 Current Practice

NO DESIGN ENGINEERING POLICY ON CORROSION MITIGATION AND CONTROL

Corrosion control is an “after thought process”:

- Pre-treatments and coatings are major defence against corrosion.
- Sealant in joints, splices and galvanic couples where possible.
- Sacrificial metallic coatings for landing gear steels.
- Ceramic coatings as high temperature corrosion barriers.
- Temporary protection schemes: Corrosion Preventive Compounds (CPC), water displacing compounds and wash primers.
- Frequent equipment washes with/without corrosion inhibitor in wash/rinse waters.
- Damage assessment at ASPA/PDM cycles: select area corrosion inspection at depot level.

6.12.4 How are Corrosion Repairs Done Now?

During the three levels of maintenance, O, I and D:

- Remove condensed water from hidden structural cavities via drain holes and/or wicks.
- Replace components when repair is cost prohibitive.
- Fix when broken – schedule-based inspection and maintenance (PDM cycle).
- Remove surface corrosion by grinding off corrosion products and applying touch up coating system.
- Repair of fastener hole crevices/pits/cracks – reaming the hole up to 30 mils wider and replacing with larger fastener.
- Use of composite patches where skin replacement is cost prohibitive.
- Strip and repaint after every 3 – 5 years.
- Material substitution/processing when/where possible.
- Use only Mil-Spec approved materials and processes.

6.12.5 What is Not Done?

We do not:

- Design a system component with built-in design controls for corrosion resistance as an engineering requirement.
- Use best corrosion control fabrication practices in construction and assembly.
- Use best possible corrosion resistant construction materials – allowed under **acquisition cost and performance guidelines**.
- Use diagnostics and prognostics tools for life prediction and assessment – on-board sensors and devices.
- Use proper prediction models and software as a performance and maintenance tool.
- Use performance-based logistics strategy to determine life-cycle cost, down time and maintenance man-hours.
- **Apply corrosion engineering practice as a policy in all acquisitions**.

6.12.6 Some Advanced Technologies for Corrosion Management

6.12.6.1 Corrosion Preventive/Inhibiting Compounds

P-3 operator/maintainers accepting aircraft back from depot maintenance (PDM) will begin the application of WDCPS in specific areas of the aircraft. These areas are as follows:

- Aileron, elevators, flaps, and rudder control surfaces (internal surfaces / front spars / counter balance weights).
- Vertical stabilizer (internal surfaces / front and rear spars).
- Horizontal stabilizer (internal surfaces / front and rear spars / under upper and lower horizontal stabilizer-to-fuselage filler panels).
- Internal surfaces of aft hydraulic service centre.
- Wings (internal surfaces of flaps and aileron shrouds / under upper and lower wing-to-fuselage fillet panels / forward and aft spar webs / wing access panel dome nut rivet heads / internal surfaces of engine nacelles and cowls.
- Internal surfaces of bomb bay doors and bomb bay.
- Main landing hear wheel wells (internal surfaces of doors and MLG wheel wells).
- Nose landing gear (internal surfaces of wheel well between FS150 and FS288 bulkhead).
- Forward fuselage of pressure bulkhead-FS156.
- Internal structure adjacent to lavatory area, including floor supports and frames.
- Internal structure adjacent to entry ladder area, including floor supports and frames.
- Internal structure adjacent to galley area, including floor supports and frames.
- APU compartment structure.
- Internal empennage structure including forward face of FS1117 pressure bulkhead.

6.12.6.2 Trivalent Chromium Pre-treatment (TCP)

A trivalent chromium pre-treatment for painting (Figure 6-92) has been developed by the US Navy to replace the hazardous hexavalent chromium pre-treatments:

- Environmentally friendly – no hexavalent chromates:
  - A room temperature less than 5 minute process.
  - Applied by immersion, spray or sponge process.
- A US Navy patented process:
  - TCP can be used as post treatment for anodized aluminium and metallic coatings (IVD aluminium, cadmium, zinc-nickel).
- Highly flexible process:
  - “Drop in” replacement for chromate [Cr+6] conversion coatings in all applications and methods.
- Performance:
  - Performing as well as chromates in aircraft field tests.
  - Tested on four S-3s Viking; F/A-18 C/D and H-46.

Figure 6-92: F/A-18 Undergoing Repaint.

6.12.6.3 Demonstration of Trivalent Chromium Pre-treatment (TCP) H-46 Helicopters

A demonstration of a Trivalent Chromium Pre-treatment (TCP) has been performed on H-46 helicopters (Figure 6-93 and Figure 6-94).

Figure 6-93: H-46S Helicopter Masked for Painting.

Figure 6-94: H-46S Helicopter After Painting.

6.12.6.4 Advanced Organic Coatings

- High Performance Epoxy Primers (non-chromate version) – exceptional adhesion and chemical resistance for Al alloys. Being tested on F-18, T-45 and F-15 (joint services) aircraft.
- High Performance Polyurethane Topcoat for desired optical properties.
- Self-Priming Topcoat (SPT) – a low VOC non-lead, non-chrome high solid polyurethane coating. Reduces one process step and minimizes toxic waste management.
- Appliqué Films – alternative exterior finishing in lieu of topcoat. Flexible thin film with a pressure sensitive adhesive serves as an excellent moisture barrier. Avoids VOC from painting operations.
- E-Coat Films – a bath process where charged paint particles are deposited electrochemically on an oppositely charged conductive substrate with controllable thickness.
- Powder Spray Coat – applied by dip coating using fluid bed, depositing in electrostatic cloud chamber, and mostly by electrostatic spray process. Cure temperatures are usually ~ 150°C.

6.12.6.5 Photostrip – Photochemical Stripping of Aircraft Coatings

Process highlights (Figure 6-95 and Figure 6-96):

- Photochemical process uses UV light and inorganic chemicals to debond paint from painted surfaces.
- Process duration is less than 8 hours.
- Process applicable on a variety of substrates, such as, aluminium, stainless steel, composites, fibreglass, wood, and radome material.
- Process can be automated for each application.
- Minimal waste; no toxic waste contributed by the process and the chemicals used.

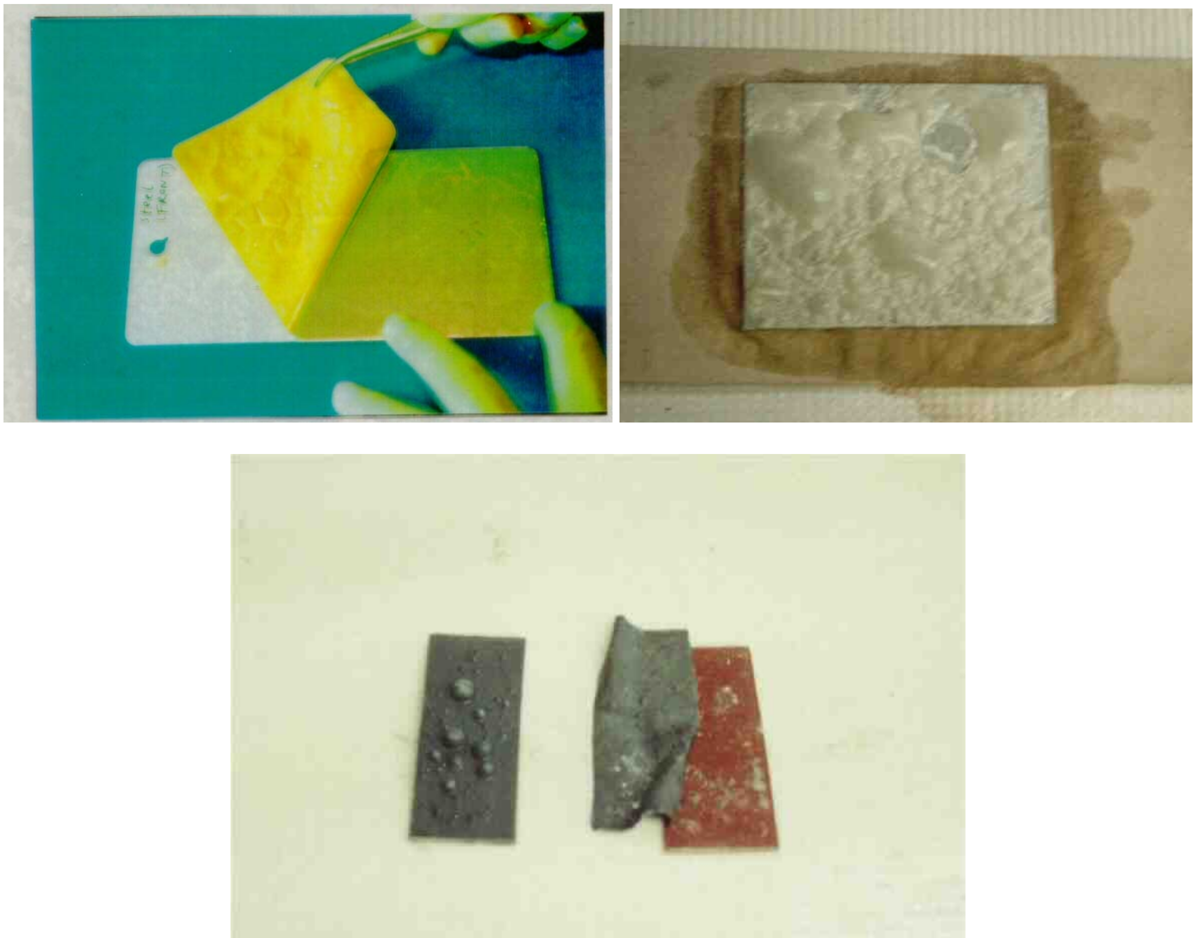


Figure 6-95: Photostripping of Paint.

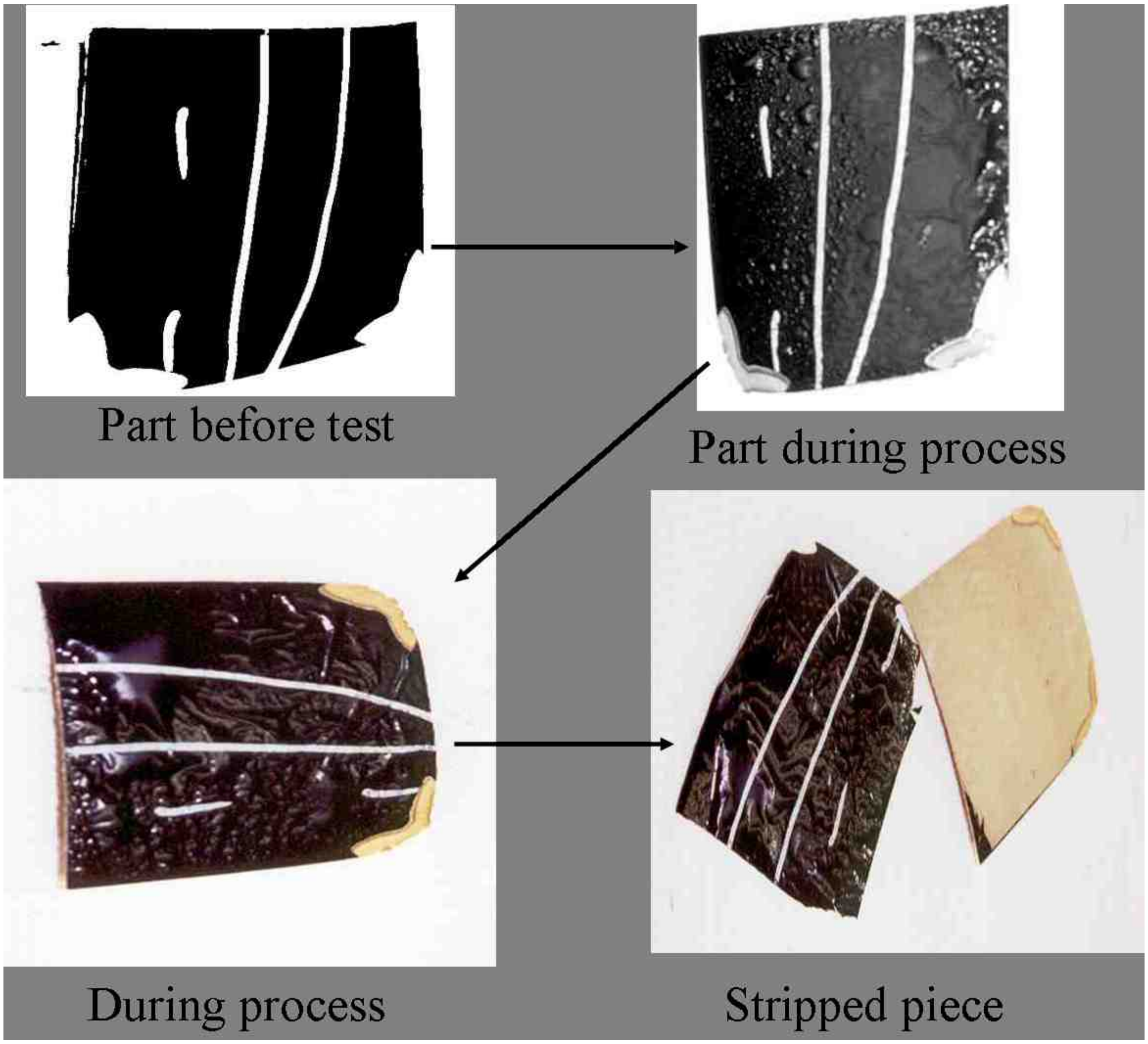


Figure 6-96: Photostripping of Rotor Blade Coating.

6.12.6.6 Advanced Sealants and Adhesives

Need light weight / fast cure sealants qualified for aircraft. New sealants are 25% lighter → weight savings → lower fuel consumption → longer mission range. New sealants are faster curing (4 hours vs. 48 hours) → improved mission readiness.

There are a number of advanced sealants and adhesives that improve the effectiveness and reduce the time and cost of corrosion protection during manufacture and maintenance:

- Surface sealants for magnesium:
  - Sermetel, Rockhard.
  - Exterior – under primer; interior – replaces phenolic epoxy resin.
  - Required at depot repair when damage justifies stripping.

- Polysulfide (RTV):
  - Hardens with age and UV.
  - Difficult to remove.
- Polythioether:
  - Stays flexible with age.
  - Good adhesive.
- Waxwrap (tape and spray):
  - Excellent dielectric (good insulator of galvanic joints).
  - Joints remove easy; leave greasy surface.
  - Not for high temperature application.
- Skyflex (TFE Foam Tape) – (for pressure joints):
  - All fastener joints.
  - All lap and butt joints.
  - Canopy seals.
  - Easily detachable.

Of these, Skyflex sealant is an outstanding example (Figure 6-97):

- An expanded polytetrafluoroethylene (ePTFE) sealant/gasket material; i.e. a "peel and stick" teflon foam tape substitute for 2-part paste sealants.
- Excellent environmental seal, hydrophobic and removable/reusable; results in reduced corrosion.
- Reduced damage to parts during removal.
- Reduces need for frequent reapplication (typical for current sealants).
- Requires no mixing, masking or lengthy cure times.
- Replaces toxic polysulfide, which contains chromates and HAP solvents.
- Current Navy efforts include access panels of P-3, S-3, H-1, E-6 and H-60.
- Approved fleet-wide for most aircraft platforms (access panels, floorboards), including sealing floorboards for the P-3, H-60 and H-53 platforms.

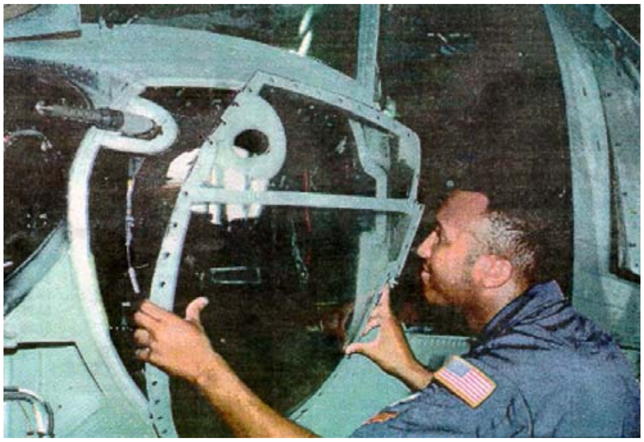


Figure 6-97: Skyflex Aircraft Sealant – "Peel and Stick" Teflon Foam Tape Substitute for 2-Part Paste Sealants.

6.12.6.7 Emerging Sealant Technologies

The following sealant technologies exist with limited application approval:

- Improved firewall sealants provide longer structural protection = improved survivability during fire (TA Mfg. and D-Aircraft).
- New conductive sealant provides improved durability and reduced shrinkage = lower maintenance/ faster application (PRC – DeSoto Chemicals).

The following technologies are under evaluation:

- Conductive gaskets under evaluation provide environmental seal, corrosion protection, removeability option (manufacturer AV-DEC).
- Sealant removal techniques – bristle discs and rotary cutters from 3M simplify and speed sealant removal and reduce solvent use (Figure 6-98).

Figure 6-98: Bristle Discs and Rotary Cutters from 3M Simplify and Speed Sealant Removal and Reduce Solvent Use.

6.12.6.8 Fleet Outreach Program for Corrosion Management Technologies

There is a major fleet outreach program to advertise the benefits of these advanced technologies (Figure 6-99).

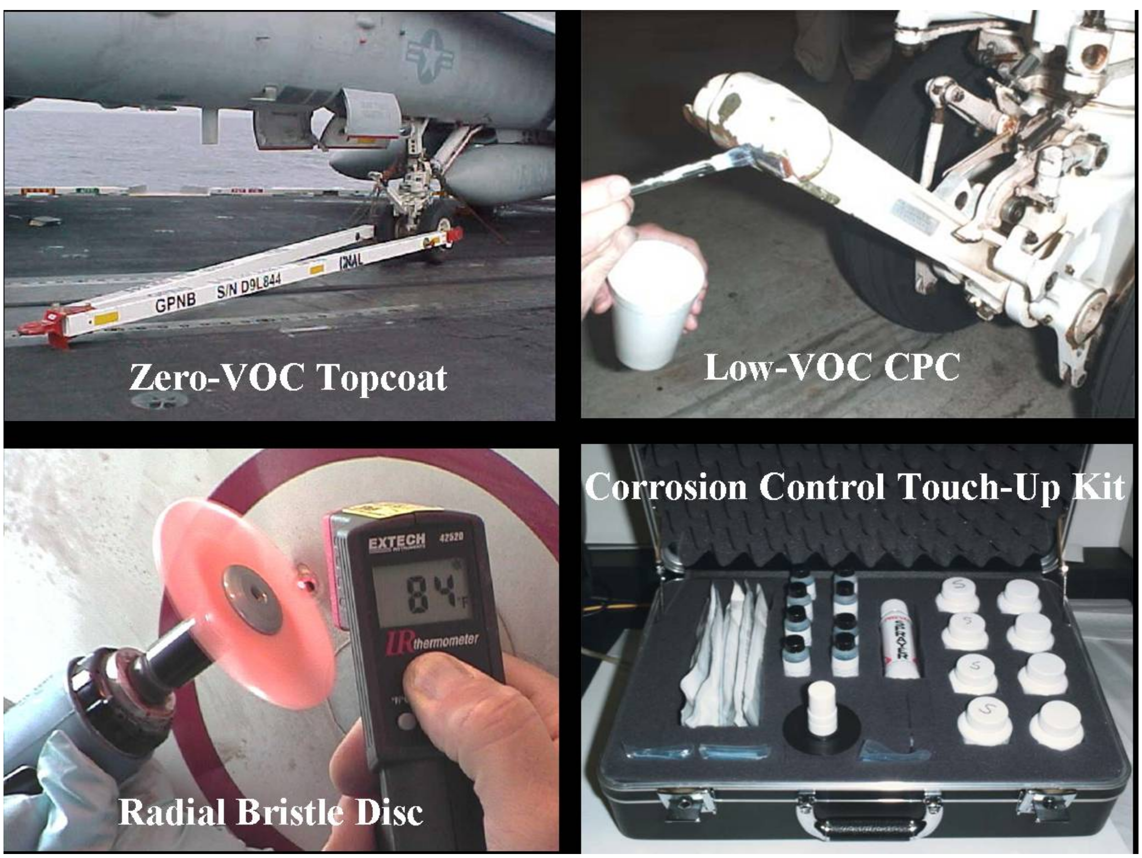


Figure 6-99: Fleet Outreach Program.

6.12.6.9 Aircraft Inspection – NDE of Corrosion

There are several new microwave NDE Concepts. An example of a hand held device for directed inspections is the Alpha MCD hand-held device (Figure 6-100):

- Routine/spot NDE for corroded areas.
- Reachable into small areas to detect oxides.
- Very useful in high risk corrosion areas.
- Simple, portable, fast, battery powered.

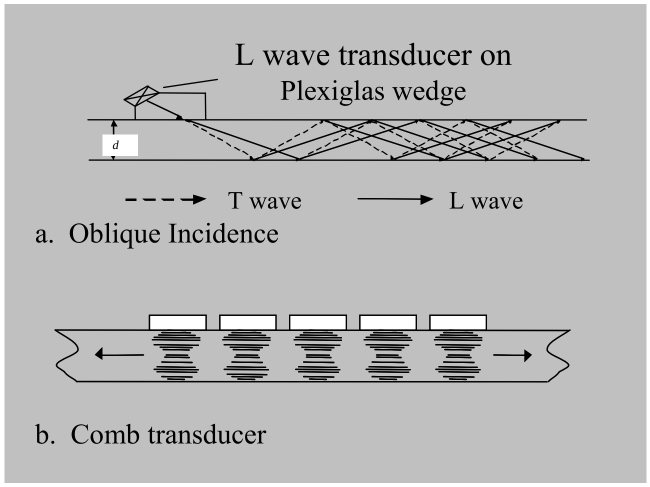
Figure 6-100: Alpha MCD Unit.

Several new NDE concepts are available for wide area coverage. Many of these are robotic with automatic evaluation and detection systems:

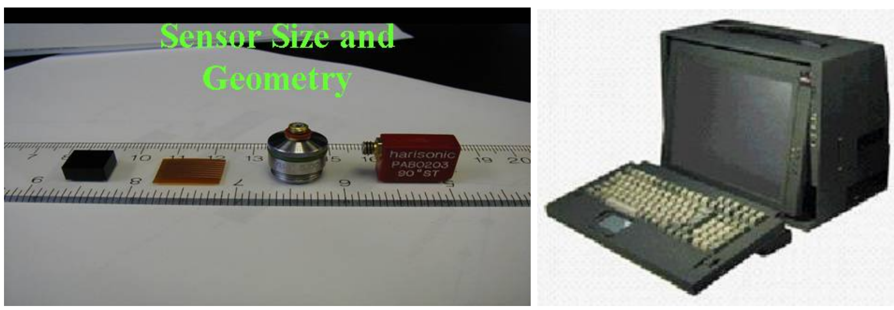
- “Rake-like” array device could carry 10 to 12 sensors.
- Wide area coverage for fuselage, wing, etc.
- Alarms would indicate corrosion location/severity.

An example of the application of advanced NDE for detecting and monitoring environmentally assisted cracking is the H-60 transmission support beam cracks (Figure 6-101). A major contributor to the problem is the increase in the working gross weight with no increase in the strength of the structure. Ultrasonic guided wave inspection was developed for the detection of the cracks (Figure 6-102).

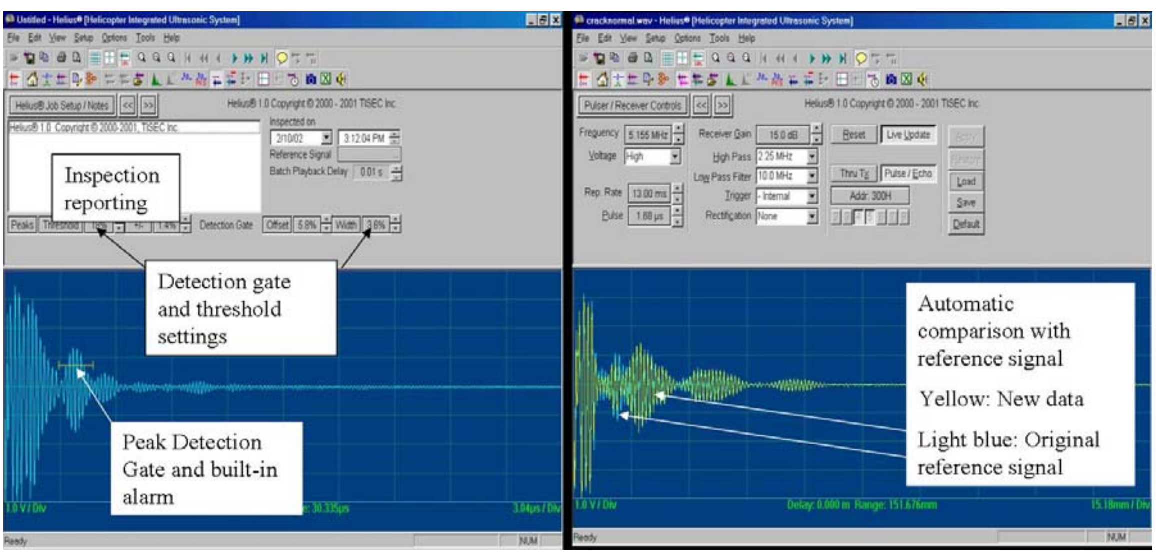
Figure 6-101: H-60 Transmission Support Beam Cracks.



a) Technique for the generation of guided waves.



b) Sensors (left) and HELEUS hardware (modules in a PC environment supported by powerful software).



c) Built-in Crack Detection Gate and Reporting Guided Wave Sensor.

Figure 6-102: Ultrasonic Guided Wave Inspection Developed for Detection of H-60 Cracks.

6.12.6.10 Corrosion and Environmental Sensors

A variety of corrosion sensors and associated data processing and management accessories are under development. Some examples are in Figure 6-103.

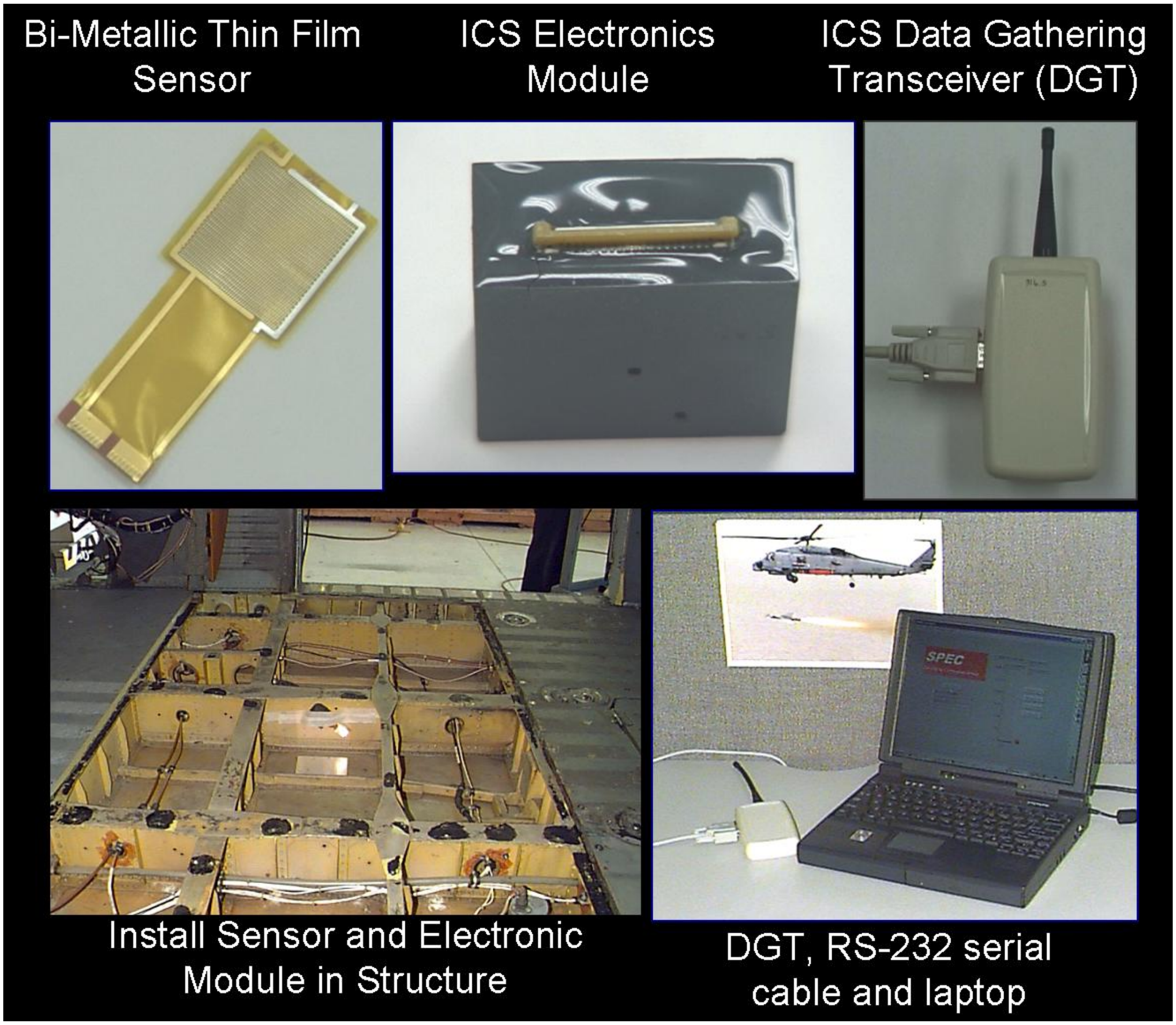


Figure 6-103: Environmental (Moisture) Sensor for Use on Aircraft Structure.

6.12.7 Our Challenge

Our challenge for corrosion control and life management:

- Re-capitalize with best corrosion control practices.
- Transition enabling technologies.
- Promote corrosion engineering education.

- Implement diagnostic/prognostic tools.
- Continue to develop innovative solutions – promote R&D.
- Modify acquisition policy.

Figure 6-104: Our Challenge for Corrosion Control and Life Management.

6.12.8 Dehumidification to Reduce Preventive and Corrective Maintenance for Corrosion

The information on dehumidification in this section is based on Paper 4.10c by Schweitz.

6.12.8.1 Swedish Air Force Experience with Dehumidification of Aircraft

The Swedish Army has used the dry air technique since 1958. Until 1984 it was used only for materiel in depots (mobilization storage). The aim was that all materiel could be stored during four years without any maintenance inspections or measures. For all materiel which contained electronic components it was necessary to use dehumidification. The four-year cycle fit with Army mobilization training cycles.

Sweden uses several ways to store the materiel in a dry air environment, such as:

- Dehumidification of the entire storage building;
- Dehumidification of some part of a building – " dry air box";

- In a plastic bag; and
- By a duct system from a dehumidifier let dry air inside a vehicle or into a staff cabin.

6.12.8.2 Investigation on Material in Mobilization Storage

Comprehensive studies have been done of the materiel in mobilization storage, to determine the best materials and most efficient processes for maintaining equipment reliability. Between 1972 and 1986, continuous measurements of storage effects were made in collaboration with industry at three locations in Sweden, using the combinations of environments and materiel indicated in Table 6-6.

Table 6-6: Combinations of Environments and Materiel in Long-Term Storage Study.

Environmental Parameters Measured	Storage Environment	Equipment Stored	Raw Material Stored
Relative humidity. Sulphur oxide. Hydrosulphuric acid. Nitrogen dioxide. Ozone. Intensity of the sun. Gliding ashes. Falling ashes. Direction of the wind.	Outdoor. On an open shelf indoors. In a dry air box. In a dry air box with filtered air.	Tanks. Cross country trucks. Radio transmitters. Spare parts. Packing of rubber and plastic. Textiles. Medical articles.	Sheet of steel, unprepared and zincified. Sheet of aluminium, unprepared. Sheet of silver, unprepared. Sheet of copper, unprepared. Rubber, 14 different kinds. Plastic, 7 different kinds.

6.12.8.3 Experience from the Storage Test Project

A summary of the observations made on different materiel during storage for up to eight years is as follows:

- Rubber details:

  The material was found to be sensitive to the environment. Important changes were noted in specimens stored outdoors and inside storage-rooms with untreated air. Tyre rubber was particularly sensitive. In all other environments no deterioration was noted. It was concluded that a storage-environment of dry air at 50% RH would be acceptable for all the tested qualities of rubber. However, poor quality rubber should not be used.

- Plastic material:

  A number of plastic bars were included in the test. Polypropylene showed a reduction in tensile strength in all environments, while other plastics passed without any remarks.

- Printed circuit cards and contact instruments:

  No printed circuit cards showed significant changes in any of the storage conditions.

- Condensers:

  The attacks of corrosion on the metal-enclosed condensers were the most serious outdoors. The test result shows that no alarming interruptions have occurred. However, when using condensers in equipment attacked by corrosion and exposed to mechanical strain, such as from vibrations or outdoors environment, it is to be feared that this corrosion might cause a break on some connection.

- Packing:

  Nitrile rubber is the most commonly used material in packing. Research has shown that nitrile rubber is affected in a relatively short time by the ozone of the atmosphere. Fluorine rubber showed the least change in storage.

The storage test program showed that dehumidification was necessary to ensure:

- High reliability and readiness after long-term storage; and
- Limited maintenance requirements during storage.

6.12.8.4 Dehumidification of Aircraft in Service

The Swedish Ministry of Defence, FMV, started a test program in 1980, to determine whether dehumidification of the air within the aircraft would reduce the rate of corrosion in engines and the rate of failures in different systems.

Thirty-three fighter aircraft were included in the study. Twenty-three of these aircraft were randomly selected as a control sample that would receive no special treatment. The other ten aircraft were connected to dry air and placed in a hangar at the end of each day's operations. The dry air was supplied to the engine through one intake. It was supplied to the radar, wing electronics, front and rear electronics compartments, and cockpit through existing ground venting/cooling connections. Measurements of the distribution of the dry air within the whole aircraft were performed. In the targeted zones, the relative humidity was maintained below 50%. The measurements also showed that, through leakage, the dry air was also effective in reducing the relative humidity below 50% in several other internal regions of the aircraft. In the control group of aircraft, the relative humidity was above 50% in all zones measured.

Figure 6-105 shows the number of failures in each sample group of aircraft during 2,300 flying hours. The data for three zones in the aircraft are shown. The graph shows significantly more failure in the control sample than in the dehumidified sample. This was consistent with previous experience, which had indicated that failure rates in electronic equipment increase significantly when the relative humidity exceeds 50%.

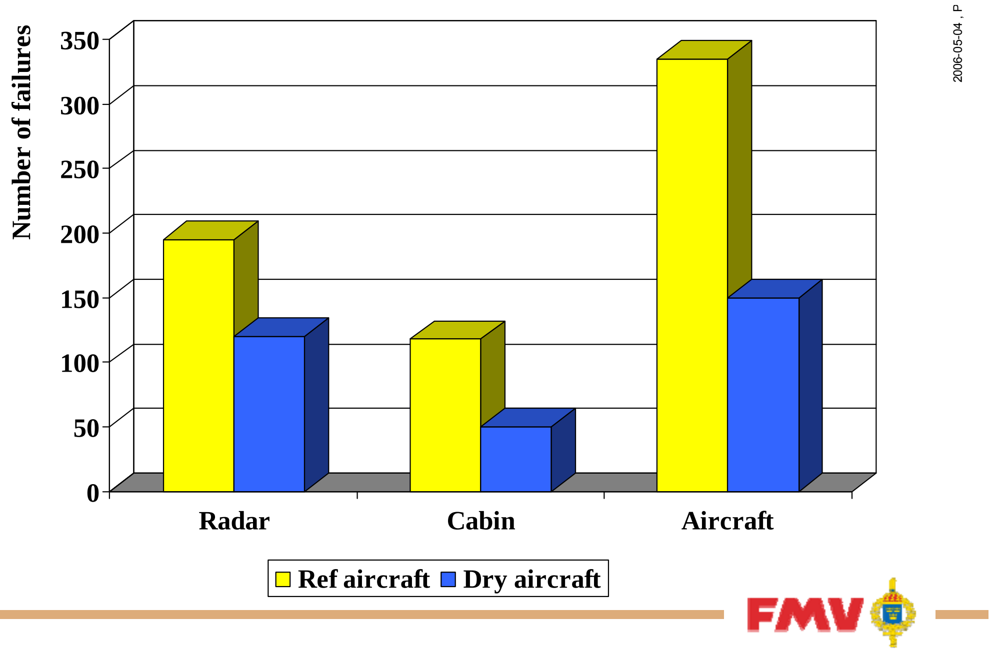


Figure 6-105: Effect of Dehumidification on the Number of Failures in 2,300 Flying Hours.

The comparative MTBF figures are shown in Figure 6-106. A remarkable improvement in achieved reliability is evident in the dehumidified aircraft. The overall average increase in MTBF was 26%. It was estimated that a general increase in fleet reliability of this magnitude would yield a corresponding increase in aircraft availability of 5%. In a division of 20 aircraft, this is equivalent to one extra aircraft on the line ready to go each day.

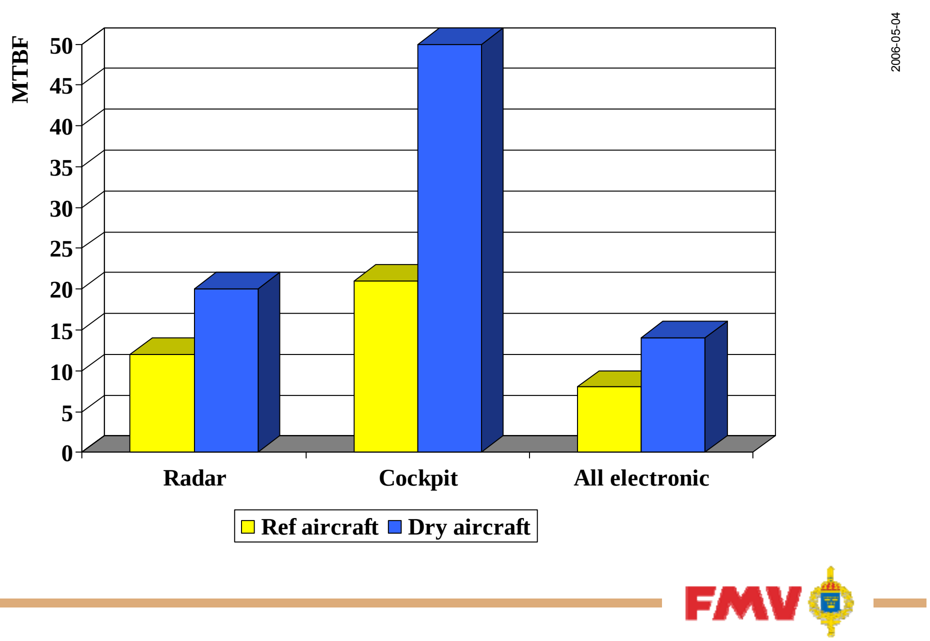


Figure 6-106: Effect of Dehumidification on MTBF.

The above differences between the control and test samples were not due to differences in design configuration or operating environment. The study data were gathered over a calendar period of approximately one year. During the two-year period immediately preceding the study the reliability of the control and test samples of aircraft were comparable. The reliability of the control sample did not change significantly during the study period, whereas the reliability of the dehumidified sample increased substantially.

The annual reduction in corrective maintenance costs for the test sample has been estimated as US$100,000. The installation cost of individual aircraft dehumidification per division of 20 aircraft is estimated to be US$85,000. The corresponding operating costs are US$4,000 per year.

The benefits in reliability and net reduction in maintenance/support costs have prompted the Swedish Ministry of Defence, FMV, to equip most divisions of aircraft for individual dehumidification. A system for the Gripen is currently under development.

The study period was too short to assess the effects on engine reliability and maintenance. However, there is anecdotal evidence of improvements in service.

The study and other work have indicated that the storage of aircraft in hangars below 50% RH at any temperature may result in comparable improvements to the use of individual aircraft dehumidification.

FMV has developed an easily deployable system for dehumidification which can be used during operation from temporary airfields in Sweden, peace keeping operations, and other expeditions. This equipment is illustrated Figure 6-107.

Figure 6-107: A Dehumidifier for Aircraft.

On-Board Oxygen Generators (OBOGs) are particularly sensitive to humidity. FMV have developed special dehumidification equipment for use on OBOG (Figure 6-108). This equipment is also deployable.

Figure 6-108: Dehumidification of the On-Board Oxygen Generator System (OBOGS).

FMV has also experimented with the use of dehumidification in C-130 transport aircraft. Dehumidification can be performed quickly, and an improvement in MTBF was achieved. Dehumidification would also protect the cargo. FMV is studying the feasibility of dehumidifying an aircraft during flight.

A Swedish company – CTT – has developed a dehumidification system which will remove condensation from the thermal and acoustic insulation between the transport cabin wall and the fuselage skin (Figure 6-109). Condensation in this area causes corrosion and significantly increases weight. CTT has installed this system in the Airbus A380 and Boeing 787 passenger aircraft.

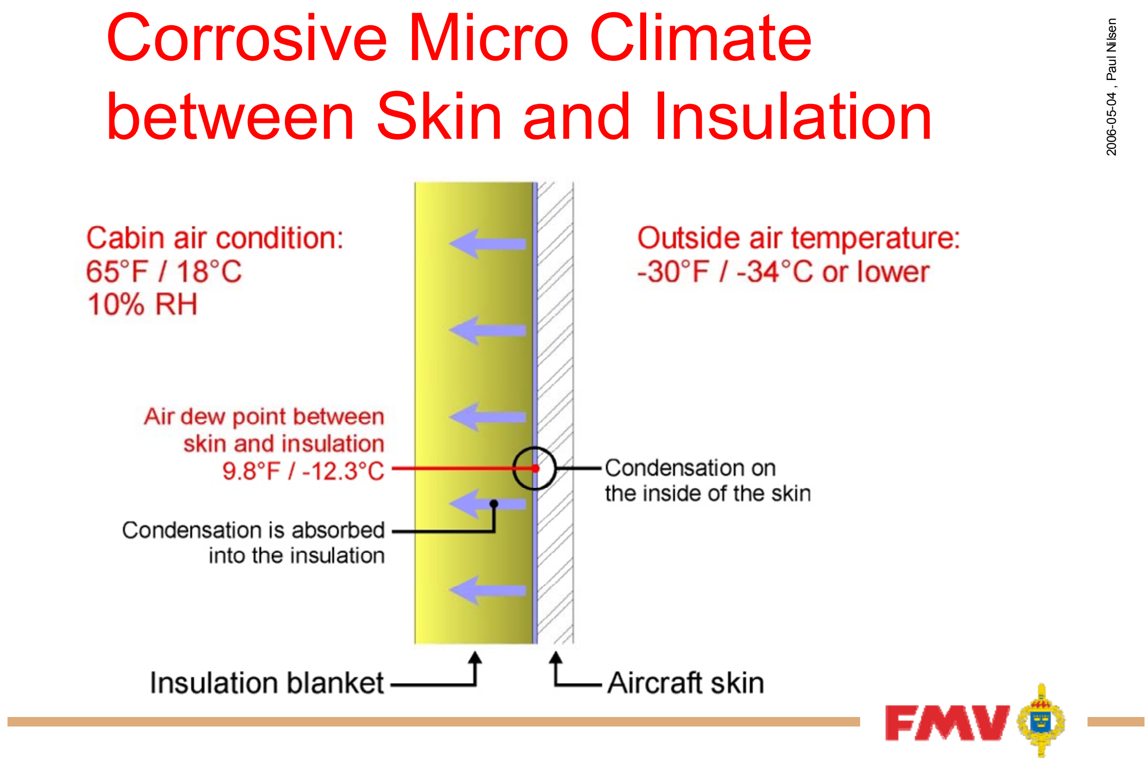


Figure 6-109: Condensation Absorbed by Insulation Blankets on the Interior of an Aircraft Skin.

Chapter 7 – SUMMARY AND CONCLUSIONS

7.1 ACHIEVEMENT OF OBJECTIVE

The AVT-144 Technical Team was established by the NATO Research and Technology Organisation Applied Vehicles Technology (AVT) Panel to identify advanced maintenance/support concepts and technologies that could enhance aircraft platform availability, and to provide information to help NATO forces in selecting the ones that might provide a Return On Investment (ROI).

This report has identified and described many such concepts and technologies. In view of the large scope of the subject, the amount of detail provided on individual concepts and technologies has been limited to that necessary to convey their relative importance and provide some guidance on their use a part of an integrated maintenance strategy. The AVT-144 Technical Team judges that the concepts and technologies outlined in the report could provide a significant ROI if properly applied using the systems engineering managerial approach described in the report.

A philosophical and contextual framework for the report was established in Chapter 2, and the current chapter sets out conclusions according to this framework. Many of the concepts and technologies described in the report will continue to evolve for many years. It is important for optimising aircraft availability and mission reliability that engineers and managers in aircraft design and maintenance/support take into account the latest developments. The report is amply indexed for selective reading, and the team hopes that engineers and managers in NATO and PfP countries will find it a useful guide and reference.

In interpreting the objective, the AVT-144 Technical Team regarded advanced concepts and technologies as those which had recently resulted in improvements in the availability and/or life-cycle cost of military aircraft in one or more NATO or PfP Air Forces, or that offered potential improvements. In keeping with standard definitions, maintenance was taken as including all in-service support. The dual term “maintenance/support” has been used frequently in this report to reinforce this perspective.

In discussing maintenance/support there is considerable scope for misunderstandings due to the variety of interpretations given to commonly used terminology. To minimise such misunderstandings without overburdening the text of the report, an extensive list of relevant definitions has been provided in Annex C. In many cases several alternative standard definitions are listed. The report has chosen one definition where absolutely necessary, but has otherwise tried to communicate in terms that would be immediately understood by most maintenance/support engineers and managers regardless of their backgrounds.

7.2 THE IMPORTANCE OF AIRCRAFT PLATFORM AVAILABILITY

Aircraft availability is a key component of military capability and an important measure of the readiness and effectiveness of a force. For years, NATO accepted trade-offs between reliability and technical performance in tactical systems because it was compelled to pursue technological superiority over the Soviet Union during the Cold War. There is now a need to place more emphasis on availability and mission reliability, together with an enduring ability to provide these in tactical deployments with a small logistics footprint. There has been a trend to concentrate more capability in fewer aircraft. This trend has heightened the importance of aircraft availability, while making it more difficult to achieve.

In general, NATO Air Forces appear to be dissatisfied with the average availability of their fleets, and with the costs of maintenance/support. Transformational changes in the organisation of maintenance/support have been made in some countries to bring availability up to target levels and reduce maintenance/support costs. There has also been a renewed emphasis on the importance of robust systems engineering and management practices during acquisition and the full life-cycle. This emphasis is now built into maintenance/support doctrine, and integrated project teams have been given the responsibility and authority to provide it.

Some impressive successes have been achieved in improving availability while substantially reducing costs, but the pressure to improve availability and efficiency continues. In this context, it is fortunate that efficiency and availability are mutually supportive objectives. Improvements in one will often result in improvements in the other. Moreover, improvements in efficiency can be traded for improvements in availability, and vice-versa.

Availability is generally viewed as the average availability of mission-capable aircraft on the flight line in a given period. When a long period of a year or more is chosen, availability statistics or predictions give a steady-state indication of the contribution that a fleet can make to joint force capabilities.

For military effect, high availability on the flight line must be accompanied by continued availability throughout a mission profile. This is usually expressed as a need for high "mission reliability". Hitherto, metrics related to average availability have been used for managing force capability and readiness. Metrics related to mission reliability will be given a higher profile in the management of the maintenance/support of the F-35 Joint Strike Fighter (JSF), and this approach may be extended to some existing fleets.

During deployments/expeditions, a higher than average availability is usually desired, and is usually achieved with the help of temporary adjustments to fleet maintenance/support. There has long been interest in going further in this direction by providing tactical aircraft with a capability for a "Maintenance-Free Operating Period (MFOP)". This is a limited period of extremely high availability combined with a small logistics footprint.

The report has dealt with all three concepts of availability: average availability, mission reliability, and the MFOP concept.

7.3 GOALS FOR IMPROVING AVAILABILITY

Average aircraft availability is governed by the *need for maintenance* and the time taken by the maintenance/ support system to perform this maintenance – known as *downtime*. To improve average availability, both the need for maintenance and the associated downtime must be reduced.

The continued availability of an aircraft during a mission – mission reliability – is governed only by the conditional probability of a mission-critical failure. The specified level of mission reliability is the main driver of preventive maintenance, and therefore constrains average availability within a fleet. Measures to improve mission reliability will usually also improve availability on the flight line, but the reverse is not necessarily true. For this reason, the goals and strategies for improving mission reliability have been presented in the report as part of the goals and strategies for improving average availability.

The goals and strategies for the provision of a useful "Maintenance-Free Operating Period (MFOP)" capability correspond with those described for maximising average availability and mission reliability. In addition, a good MFOP capability is likely to require a particular emphasis on certain advanced equipment concepts and technologies. These were identified in the report and are summarised later in the aircraft and equipment portion of these conclusions.

Through-life goals for minimising the need for maintenance are as follows:

a) Design to maximise the inherent (design) reliability and mission reliability.

b) Resolve any shortcomings in manufacture and maintenance that are inhibiting the achievement of the inherent reliability, or at least the specified reliability, in service.

c) Limit maintenance to essential tasks.

Through-life goals for minimising downtime are as follows:

a) Design the aircraft for maintainability (ease of maintenance).

b) Reduce the downtime for servicing (replenishments).

c) Reduce the downtime for replacement/restoration of lifed components by:
    1) Designing for aircraft maintainability with particular attention to the components in question;
    2) Extending remaining useful life;
    3) Improving the scope and accuracy of usage monitoring; and
    4) Using on-condition inspection instead of component replacement/restoration.

d) Reduce the downtime for inspections, i.e. on-condition and failure-finding tasks.

e) Reduce the downtime for “age exploration”.

f) Reduce the downtime for diagnostics.

g) Reduce the downtime for failures that cannot be duplicated (CND).

h) Reduce the downtime for repair.

Management and equipment strategies for achieving each of these goals were outlined in Chapter 2.

7.4 MANAGEMENT CONCEPTS AND TECHNOLOGIES

7.4.1 Categories of Management Concepts and Technologies

The management concepts and technologies that can help achieve the goals just listed in Section 7.3 were discussed in Chapters 4 and 5, and are categorised as follows:

a) Systems engineering and project management.

b) Modelling and simulation of the maintenance/support system.

c) Integrated Logistics Support (ILS).

d) Availability-based contracting – also known as Performance-Based Logistics (PBL).

e) Reliability and Maintainability (R&M) management.

f) Aircraft/Engine Structural Integrity Program (ASIP and ENSIP).

g) Total Life-Cycle Systems Management (TLCSM) and Through-Life Capability Management (TLCM).

h) Integrated Project Teams (IPT).

i) Technology Insertion (TI).

j) Manufacturing management (primarily quality control).

k) Reliability-Centred Maintenance (RCM) to determine essential maintenance and optimum failure management strategies.

l) Lean and other enterprise management concepts.

m) Maintenance management decision support.

n) Integrating the maintenance/support system for a major program.

o) Other maintenance/support management concepts and technologies.

The information and conclusions of the report on these management concepts and technologies are summarised in the following sub-sections.

7.4.2 Systems Engineering and Project Management

The design and management of an aircraft and its maintenance/support occurs in the context of many competing priorities for the available development and operating funds. Therefore, it is important that a systematic approach is followed that takes account of all important requirements and factors. Systems engineering is the systematic, comprehensive, and integrated approach needed. Project management is the discipline used to manage the systems engineering process so that there will be a high probability of meeting the project requirements, including aircraft availability, within the required budget and schedule. Both disciplines are constantly evolving. It is important that the aircraft program employs the most advanced methods and that the senior engineers and managers are thoroughly trained and experienced in both disciplines.

7.4.3 Modelling and Simulation of the Maintenance/Support System

To optimise the design and through-life management of the aircraft and its maintenance support system with respect to availability, it is important to be able to model the maintenance/support system and measure relevant parameters in service. Sophisticated Discrete Event Simulation (DES) modelling of military maintenance/support is performed in some NATO countries, but is still an emerging technology. The report describes DES models under development by Boeing IVHM Centre and MOD UK, and provides modelling results for a large transport aircraft and a group of Chinook helicopters. These results illustrate how the models can be used to identify the key parameters affecting aircraft availability. Maintenance data systems also exist in many NATO countries, but the historical data in these systems is based on the data systems and computer technology that is more than 10 years old. Nevertheless, time and perseverance can produce valuable results with these early systems, and this is illustrated in the report by a detailed study of USAF data. There remains considerable scope for further development in both modelling of maintenance/support and maintenance data systems. The trend to PBL will provide considerable impetus for improvements in these technologies, because they are needed by the air forces to manage the contracts, and they are needed by the contractors to manage risk and maximise profit. The use of maintenance data systems to support availability-based contracting was illustrated in the report in a case study of the new Canadian Maritime Helicopter Program.

7.4.4 Integrated Logistics Support (ILS)

The decisions taken during the design and development phase of an aircraft can determine about 95% of total life-cycle cost. Within the system life-cycle framework, many NATO Nations use a major sub-process known as "Integrated Logistic Support" (ILS) to co-ordinate the design of the aircraft and its in-service support to meet the aircraft specification at lowest cost. ILS provides the disciplines for ensuring that supportability and cost factors are identified and considered from concept design to retirement, with the aim of optimizing the life-cycle cost. *Supportability* is the degree to which system design characteristics and planned logistic resources, including manpower, meet the system peacetime and wartime *availability* requirements.

The US DoD introduced a new all-embracing maintenance/support policy named Condition-Based Maintenance Plus (CBM+) in 2007. This appears to have comparable aims to the previous ILS process, and includes RCM and R&M management. It emphasises Total Life-Cycle Systems Management (TLCSM) and the RCM on-condition maintenance strategy, which it calls Condition Based Maintenance (CBM).

7.4.5 Availability-Based Contracting and Performance-Based Logistics (PBL)

We have recently seen a dramatic transformation in contracting for aircraft acquisition and maintenance/ support, particularly in the USA and UK. Governments have started to enter into long-term partnerships with aircraft manufacturers, whereby they are assured of contracts for series production and maintenance/support, including supply management. In some cases, the contracts hold the OEM accountable for the availability of the aircraft and other key performance parameters for periods of twenty years or more, and provide incentives and penalties related to the achievement of the required availability at minimum life-cycle cost. This management strategy is generally referred to as either "availability-based contracting", or "Performance Based Logistics (PBL)". The results of this strategy appear to be generally positive, but government accounting systems need to be adjusted to allow a full assessment. The UK is trending towards full integration of industry with the Armed Forces in the provision of maintenance/support, while locating depth maintenance at main operating bases in some cases. The US Government favours retaining at least 50% of depot maintenance within the DoD.

7.4.6 Reliability and Maintainability (R&M) Management

A well-resourced and proactive R&M management program is crucial to aircraft availability. It is standard practice in NATO to establish a formal Reliability and Maintainability (R&M) management program at the concept design stage. The R&M management program is continued during series production and the life of the aircraft, to ensure that the inherent reliability, or at least the specified reliability, is achieved and sustained in service. By definition, the maintenance/support system cannot improve on inherent reliability, but it can try to ensure that maintenance shortcomings do not degrade reliability. It can also mitigate the effects on availability of a shortfall in reliability due to shortcomings in manufacturing. While a typical R&M management program initially focuses on design and manufacture, it provides essential information for the design of the maintenance/ support system and for dealing with any later shortfall in reliability. Consequently, when the aircraft enters service, the R&M management program typically evolves to become an integral part of the maintenance/ support program. The management of R&M is as important as the equipment technologies used by designers to improve R&M. The broad principles and practices of R&M management apply to all aircraft components. They have been developed to a high level in NATO countries, but the resources allocated to implementing them are under the control of project managers.

7.4.7 Aircraft and Engine Structural Integrity Programs (ASIP and ENSIP)

The USAF developed a program known as the Aircraft Structural Integrity Program in the 1960s, following a series of serious reliability problems with aircraft structure that resulted in some catastrophic failures and had a long-term impact on aircraft availability. This program is effectively an R&M program dedicated to airframe structure. Most if not all NATO Air Forces follow a dedicated airframe structural integrity program comparable to the USAF's ASIP program, although terminology and some of the details vary. The program is mandatory in the USAF as laid out in Mil-Std-1530C, and governs design as well as maintenance/support. The integrated design and maintenance requirements of ASIP have greatly reduced the risks of catastrophic structural failure and major fleet availability problems. These risks are likely to be higher in air forces who do not apply an airframe structural integrity program with the same rigour as the main NATO Air Forces.

A comparable management program to ASIP for engines, called ENSIP, is applied by many NATO Air Forces. There are difficulties in applying the on-condition (damage tolerance) maintenance approach used in ASIP to engines, and so engine and airframe maintenance/support strategies differ in some respects. ENSIP as laid out in Mil-Hdbk-1783B is not mandatory in the USAF. Several NATO Air Forces have promoted the development of technologies to allow a greater degree of on-condition maintenance. Civil regulators have recently modified the regulations for engine design and maintenance to make the design for on-condition maintenance mandatory where feasible; however, a safe life maintenance concept must be superimposed on this in the case of critical components.

7.4.8 Total Life-Cycle Systems Management (TLCSM) and Through-Life Capability Management (TLCM)

An important feature of the transformations being made in acquisition and maintenance/support in the USA and the UK is that much greater emphasis is now placed on the continuity of program management throughout the life-cycle, and on merging the different cultures of acquisition and maintenance/support. One of the tangible changes in this regard is the appointment of program managers as leaders of Integrated Project Teams (IPT) with the responsibility and authority to manage acquisition and maintenance/support throughout the life cycle. In the USA, this is referred to in policy documents as Total Life-Cycle Systems Management (TLCSM).

In parallel, new processes within the US DoD and MOD UK have been established to ensure a rigorous, joint forces approach to the development and management of military capabilities. In the UK, this has extended to the creation of an inter-departmental structure headed by a single senior officer responsible for "Through-Life Capability Management". This change is associated with a general shift in UK defence acquisition towards the incremental enhancement of existing capabilities.

The introduction of total life-cycle systems management by an empowered project team, the focus on clear management performance targets, and the parallel effort to ensure good joint force capability definition and management should ensure that the key elements of capability, such as aircraft platform availability, receive appropriate and sustained attention. There is more discussion of the IPT and technology insertion concepts in the next two sections.

7.4.9 Integrated Project Teams (IPT)

Project teams have traditionally been established for the acquisition of new aircraft, but until recently they did not generally have a continuing role throughout the life of an aircraft. Problems with poor availability and high maintenance/support costs have been traced to inadequate design priority on parameters that affect maintenance/support and on insufficient integration between the design of the aircraft and the maintenance/support system. As just mentioned, the extension of the mandate of integrated project teams to cover the full life-cycle is one tangible measure taken in the USA and UK to remedy this situation. The French Air Force organisation

SIMMAD does not employ cradle-to-grave IPT, but it effectively fulfils the same purpose: it has a mandate to ensure that all aircraft achieve and sustain adequate in-service availability; it controls ILS policy and application; and it is involved in all relevant acquisition and support issues.

7.4.10 Technology Insertion (TI)

The UK's Defence Industrial Strategy Review of 2005 reports that there is a general shift in defence acquisition away from the traditional pattern of designing and manufacturing successive generations of platforms – leaps of capability with major new procurements or very significant upgrade packages – towards a new paradigm centred on support, sustainability, and the incremental enhancement of existing capabilities by technology insertions.

The UK Defence Scientific Advisory Council (DSAC) has made five recommendations for managing Technology Insertion (TI) from design onwards:

- Strive for modularity of system design.
- Ensure that certification processes will not be an obstacle.
- Plan for early technology demonstration to reduce risks.
- Ensure that contracts with industry provide incentives to make cost-effective use of new and up-to-date technology.
- Appoint a 'Systems Architect' to take responsibility for the through-life trade-offs involved in TI.

7.4.11 Manufacturing Management

Manufacturing must be considered in the context of maintenance/support, because, as mentioned in Chapter 2, shortcomings in manufacturing can result in a shortfall in aircraft reliability. The maintenance/support system must somehow maintain the required aircraft platform availability despite such shortfalls, while longer-term remedial measures are taken. Manufacturing is also important to maintenance/support, because the supply of spare parts is a maintenance/support function. There are well-established principles for quality management in industry and organic (government) depots. The advanced enterprise management concepts discussed in Chapter 5 and summarised in Section 7.4.13 below provide means of ensuring that quality management is integrated as effectively and as efficiently as possible into the manufacturing processes, to minimise defects and ensure batch repeatability.

7.4.12 Reliability-Centred Maintenance (RCM) to Determine Essential Maintenance and Optimum Failure Management Strategies

The design of an aircraft and its maintenance/support system is an iterative process. A process known as "Reliability Centred Maintenance (RCM)" is widely used in NATO and civil aviation in designing preventive maintenance programs. The RCM process provides a means of determining in progressively greater detail during successive design iterations what preventive maintenance tasks are necessary and how best to perform them. During the remaining life of the aircraft, it provides an objective basis and process for reviewing the maintenance program. The data generated during the RCM process, in particular the results of the Failure Modes and Effects Criticality Analysis (FMECA), also facilitate the planning of corrective maintenance, although this is not the primary aim of RCM. The application of the RCM process together with the R&M management program from an early stage helps to highlight the areas where improvements to inherent R&M and the maintenance/support system would provide a good return on investment. A full understanding of the principles and processes of RCM are essential for the cost-effective use of advanced aircraft and equipment concepts and technologies in the aircraft design or for later technology insertion.

The report described the history and principles of RCM, and discussed the various RCM failure management strategies. These included "on-condition" inspection, which is widely used in airframe structure, where it is usually referred to as "damage tolerance" inspection. It is now also often referred to as "Condition-Based Maintenance (CBM)".

On-condition inspections can only be employed on components that can be relied on to give detectable signs of potential failure well before actual functional failure. In other words, candidate components must have a long Potential Failure (PF) interval that can be reliably predicted for the different states of potential failure that might be observed during inspection. It is also necessary to be able to estimate the Remaining Useful Life (RUL) accurately at any time, so that the optimum combinations of inspection method and frequency can be applied for all predicted failure modes. In certain cases, it is possible to gain a "Predictive Maintenance Window (PMW)" during which corrective action (after detecting a potential failure) could be deferred with tolerable risk.

In airframe and engine structure the on-condition strategy is usually called the "damage tolerance" strategy. This strategy is mandatory for most airframe structural components in USAF and civil aircraft. A "safe life" replacement/restoration strategy is only allowed by exception. In the US Navy and some other NATO Air Forces the "damage tolerance" strategy is preferred but not necessarily enforced. There are many airframe structural components for which a PMW would be feasible, but there does not seem to be a significant need for the concept. In engines, transmissions, and helicopter rotors, an on-condition maintenance strategy is currently only feasible and cost-effective for a few components, because the PF intervals in these systems are generally short and inspections are difficult. Nevertheless, civil regulators have for safety reasons recently mandated the use of an on-condition (damage tolerance) strategy in addition to a hard time replacement/ restoration (safe-life) strategy on engines and some other components.

The number of suitable candidate components for on-condition maintenance is increasing with the improvements in failure modelling and inspection technologies discussed in the report. In particular, the option to apply frequent or continuous inspections using embedded systems allows components with short PF intervals, such as those just mentioned, to be considered.

Since most electronic equipment has a constant failure rate, a "run to failure" strategy is often employed. However, for mission-critical equipment it may be appropriate to design for redundancy, fault tolerance, and graceful degradation (a gradual reduction in functionality), so that an on-condition inspection strategy can be applied. Built-In Test (BIT) would have to be included to perform the necessary failure finding inspections. As with any on-board system, there would be cost, weight, (general) reliability, and maintenance implications to balance against the gains in mission reliability and MFOP capability.

7.4.13 Lean and Other Enterprise Management Concepts

Advanced business management concepts that have been applied to aircraft maintenance/support by NATO forces and the defence industry include:

- Theory of Constraints (TOC).
- Lean Enterprise Management (Lean).
- Reliability-Centred Maintenance (RCM) – development sponsored by the US Navy and the civil airline industry (described earlier in this chapter).

- Six-Sigma.

RCM has already been discussed. Lean management methodologies have been successful in reducing costs and maintenance downtime at all maintenance organisational levels. At 3rd and 4th Line they may be applied in combination with TOC and Six-Sigma methodologies.

7.4.14 Maintenance Management Decision Support

The Eurofighter Typhoon multi-role combat aircraft exemplifies how advanced air and ground systems can provide strategic and tactical decision support to improve the efficiency of maintenance planning and execution. It incorporates one of the most advanced maintenance decision support systems currently available. It is known as the Integrated Monitoring and Recording System (IMRS). There are two main decision support levels: the "Tactical Level" and the "Strategic Level". Each requires information at a different level of detail. The IMRS forms an integral part of the avionics suite on Eurofighter. Maintenance decision support is integrated with many other functions performed by the IMRS. These include:

- Structural Health Monitoring (SHM);
- Mission data loading;
- Video and voice recording;
- Mission data recording;
- Crash recording;
- Maintenance data loading;
- Limited configuration checking;
- Special study recording;
- Warnings handling;
- (Externally) Initiated Built-In Test (IBIT) handling;
- Recording of consumables information; and
- Erasure of secure data.

7.4.15 Integrating the Maintenance/Support System for a Major Program

The report's description of management concepts and technologies concludes with a broad overview of a major international aircraft acquisition program, to illustrate how the various management concepts discussed earlier can be integrated. The programme in question is the A400M tactical transport aircraft. This is a cooperative European programme between seven European Nations, which is managed by the Joint Organisation for Armaments Cooperation (OCCAR). The prime contractor is Airbus Military. As a new programme built on a commercial approach, it is bringing together many improvements that will impact aircraft availability. The report explains the maintenance and support concepts used in this program to improve availability and reduce costs. These include a commercial approach, the optimisation of the scheduled maintenance programme, the extensive use of on-condition maintenance, the application of a Maintenance-Free Operation Period (MFOP), and the use of common support solutions among Nations. It also explains the technological measures applied during the design of the aircraft to improve availability, such as computer-aided design, damage-tolerant design, on-board systems integration, and increased components reliability. It also shows that availability cannot be dissociated from costs, and that a higher operational availability and lower costs can have organisational and industrial effects that could increase the overall efficiency of both the Armed Forces and the European defence industry.

7.4.16 Other Maintenance/Support Management Concepts and Technologies

The following maintenance/support management concepts and technologies have been mentioned in the report, but, because of limitations in the time and resources available to the AVT-144 Technical Team, the coverage did not adequately reflect their importance:

- Some of the management concepts and technologies to improve the speed and reliability of the supply chain, including the following: ICT; supply system modelling; Packaging, Handling, Storage, and Transportation (PHS&T) concepts for aircraft and components, particularly for deployments/ expeditions; long-term storage concepts; the potential of Radio Frequency Identification (RFID); concepts and technologies to deal with parts obsolescence.
- Concepts and technologies associated with the management of Human Factors Integration (HFI) in maintenance/support, in particular those associated with training and modelling/simulation.

7.5 AIRCRAFT AND EQUIPMENT CONCEPTS AND TECHNOLOGIES

7.5.1 Categories of Aircraft and Equipment Concepts and Technologies

The aircraft and equipment concepts and technologies that can help in achieving the goals listed in Section 7.3 were discussed in Chapter 6, and were categorised as follows:

a) Usage monitoring.

b) Failure modelling for prognostics (life estimation).

c) Inspection using NDE.

d) Sensors for on-board usage monitoring and inspection systems.

e) Diagnostics for electrical and electronic systems.

f) Automated inspection and diagnostics for mechanical systems, structure, and engines.

g) Information analysis.

h) Integrated systems for usage monitoring, inspection, diagnostics, and prognostics.

i) Maintenance concepts and technologies for achieving a Maintenance-Free Operating Period (MFOP).

j) Rapid repair of aircraft damaged in action.

k) Corrosion prevention and repair.

l) Other aircraft and equipment technologies.

The information and conclusions of the report on these aircraft and equipment concepts and technologies are summarised in the remaining sub-sections.

7.5.2 Usage Monitoring

Usage monitoring is fundamental to aircraft maintenance, because it is used to schedule maintenance tasks. More accurate usage monitoring and an increase in the scope (number of components monitored) would help in making progress towards several of the goals listed above. Both would require the installation of additional sensors, hardware, and software, and so there would be corresponding increases in weight, cost, complexity, and maintenance tasks. To help minimise these negative aspects, it is feasible to use data already on the databus, particularly if the aircraft has already been equipped with a flight data recorder, a maintenance data recorder, or other maintenance system. The report illustrates this concept by describing in some detail the approach being used on helicopters by MOD UK.

7.5.3 Failure Modelling for Prognostics (Life Estimation)

Advanced failure modelling technologies for mechanical components can help identify and characterise failure modes and to provide more options for failure management, such as the use of:

a) An on-condition *rather than* a safe-life maintenance strategy, to extend component life, and thereby reduce maintenance, without increasing risk;

b) An on-condition *as well as* a safe-life maintenance strategy, to improve mission reliability and/or safety – as in recent civil regulations for engines; and

c) A Predictive Maintenance Window (PMW) to allow corrective maintenance to be planned instead of unscheduled, i.e. to be deferred instead of performed before the next flight.

There has been strong interest in physics-based failure modelling for mechanical/structural components. There may be several reasons for this: mechanical/structural components tend to consist of only one or a few monolithic, non-standard piece-parts; their failure rate is not constant; there is usually a need to investigate all the failure modes of each piece-part through analysis and testing; and there is limited flexibility to lower stresses and add redundancy.

Physics-based modelling is also of interest for electronic equipment, but the general situation is different. Electronic hardware typically contains many discrete, standard piece-parts. The equipment failure rate is approximately constant with time, and so a “run to failure” maintenance strategy has often been employed. Hardware reliability has generally been predicted using standard circuit analysis and statistical procedures together with empirical handbook data on piece-part reliability. The associated reliability engineering methods have developed to an advanced stage over several decades, and circuit design can be used to build redundancy and fault tolerance into the equipment.

The report illustrated the state of the art in mechanical failure modelling by means of a detailed case study in physics-based modelling at the microstructural level of creep failure in a turbine blade in an aircraft engine. This modelling technology is now commercially available.

7.5.4 Inspection Using Non-Destructive Evaluation (NDE)

NDE is used in aircraft maintenance for “on-condition” and “failure-finding” inspections. The purposes of these inspections were explained in Chapter 5 in connection with the RCM concept. Such inspections are usually scheduled for application at 3rd and 4th Line, but may be applied at 1st and 2nd Line in some situations. Inspections for failures and potential failures account for a large portion of the downtime for 3rd and 4th Line maintenance. Reductions in downtime may be achieved directly through the use of advanced NDE technologies to minimise inspection time. They may also be achieved indirectly through the use of advanced NDE technologies to apply a more efficient failure management strategy for some components. For example, advanced NDE may enable the use of on-condition inspections rather than hard time component replacement/restoration. For these purposes, one or more of the following attributes are sought: faster area coverage, higher resolution, higher Probability Of

Detection (POD), improved multi-layer capabilities, less disassembly for access, and a greater degree of automation in the manipulation of instrumentation and data analysis.

Improvements can be made in some cases by adopting radically new methods, but often evolutionary development of existing methods can bring about the necessary increase in capability, particularly when the recent improvements in computing power and automation are utilised. Improvements to traditional methods have involved the development of multiple array probes using many parallel channels to allow faster scanning. The incorporation of automated data analysis with such probes allows rapid, real-time analysis of the huge data sets they generate, and can enhance capability as well as operator efficiency. Chapter 6 provides several examples from EADS on how the use of advanced NDE technologies can reduce the inspection downtime on legacy aircraft.

There has been considerable R&D effort on new techniques based on imaging rather than scanning technologies for the inspection of large areas. The following have been the principal techniques investigated:

- Thermal Methods.
- Pulsed Thermography.
- Lock-in Thermography.
- Sonic IR / Thermosonics.
- Optical Methods.
- Holographic Interferometry.
- Electronic Speckle Pattern Interferometry (ESPI).
- Shearography.

The following NDE techniques have limited resolution and depth of penetration, but continue to be developed for monitoring large areas of structure quickly:

- Acoustic Methods.
- Guided Waves.
- Acousto-Ultrasound.
- Acoustic Emission.

7.5.5 Sensors for On-Board Usage Monitoring and Inspection Systems

In on-board maintenance systems sensors are used for usage monitoring, the detection of failure and potential failure, and the measurement of the rate of degradation. A variety of sensors may be used for these purposes, depending on the nature of the component in question, the local environment, and the parameters that provide the desired indications of usage, failure, or potential failure. Advances in sensor technology continue to expand the variety of sensors and sensory networks available for use in aircraft maintenance.

Some aircraft sensors have adapted pre-existing NDE technologies. An example is the Meandering Winding Magnetometer (MWM) system, a type of eddy current NDE device marketed by Jentek Sensors Inc. Other sensor technologies that are mature enough to allow some applications on aircraft include Micro-Electro-Mechanical-Systems (MEMS) sensors, fibre optic sensors, piezoelectric sensory networks, and Comparative Vacuum Monitoring (CVM) sensors.

Fibre Bragg gratings (FBG) are the most commonly used fibre optic sensors. They are attractive for integration into advanced on-board inspection systems, due to their sensitivity, small size (40 – 125 μm), and ability to form a highly effective sensor network through multiplexing. These sensors can be used to monitor various parameters, such as acoustic emissions from a growing fatigue crack, chemical changes indicative of corrosion, and parameters indicating bond line integrity in bonded joints,. A large network of sensors (up to 1,000) can be manufactured on a single fibre strand. MEMS technology is being exploited to develop interrogation systems for FBG sensor arrays that are sufficiently small and lightweight for aircraft use. Such systems could be of particular value in the inspection of composite structure for quality control and for deterioration in service.

MEMS are also useful in creating miniaturized multi-sensor arrays, in which several MEMS sensors are packaged on a single flexible base as a self-contained system that communicates by wireless transmission or is connected to the aircraft databus. Such systems have been packaged with sensing, interfacing, signal processing and intelligence (self-testing, self-identification or self-adaptation) functions, such that they classify as autonomous “smart sensors”. They could conceivably be designed as part of a composite structure.

Piezoelectric sensors are used either in an active or passive mode. In the active mode, they can be used in the same way as comparable ground-based NDE systems. In permanent sensor systems for detecting cracks in structure, it is also useful to use an array of piezoelectric sensors to detect the energy emitted by a piezoelectric actuator. An anomaly in the component will affect the signals received by the sensor array in a way that allows the size and location of the anomaly to be inferred. In the passive mode, the sound energy emitted during crack growth in airframe structure can sometimes be detected against background noise, and can provide enough information to measure crack growth. Passive piezoelectric systems can also be used to look for anomalies in vibration signatures that indicate a potential failure. On-board maintenance systems using this approach are currently in use on helicopters for detecting potential failure in transmission components.

A new technology known as Comparative Vacuum Monitoring (CVM™) is gaining increasing acceptance as a method of detecting cracks in airframe structure in known “hot spots”. CVM sensors typically consist of grooved strips of a flexible material that are bonded to a surface of interest. One set of grooves is at ambient pressure, while an alternating set is maintained at very low pressure. The presence of a crack is detected by a change in the pressure differential. The CVM sensor has several useful features: it can detect cracks smaller than 1 mm; it can be self-tested; it does not create Electromagnetic Interference (EMI) problems; and it is safe for use in fuel tanks. It might be possible to measure crack size with CVM.

7.5.6 Diagnostics for Electrical and Electronic Systems

“Diagnostics” is usually viewed as the first step in corrective maintenance. Without the help of specially designed on-board or off-board systems, such as Maintenance Data Recorders (MDR), Built-In Test (BIT) systems, and ground-based Automatic Test Systems (ATS), it can be very time-consuming to isolate faults and failures to components that can be repaired or replaced at 1st Line. Often, technicians at 1st Line are unable to reproduce a fault reported by the aircrew or on-board maintenance data system. This is referred to as a “Cannot Duplicate (CND)”, “Re-Test OK (RTOK)”, or “No Fault Found (NFF)” occurrence. Such occurrences can cause additional delay, unnecessary component replacements, and an implicit loss of mission reliability.

The report described the DoD generic ATS program and the concepts and technologies that will be included in future equipment. MDR technologies are covered under health management. BIT is crucial to efficient diagnostics, but the relevant design concepts and methods are outside the scope of this report.

The following are some of the emerging hardware and software technologies being demonstrated by DoD that are described in the report:

- Advanced Synthetic Instruments.
- Programmable Serial Bus Test.
- Reusing Diagnostic Data.
- Multi-Analog Capability (MAC).
- High Density Analog Instrument.
- Common Tester Interface (CTI).

These technologies offer unprecedented opportunities for improvement in warfighter support throughout DoD including improved aircraft availability and mission reliability

The US DoD's Agile Rapid Global Combat Support (ARGCS) Advanced Concept Technology Demonstration project is demonstrating most of the test technologies listed above in a combat support system that will provide electronic systems support at all levels of maintenance. ARGCS can be used to test, troubleshoot, and repair a wide range of digital, radio frequency, analogue, and electro-mechanical units. The concept is a DoD-common core system using common control and support software with complementing/augmenting power and stimulus and measurement hardware as necessary to meet specific test and diagnostics requirements. Integrated diagnostic feedback capability will be included so that diagnostic data captured during the maintenance cycle can be reused. Reconfigurable and scalable, ARGCS will be easily and quickly deployable worldwide with reduced airlift and logistics footprint requirements. One of the key performance parameters will be interoperability among the weapon systems used in coalition partner Nations as well as the US Services.

7.5.7 Automated Inspection and Diagnostics for Mechanical Systems, Structure, and Engines

As with electrical and electronic LRU, the downtime and cost associated with replacing and repairing mechanical LRU, such as flight control actuators, brake systems, flight control surfaces, and some airframe structure at 1st Line can be substantial. The downtime may in general be greater than with electronic LRU, because of the more complex interface with the aircraft and difficulties of access. The implications for availability and cost are potentially greater with engines. Therefore, fast and accurate on-aircraft diagnosis of failures and anomalies at 1st Line is important.

The report gave an overview of the current capabilities and future potential for automated inspection and diagnostics for mechanical systems and structure in general. It also discussed the scope for using advanced inspection and diagnostic technologies in the design of new engines, and for technology insertion in an ageing fleet of engines.

General diagnostic tools and techniques for mechanical components fall into three categories: data fusion methods, retrofitable troubleshooting systems, and fully integrated sensor suites. The objective of each category is slightly different, but the overall thrust is to increase the availability of the aircraft.

Data fusion methods, or statistical fleet monitoring approaches, involve using software and database systems to archive and analyse recorded data from each aircraft in a specific fleet. There are a variety of companies offering systems to perform this analysis. An advanced system is capable of running complex heuristic analyses on data to highlight not just pre-set limits, but also to spot anomalies. This can be an important tool to spot early warning signs of impending system failures. Trending and analysis of existing data can provide significant maintenance benefits, including substantial cost savings through the early recognition of technical problems.

There are two sub-categories of retrofitable systems: those that meet an ongoing maintenance need, and those that are employed to solve a short-term problem. In both cases available sensor and information analysis technologies are assembled and tailored as required. The report gave an example of where a significant ROI was achieved in automating a routine landing gear strut inspection. This example had wider application on other aircraft types. A self-contained strain recorder system for temporary installation was also described. This could provide strain data for a variety of maintenance purposes, including fatigue diagnostics and repair design.

The concept of fully integrated sensor suites for inspection and diagnostics is now coming to fruition in aircraft such as the F-35 Joint Strike Fighter (JSF). In this concept, distributed sensors, each suited to their specific task, are connected to the aircraft data bus and a central diagnostic system. The aircraft is able to assess damage, faults, and inconsistencies. In addition, it is able to recommend to the pilot or maintenance technician an appropriate course of action. To provide this diagnostic ability, algorithms are being developed that exploit existing sensors in new ways and interpret data from new sensors.

The diagnostic system on the SNECMA M-88 engine for the Rafale fighter is integrated with condition monitoring and prognostic systems. These systems work together to reduce maintenance downtime and improve mission reliability. At one level, there is ongoing diagnosis and prognosis. At another level, there is the capability for complementary tests, performed without a test bench and with the engine shut down. The tests include fuel leakage tests, fault localization tests, control loop tests (e.g. inlet air control system), tests of the anti-icing vane, tests of the fuel flow meter, etc. On-board diagnostics includes the following functions:

- Analysis of vibration and oil debris for bearing degradation;
- Analysis of accelerometers for shaft balance;
- Collection of comprehensive usage data for use in models of general fatigue, high cycle fatigue, and crack propagation;
- Analysis of start sequence performance anomalies, such as overheating, stall, and slow start;
- Analysis of other performance anomalies such as prolonged rotation at shutdown, turbine overheat, electronic control unit overheating, compressor stall, HP or LP shaft overspeed, and post-combustion anomalies;
- Comparison of two duplicate data channels to minimize false alarms; and
- Interface with the ground-support system HARPAGON for full diagnosis and prognosis, including reviews of the preventive maintenance schedule to optimize aircraft availability.

Ten years ago the Australian Defence Force with the help of the DSTO undertook the insertion of advanced diagnostic concepts and life assessment and extension technologies in an ageing fleet of Pratt and Whitney TF30 engines for its fleet of F-111 strike aircraft. The aims were to extend the life of the fleet and reduce maintenance costs. One strategy for reducing costs was to lengthen substantially the intervals between preventive engine maintenance. The strategy included technology insertion to improve reliability, a shift to on-condition maintenance where possible, and the development of diagnostic systems. Three diagnostic systems were developed: the Engine Diagnostic and Acceptance System (EDAS) for troubleshooting and acceptance testing at the test-cell; a set of advanced Gas Path Analysis (GPA) methods for diagnosing faults to a modular level at the test-cell; and the Interactive Fault Diagnosis and Isolation System (IFDIS) for troubleshooting engine faults at the flight line.

Gas Path Analysis (GPA) serves a different role than the other main Health Monitoring Technologies of Vibration Analysis (VA) and Oil Condition Monitoring (OCM). VA and OCM attempt to diagnose events that lead to a catastrophic failure of an engine component, and so they have a safety or airworthiness impact. GPA attempts to diagnose events that lead to a more graceful degradation in the function of the engine, and so it has a performance or mission-worthiness impact. The report described the modelling and diagnostic concepts used in the GPA methods in detail. These are as follows:

- A “Performance Stack” approach which is based on Pratt and Whitney influence coefficients to attribute the performance loss to specific faults as selected from a total set of 21 faults.
- The combination of a Probabilistic Neural Network (PNN) with the “case studies” of previous TF30 engine repairs. The fault diagnosis is based on how closely the engine being investigated matches previous symptoms and repairs.
- A robust adaptive approach to fault diagnosis based on the use of an adaptive component-based thermodynamic model of the TF30 engine. In such modelling, the user inputs the engine measurements, and the generic model adjusts or ‘adapts’ its internal operation to achieve the particular values.

The Interactive Fault Diagnosis and Isolation System (IFDIS) for 1st Line is an advanced web-based expert system. Standard commercially available software packages have been used to implement most of its functions, such as the database engine, the active web server, and the web browser.

The retro-fitting of such modern engine health management systems to old engines poses a number of difficulties – such as a lack of instrumentation, information, and policy – which can lead to trade-offs that blunt the effectiveness of the retrofitted systems. A number of lessons were learned in the course of developing the F-111 diagnostic systems. Firstly, no one single technology or methodology can provide all the answers. Each technique detects different faults, and even the three gas path methods listed above have different levels of fault coverage. Secondly, a robust gas path diagnostic system requires the simultaneous use of a number of complementary methods, to play to the strengths and overcome the weaknesses of the individual methods. Finally, the successful development of gas turbine diagnostics requires the early and active participation of the end-user in their development and evaluation.

7.5.8 Information Analysis

Information analysis technology, including data fusion and integrated reasoning, designed to exploit existing sensors and instrumentation for usage monitoring, inspection, and diagnostics is a key technology in on-board and ground-based maintenance systems. Information analysis technology is a highly specialised area, which is still in the early stages of development for aircraft and many other applications. The report has provided some insight into information analysis technologies that are under development for aircraft maintenance. Three concepts/technologies were featured:

- Artificial intelligence (AI) techniques to enhance diagnostics and improve maintenance efficiency at 1st Line;
- Data mining to build prognostic models; and
- Case based reasoning in diagnostics.

In the first concept the objective was to develop innovative software – called the Integrated Diagnostic System (IDS) – to improve the efficiency of 1st Line maintenance operations at Air Canada. Key functionalities of the proof of concept software developed included: reducing the ambiguity in fault isolation, providing advice on real-time repair action, providing clues on incipient failures, accessing and displaying relevant maintenance information, and facilitating communication among maintenance staff. The IDS system supports 1st Line activities by integrating and delivering key information in a timely manner to the various staff involved. It also automates some of the steps mentioned above. Specifically, while the aircraft is still in the air, the IDS system: clusters recent warning, failure, and snag (pilot) messages; identifies probable causes by automatically searching the Trouble Shooting Manual (TSM); provides links to the TSM pages as needed; automatically assesses Minimum Equipment List (MEL) conditions (GO, NOGO, GOIF); and retrieves relevant recent maintenance actions. All the information is displayed in an effective user interface. The reasoning in IDS relies on two core AI techniques. First, rule-bases are used to encode information contained in the TSM and MEL manuals. Rules were also developed to implement heuristics for linking in-flight messages (warning and failure messages) with the TSM, automatically assessing the MEL conditions, and aggregating information with temporal or textual proximity. The IDS also exploits case-based reasoning to retrieve relevant historical maintenance information and to suggest potential repairs for the current situation.

The second concept, data mining to develop prognostics, extends the IDS concept to other users. It involves using readily available sensor and maintenance data to build predictive models for a given component. There are four steps in this process: data gathering, data transformation, modelling/evaluation, and model fusion. Very promising results have been obtained with predictive models for some components but not others.

The third concept, case based reasoning, was illustrated by describing some commercial software called SpotLight™ that is used on the C-130 and the F-35 JSF. This software helps technicians diagnose failures, when Built-In Test (BIT) and other automatic diagnostics systems fail to do so or are unavailable. It provides a framework for capturing documented experience and updating it as technicians use the system. Each failure mode (not each failure event) is represented as a “Solution” in the knowledgebase. Each failure is researched, confirmed, described with discriminating symptoms, sanitized of user-identifying information, and enriched with helpful content such as references to maintenance instructions, tips, and explanations. The software links with data downloaded from BIT systems, with the Fault Isolation Manual (FIM), and with Integrated Electronic Technical Manuals (IETM). Finally, the system delivers this integrated field experience as “guided diagnostics” that is comparable to the line of questioning that a human expert would follow. The guided diagnostics are generated automatically by the system’s reasoning algorithm, and are updated with all new information received.

7.5.9 Integrated Systems for Usage Monitoring, Inspection, Diagnostics, and Prognostics

Historically health monitoring/management systems have been implemented where necessary for safety. Consequently, some aircraft may have several separate health monitoring/management systems for specific parts, such as the engines on fixed-wing aircraft and the drive train on helicopters. Scaling up this approach to cover more aircraft components has generally not been feasible, because it entails significant penalties in cost, weight, and complexity. A potential solution to this problem is to strive for greater integration of health management systems with other aircraft systems. One of the first programmes to invest in a comprehensive Integrated Vehicle Health Management (IVHM) system is the F-35 JSF. On this aircraft, it was determined that an IVHM was necessary to meet the specified availability and mission reliability.

There have been two major developments that have allowed IVHM to provide clear availability, safety, and cost benefits for operators:

- Advanced databus technologies with modern integrated aircraft architectures; and
- Open standards for IVHM systems.

The leading IVHM standard, which is being used in major international R&D programs, is the Open Systems Architecture for Condition Based Maintenance (OSA-CBM). This standard was developed collaboratively by several organisations in 2002 under a NAVAIR Dual Use Science and Technology (DUST) programme.

With regard to the first of these enabling technologies, one of the biggest changes in the design of modern aircraft systems has been the development of Integrated Modular Avionics (IMA). IMA, such as the GE Aviation Systems Common Core System (CCS) selected for the Boeing 787, provides a common avionics platform on which multiple applications can be run in parallel. This has been a major breakthrough in terms of hardware and software design, especially the latter.

As part of this transformational change in the design of systems, aircraft have implemented high speed digital buses such as the IEEE-1394B databus on the F-35 JSF, and AFDX databus on the Boeing 787 and Airbus A380. The GE Aviation Systems Remote Interface Unit (RIU), variants of which have been selected for both the JSF and the 787, allows up to 200 signals to be collated near the point of generation and streamed onto these buses. It thereby reduces the wire count by up to two orders of magnitude. Once signals have been collected by the RIU they can be made available in the Common Core System (CCS) in a standard format, which simplifies subsequent storage, processing and distribution.

One of the main drivers of IVHM in the civil and military worlds has been a desire to avoid excessive Turnaround Time (TAT) at 1st Line due to corrective maintenance. In the near future, it should be possible to expand the number of mission-critical components for which the maintenance/support system receives advance warning of failures and potential failures during flight, and for which diagnostics and management decision support are automated. This will at least streamline corrective maintenance at 1st Line.

Eventually, it may be possible to design the aircraft, the IVHM system, and the maintenance/support system such that corrective action for potential failures detected in mission critical components can be deferred for a limited period. Dr Jonathan Cook of MOD UK referred to this period as a “Predictive Maintenance Window (PMW)”. To the extent that this strategy becomes feasible, corrective maintenance would not delay missions and there would be some improvement in average availability. The concept could be extended to improve an aircraft’s capability to provide a “Maintenance-Free Operating Period (MFOP)” during limited deployments/ expeditions.

To realise fully the benefits of IVHM, it is necessary to use the RCM on-condition failure management strategy for mission-critical components, as far as possible. This means that a potential failure must be detectable well before the failure of a mission-critical function. For some components special efforts may be needed in design, failure mode analysis, and failure modelling to create the necessary conditions. This work may have to be accompanied by the use of new techniques and sensory systems to detect potential failure in flight. The report provided two examples where the simulation, analysis, and modelling of failure modes led to the discovery of useful new indicators of potential failure in control surface actuators and fuel pumps.

As mentioned earlier in these conclusions, the term “Condition-Based Maintenance” (CBM) is now frequently used to denote the RCM on-condition maintenance strategy. Unfortunately, the definitions of CBM in international standards and military handbooks are not complete or consistent, and the usage of the term in the literature varies. Sometimes, CBM is linked exclusively with on-board health management systems. Sometimes, it includes ground based inspection, diagnostic, and prognostic systems. It is advisable to ensure that the term CBM is clearly defined whenever it is used.

7.5.10 Using Advanced Maintenance Concepts and Technologies to Achieve a Maintenance-Free Operating Period (MFOP)

With the trend to more expeditionary operations by NATO forces, it is important to have the ability to enhance the availability of deployed aircraft while simultaneously minimising their logistics footprint. The term "Maintenance-Free Operating Period (MFOP)" is sometimes used to describe this maintenance concept.

A MFOP, or at least a period of substantially reduced maintenance and higher availability, can be achieved to some extent by the appropriate management of maintenance/support. The necessary measures include focussing resources on the deployed aircraft, and so the availability of non-deployed aircraft may be reduced for a period before and during the deployment. However, there need not be any adverse effects on the long-term average availability of the whole group, unless an unusually high operating tempo has to be maintained for an extended period.

To achieve a near-ideal MFOP capability, it is necessary to design an aircraft and its maintenance/support system specifically for the purpose. In general, this means giving special attention to the maintainability of the aircraft when operating with a reduced range of specialised personnel, spares, facilities and other maintenance/support resources. Additional measures may need to include: increasing the degree of automation in usage monitoring, inspection, diagnostics, and prognostics; lengthening the intervals between some servicing; providing internal auxiliary power and oxygen generation; substantially increasing the general reliability and mission reliability of the least reliable components; and modularising the aircraft in a way that permits major airframe and engine repairs to be performed without special facilities. Despite such measures, the targeted reliability improvements may be difficult to achieve without increasing redundancy and fault tolerance.

A substantial MFOP capability might only be achievable on a new aircraft design, but a useful partial MFOP might be achievable on some legacy aircraft by appropriate management of maintenance/support. This capability could be further improved by technology insertion.

7.5.11 Rapid Repair of Aircraft Damaged in Action

Wars and battles can be won or lost through attrition, and so there is a potentially critical need for rapid salvage and repair strategies and technologies for aircraft disabled or damaged in action. This need has been magnified by the trend to greater concentration of capability in fewer aircraft, the need for expeditionary operations, and the long lead times for the manufacture of new aircraft and components. The salvage and repair strategies need to cover structure, engines, mechanical systems, and wiring. They should include temporary battle damage repairs. While many of the concepts and technologies addressed in developing the general maintenance/support system will help in the rapid repair of aircraft, it is also necessary to consider the specific additional measures needed to succeed in a prolonged combat scenario.

Dassault Aviation has studied this topic in depth and has developed computer tools to assist an air force engineer at a forward base to: assess structural and system damage; determine the feasibility of repair in the field; assess the associated risk; design the repairs; and determine any limitations on post-repair mission capability. The latest generation of the computerised tools is directed at the Rafale fighter, but could be adapted to other aircraft types. These concepts and tools are described in the report.

The design of the aircraft can greatly facilitate field repairs. Integrated testability can help considerably with the systems assessment. In addition, structural maintainability, particularly modularity and accessibility, are important. These features are needed anyway in an aircraft designed for deployed operations, like the Rafale. Interactive computer modelling and simulation tools like those described in the report, together with appropriate design of the aircraft and maintenance/support system could make major damage repairs in the field easier.

7.5.12 Corrosion Prevention and Repair

Corrosion of airframe structure and systems, engine structure, and electrical/electronic systems accounts for a large part of the inspection and component replacement/restoration needed at 3rd and 4th Line. The downtime and cost of 3rd and 4th Line maintenance for preventative or corrective maintenance related to corrosion can be reduced in several ways:

a) Firstly, a range of technologies are available for preventing and delaying corrosion. These include aircraft shelters, dehumidification, washing/cleaning, corrosion preventive compounds, improved paints, improved sealants, drainage, alternative materials, and in-situ Retrogression and Re-Aging (RRA) heat treatment to reduce corrosion susceptibility. It is likely that the use of these technologies will have a net beneficial effect on average aircraft availability and life-cycle cost. However, some of them place an additional burden on 1st Line and may increase the logistics footprint in deployments.

b) Secondly, improved NDI technologies are becoming available for wide area and multi-layer inspection for corrosion and related fatigue damage. These NDI technologies can reduce costs and provide added flexibility in the response to a corrosion arising.

c) Thirdly, methods are becoming available for modelling the stress distribution and fatigue characteristics of corroded structure, for modelling the interaction of corrosion and fatigue, and for modelling the rate of deterioration of protective paints and coatings. Experimental techniques are being developed to validate these models. These modelling technologies can be used to perform durability and damage tolerance assessments, to determine whether costly and time-consuming repairs can be deferred or replaced by some faster and less costly maintenance action.

d) Finally, new sensor technologies are becoming available that will help in assessing the actual environment or the actual rate of corrosion of a given component. These will help to automate inspections and diagnostics for corrosion and overcome accessibility problems.

Technologies in the last three categories are applicable to several aspects of aircraft maintenance and were described in various sections of the report. Technologies in category a. were described in a special section on corrosion prevention and repair. These included new technologies to replace those that are hazardous and damaging to the environment.

7.5.13 Other Aircraft and Equipment Concepts and Technologies

The following aircraft and equipment concepts and technologies have been mentioned in the report, but coverage was only brief and did not adequately reflect their importance:

- Information and Communications Technologies (ICT) needed to assist technicians in the rapid execution of maintenance tasks, including the following: Interactive Electronic Technical Manuals (IETM); Personal Information Devices (PID); local wireless communication systems; and global network systems (for linking to central databases).
- Some of the aircraft and equipment technologies relevant to the storage and movement of materiel in the supply chain, including the following: ICT to assist maintenance technicians in the rapid identification and ordering of parts; Radio Frequency Identification (RFID); Packaging, Handling, Storage, and Transportation (PHS&T) technologies, particularly those relevant to deployments/

expeditions; and technologies to reverse engineer and manufacture discontinued components. PHS&T technologies of particular interest include the following: environmental monitoring of packaged items to detect potentially catastrophic mishandling; special in-theatre and forward storage concepts; and packaging concepts for spares, repair parts, and whole aircraft.

- Some of the concepts and technologies that can reduce the downtime for repairing airframe structure at any maintenance organisational level, but particularly at 1st Line. Of particular importance are efficient and robust concepts and technologies for the repair of composite structures. Also of importance are advanced concepts and technologies for the repair of metallic components, including the use of cold working of holes and surfaces to restore fatigue life, bonded repairs, laser beam welding, friction stir processing, and thermal spray of surface protection. Finally, robotics is becoming increasingly important in many on-aircraft maintenance processes.
- Aircraft and equipment technologies associated with the Human Factors Integration (HFI) in maintenance/support, in particular those associated with the list of maintainability strategies in Chapter 2.

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Annex B – WORKSHOP PROGRAM WITH AUTHORS

Colour Codes: FRA, DEU, GBR, USA, Other

Sched. Time	Orig. No.	Proceedings No.	Description of Sessions and Papers	Dur	Nation	Lead Authors and Co-authors
			TUESDAY 3 Oct 06			TUESDAY 3 Oct 06
0800			Registration			Registration
0900			Introduction to the AVT-144 Workshop.	10 min	CAN	**Mr. Graeme Eastaugh – Chairman of the AVT-144 Technical Team** (Project Manager and Senior Research Officer, Institute for Aerospace Research, National Research Council, Ottawa, Ontario, Canada)
0910		Opening Address	Official welcome on behalf of the Applied Vehicle Technology (AVT) Panel.	5 min	CAN	**Mr. Robert Hastings – AVT Panel Member** (Director Gas Turbine Laboratory, Institute for Aerospace Research, National Research Council, Ottawa, Ontario, Canada)
	Session 1		Session Title National Perspectives on the Evolution of Aircraft Maintenance/Support Concepts with Particular Reference to Aircraft Availability.			
0915	1.1	1	Paper Title: Evolution of Aircraft Maintenance/Support Concepts with Particular Reference to Aircraft Availability – Polish Air Force Perspective.	15 min	POL	**Dr. Ryszard Szczepanik** (Director General Air Force Institute of Technology, Warsaw, Poland) **Major (Dr.) Andrzej Leski** (Team Leader, Division for Aeronautical Systems Reliability & Safety, Air Force Institute of Technology, Warsaw, Poland)
0930	1.2	2	Paper Title: Evolution of Aircraft Maintenance and Support Concepts – French Armed Forces Perspectives.	30 min	FRA	**Colonel Patrick Joubert** (Structure Intégrée de Maintien en condition opérationnelle des Matériels Aéronautiques du ministère de la Défense – SIMMAD, Ministère de la défense, France)
1000	1.3	3	Paper Title: Evolution of Aircraft Maintenance/Support Concepts with Particular Reference to Aircraft Availability – Czech Air Force Perspective.	15 min	CZE	**Ing. Jaroslav Bulanek** (Logistics Manager, Aero Vochody, Prague, Czech Republic) **Lieutenant Colonel Ing. Libor Kvetina** (Support Policy Section, Ministertsvo obrany – Ministry of Defence, Prague Czech Republic) **Mr. Ferdinand Tesar** (Logistics Manager, VTULaPVO, Prague, Czech Republic)
1015			Discussion	15 min		All participants
1030			REFRESHMENT BREAK			REFRESHMENT BREAK
1100	1.4	Presn Only	Paper Title: Evolution of Aircraft Maintenance/Support Concepts with Particular Reference to Aircraft Availability – German Air Force Perspective. (Presentation Only)	30 min	DEU	**Lieutenant Colonel (Oberstleutnant) Dirk Fischer** (ILS Manager Eurofighter EF 2000, Federal Ministry of Defence, German Air Force Office, Air Armaments Division Id, Air Force Base Wahn 501/14, Cologne, Germany)
1130	1.5	4	Paper Title: Improvements of Aircraft Availability within the Royal Netherlands Air Force.	30 min	NLD	**Drs. Ing. Carla Andela** (Collaborative Engineering and Systems, National Aerospace Laboratory NLR, Amsterdam, Netherlands)
1200	1.6	5	Paper Title: The Integration of an Aircraft Availability Performance Program with Life Cycle Management in the Swedish Air Force.	15 min	SWE	**Mr. Sorin Barbici** (Technical Expert Dependability Design, Logistics Division, Defence Material Administration - FMV, Stockholm, Sweden)
1215			Discussion	15 min		All participants

Sched. Time	Orig. No.	Proceedings No.	Description of Sessions and Papers	Dur	Nation	Lead Authors and Co-authors
1230 - 1400			LUNCH BREAK			LUNCH BREAK
1400	1.7	6	Paper Title: The Evolution of Aircraft Support Concepts within the UK MoD's Defence Logistics Transformation Programme.	30 min	**GBR**	**Captain (Royal Navy) David Elford** (Defence Logistics Transformation Programme, MOD DPA-DLO, UK)
1430	1.8	Presn Only	Paper Title: Evolution of Aircraft Maintenance/Support Concepts with Particular Reference to Aircraft Availability – Italian Air Force perspectives. (Presentation Only).	15 min	**ITA**	**Major Mario Colavita** (Aeronautica Militare, Agenzia Nazionale per la Sicurezza del Volo (ANSV), Rome, Italy) **Captain Lorenzo Aiello** (Aeronautica Militare, Centro Sperimentale di Volo (Flight Test Centre), Pomezia, Italy)
1445			Discussion	15 min		All participants
	Session 2		Session Title Metrics, Key Performance Indicators, and Modeling of Aircraft Availability/Readiness.			
1500	2.1	7	Paper Title: Metrics, Key Performance Indicators, and Modelling of Long Range Aircraft Availability & Readiness.	30 min	**USA**	**Mr. Gerrod Andresen** and **Mr. Zachary Williams** (IVHM Solution Center, Boeing Phantom Works, The Boeing Company, Aledo, TX, USA)
1530			REFRESHMENT BREAK			REFRESHMENT BREAK
1600	2.1 cont.		Demonstration of Boeing SHOAM computer model associated with Paper 2.1.	15 min	**USA**	**Mr. Gerrod Andresen**
1615			Discussion	15 min		All participants
	Session 3		Session Title Maintenance/Support Management Concepts and Technologies for Improving Aircraft Availability and Mission Reliability.			
1630	3.1	8	Paper Title: Achieving Organizational Accountability for Aircraft Operational Availability – Systems Engineering and Contracting Strategies in the Canadian Forces.	45 min	**CAN**	**Lieutenant Colonel Pierre-Paul Béland and Mr. L.J. (Ludy) Hollick** (Integrated Logistics Support, Maritime Helicopter Program, Aerospace Equipment Program Management Division, DND, Ottawa, Ontario, Canada). *Note: Paper includes 1.9. Joint presentation by both authors.*
1715 - 1730			Discussion	15 min		All participants

Time	Orig. No.	Proceedings No.	Description of Sessions and Papers	Dur	Nation	Lead Authors and Co-authors
			WEDNESDAY 4 Oct 06			WEDNESDAY 4 Oct 06
0900	3.2	Presn Only	Paper Title: The Use of Reliability Centred Maintenance (RCM) to Define Maintenance Tasks so as to Optimise Aircraft Availability and Life-Cycle Cost. (Presentation Only)	30 min	**DEU**	**Dipl. Ing. Gerhard-Michael Fresser** (Head of Integrated Logistics Support (OPL1), Dynamics Division, EADS/MBDA/LFK-Lenkflugkörpersysteme GmbH, Unterschleißheim, Germany)
0930			Discussion	15 min		All participants
0945	3.3	9	Paper Title: The Management of Reliability and Maintainability and the Choice of Maintenance Concept to Optimize Aircraft Availability and Life Cycle Cost.	30 min	**DEU**	**Dipl. Ing. Matthias Buderath** (Chief Engineer Product Support Technologies, EADS Military Air Systems, Munich, Germany)
1015			Discussion	15 min		All participants
1030			REFRESHMENT BREAK			REFRESHMENT BREAK
1100	3.4	Presn Only	Paper Title: KC-135 Lean Journey - The Use of Lean Enterprise Management to Reduce the Downtime and Cost of Depot Maintenance. (Presentation Only)	30 min	**USA**	**Lieutenant Colonel Joseph Heilhecker** (HQ USAF, AF/A3-SO, Pentagon, Washington, DC, USA) **Mr. Michael Wenzel** (Director of KC-135 Periodic Depot Maintenance, Oklahoma City Air Logistics Center, Tinker AFB, OK, USA)
1130			Discussion	15 min		All participants
1145	3.5	10	Paper Title: Availability Improvements in New Transport Aircraft – The Case of the A400M.	30 min	**OCCAR**	**Mr. Baudouin Heuninckx** (Logistic Support Officer, A400M Program Division, Organisation for Joint Armament Cooperation - OCCAR, Toulouse, France)
1215			Discussion	15 min		All participants
1230 - 1345			LUNCH BREAK			LUNCH BREAK
	4	Session 4	Session Title Aircraft, Support Equipment, and Supply System Technologies for Improving Aircraft Availability and Mission Reliability.			
1345	4.1	Presn Only	Paper Title: Introduction to Session 4 - Aircraft, Support Equipment and Supply System Technologies for Improving Aircraft Availability and Mission Reliability. (Presentation Only)	15 min	**DEU**	**Dipl. Ing. Matthias Buderath – Vice-Chair of the AVT-144 Technical Team** (Chief Engineer Product Support Technologies, EADS Military Air Systems, Munich, Germany)
	4.2		Topic Title The Use of Advanced Off-Board and On-Board Condition Monitoring Systems to Reduce the Duration and/or Frequency of Inspections and Other Preventive Maintenance.			*Three papers scheduled as shown below.*
1400	4.2.1a	11	Paper Title: Non-Destructive Evaluation (NDE) and Aircraft Availability.	20 min	**GBR, USA**	**Dr. David Bruce** (Defence Sciences and Technology Laboratory, MOD, Salisbury, UK) **Mr. Charles Buynak and Dr. Eric Lindgren** (NDE Branch, USAF Air Force Research Laboratory, Wright Patterson AFB, OH, USA)
1420	4.2.1b	12	Paper Title: The Use of Advanced NDI to Reduce the Duration and/or Frequency of Preventative Maintenance – German Air Force Experience.	10 min	**DEU**	**Dipl. Ing. Holger Manzke and Dipl. Ing. Ernst Grauvogl** (Material Testing, EADS Military Air Systems, Manching, Germany)

Time	Orig. No.	Proceedings No.	Description of Sessions and Papers	Dur	Nation	Lead Authors and Co-authors
1430	4.2.2	13	Paper Title: Corrosion Sensors to Reduce Aircraft Maintenance.	15 min	**GBR**	**Dr. Steve Harris** (Group Leader Materials Engineering, Advanced Technology Centre, BAE Systems, Bristol, UK) **Dr. Matt Mishon** (Corrosion Control Leader, Materials Integrity Group, Technical Enabling Services, MOD DPA-DLO, Gosport, UK) **Mr. M. Hebbron,** (Advanced Technology Centre, BAE Systems, Bristol, UK)
1445			Discussion	15 min		All participants
	4.3		Topic Title: Improving the Diagnosis of Electronic and Electrical Systems, Including Wiring, to Reduce Aircraft Downtime at 1st Line and Improve Mission Reliability.			*Two papers scheduled as shown below.*
1500	4.3.1	Presn Only	Paper Title: Improving the Diagnosis of Electronic and Electrical systems, Including Wiring, to Reduce Aircraft Downtime at 1st Line and Improve Mission Reliability – Dassault Aviation Rafale Fighter. (Presentation Only)	30 min	**FRA**	**Commandant Stéphane Copéret** (Chief of the Rafale Training Centre, Operational Test and Evaluation Centre, Mont-de-Marsan Air Force Base, France) Note: Presented by **Colonel Joubert**.
1530			REFRESHMENT BREAK			REFRESHMENT BREAK
1600	4.3.2	14	Paper Title: Advances in Avionics Testing to Improve Aircraft Readiness and Mission Reliability.	30 min	**USA**	**Mr. William Ross** (Deputy Program Manager for Automatic Test Systems and Member of DoD Automatic Test Systems Executive Directorate, Naval Air Systems Command, Patuxent River, PA, USA)
1630			Discussion	15 min		All participants
	4.4		Topic Title: Improving the Diagnosis of Engines, Mechanical Systems, and Structure, to Reduce Aircraft Downtime at 1st Line and Improve Mission Reliability.			*Three papers scheduled as shown below.*
1645	4.4.1	15	Paper Title: Advanced Diagnostics in the SNECMA M-88 Engine of the Rafale Fighter.	25 min	**FRA**	**M. Erick Banet** (M88 ILS Manager, Snecma, SAFRAN Group, Courcouronnes, France) **Mme. Carole Brousse** (M88 Electronic Control System Technical and Project Manager, Hispano-Suiza, SAFRAN Group, Moissy Cramayel, France) **Dr. Jean-Rémi Massé** (Dependability Engineering Senior Expert, also Strand 7400 Leader for TATEM, Hispano-Suiza) *Note: Presented by **Dr. Massé**.*
1710	4.4.2	16	Paper Title: The Insertion of Advanced Diagnostic Technologies in an Ageing Fleet of Engines, to Improve Engine/Aircraft Availability and Mission Reliability.	20 min	**AUS**	**Dr. Bryon Wicks** (Head of Propulsion Systems Life Management Group, Air Vehicles Division, Defence Science and Technology Organisation (DSTO), Fisherman's Bend, Australia)
1730 - 1745			Discussion	15 min		All participants

Time	Orig. No.	Proceedings No.	Description of Sessions and Papers	Dur	Nation	Lead Authors and Co-authors
			THURSDAY 5 Oct 06			THURSDAY 5 Oct 06
0900	4.4.3	17	Paper Title: Improving the Diagnosis of Mechanical Systems and Structure to Reduce Aircraft Downtime at 1st Line and Improve Mission Reliability.	20 min	**CAN**	**Mr. Kyle Schmidt** (Senior Research Engineer, Messier-Dowty, SAFRAN Group, Ajax, Ontario, Canada)
0920			Discussion	10 min		All participants
	4.5		Topic Title: The Use of Information Analysis Technology, Including Data Fusion and Integrated Reasoning, to Exploit Existing Sensors and Instrumentation for Condition Monitoring, Usage Monitoring, and Diagnosis.			*Three papers scheduled as shown below.*
0930	4.5.1	18	Paper Title: The Fusion of Data from Existing On-Board Monitoring and Instrumentation Systems to Achieve More Accurate Usage Monitoring.	15 min	**GBR**	**Mr. H.G. (Gregg) Cook** (Prognostic Health Management Division, Materials Integrity Group, Technical Enabling Services, MOD DPA-DLO, Gosport, UK)
0945	4.5.2	19	Paper Title: Integrating Experience with Built-In Test (BIT) to Improve First-Time-Fix Performance.	15 min	**CAN**	**Mr. Phil D'Eon** (President and Chief Technology Officer, CaseBank Technologies Inc., Toronto, Ontario, Canada) **Mr. Robert Hastings** (Director Gas Turbine Laboratory, Institute for Aerospace Research, National Research Council, Ottawa, Ontario, Canada) *Note: Presented by **Mr. Hastings**.*
			Unscheduled address by Chair of NATO RTB during visit to AVT-144 Workshop.		**RTB**	**IGA (General) Jacques Bongrand** (France) (Chairman of NATO Research and Technology Board)
1000	4.5.3	20	Paper Title: The Use of Integrated Reasoning with Flight and Historical Maintenance Data to Diagnose Faults and Improve Prognosis.	15 min	**CAN**	**Dr. Sylvain Létourneau** and **Mr. Michael Halasz** (Institute for Information Technology, National Research Council, Ottawa, Ontario, Canada)
1015			Discussion	15 min		All participants
1030			REFRESHMENT BREAK			REFRESHMENT BREAK
1100	4.6	21	Paper Title: The Use of Prognostic Systems to Reduce the Duration and Frequency of Helicopter Maintenance.	30 min	**GBR**	**Dr. Jonathan Cook** (Head of the Prognostic Health Management Division, Materials Integrity Group, Technical Enabling Services, MOD DPA-DLO, Gosport, UK)
1130			Discussion	15 min		All participants
1145	4.7	22	Paper Title: The Use of On-Board Condition Monitoring, Usage Monitoring, Diagnostics, Prognosis, and Integrated Vehicle Health Management to Improve Aircraft Availability and Mission Reliability.	30 min	**GBR**	**Dr. Jonathan Dunsdon** (Manager of Technologies for New Maintenance Concepts, also Technical Manager of TATEM European project, Smiths Aerospace Electronic Systems, Cheltenham, UK)
1215			Discussion	15 min		All participants
1230 - 1400			LUNCH BREAK			LUNCH BREAK

Time	Orig. No.	Proceedings No.	Description of Sessions and Papers	Dur	Nation	Lead Authors and Co-authors
1400	4.8	23	Paper Title: Maintenance Free Periods of Operation – The Holy Grail?	30 min	GBR	**Wing Commander (Rtd.) Chris Hockley** (Lecturer, Defence College of Management and Technology, MOD Defence Academy, Shrivenham, UK)
1430			Discussion	15 min		All participants
1445	4.9	24	Paper Title: Rapid Salvage and Repair Strategies and Technologies for Aircraft Disabled or Damaged in Action.	30 min	FRA	**Mr. Frédéric Absi** (Rafale Maintenance Manager, Military Customer Support Division, Dassault Aviation, St. Cloud, France) **Mr. Louis Lemaignen** (Head of Future Support Studies, Military Customer Support Division, Dassault Aviation, St. Cloud, France)
1515			Discussion	15 min		All participants
1530			REFRESHMENTS			REFRESHMENTS
1600	4.10		Topic Title: Measures to Reduce the Duration of Preventive and Corrective Maintenance at 3rd and 4th Line Due to the Corrosion of Structure, Engines, Mechanical Systems, and Electrical Connectors.			*Four papers scheduled as shown below. Panel leader Dr. Agarwala.*
	4.10a	25	Paper Title: Aircraft Corrosion Control and Maintenance.	25 min	USA	**Dr. Vinod Agarwala** (Associate Director for Materials Science & Engineering, US Office of Naval Research Global, London, UK)
	4.10b	Presn Only	Paper Title: Automated Monitoring and Modelling of Corrosion to Reduce Aircraft Maintenance. (Presentation Only)	10 min	GBR	**Dr. Matt Mishon** (Corrosion Control Leader, Materials Integrity Group, Technical Enabling Services, MOD DPA-DLO, Gosport, UK) Paper amalgamated with 4.2.2
	4.10c	26	Paper Title: Use of Dehumidification to Reduce Preventive and Corrective Maintenance of Aircraft Due to Corrosion.	10 min	SWE	**Lt Col Hakan Schweitz** (Dehumidification and Storage Expert, Competence Centre for Logistics, FMV, Stockholm, Sweden)
	4.10d	27	Paper Title: Galvanic Sensor for Monitoring Structural Damage.	NA	IT	**Captain Lorenzo Aiello** (Aeronautica Militare, Centro Sperimentale di Volo (Flight Test Centre), Pomezia, Italy) **Major Mario Colavita** (Aeronautica Militare, Agenzia Nazionale per la Sicurezza del Volo (ANSV), Rome, Italy) **Dr. Vinod Agarwala** (Associate Director for Materials Science & Engineering, US Office of Naval Research Global, London, UK)
			Discussion	15 min		All participants
1700		Presn Only	Closing remarks by one of the authors.	10 min	DEU	**Lieutenant Colonel (Oberstleutnant) Dirk Fischer**
		Reviewer Remarks	Closing remarks by the two official Reviewers.	10 min	CAN & FRA	**Mr. Jeff Bird** and **Mr. Louis Lemaignen**
			Closing remarks by the Chair of AVT-144.	5 min	CAN	**Mr. Graeme Eastaugh**

Sched. Time	Orig. No.	Proceedings No.	Description of Sessions and Papers	Dur	Nation	Lead Authors and Co-authors
			SUPPLEMENTARY PAPERS			
	Supp. Paper #1	28	Defending Our Aging Fleets: Defining the Impacts of Aging Aircraft Sustainment on Warfighting Capability.		**USA**	**Mr. Karl A. Hart** (Senior Engineer/Analyst, Alion Science & Technology Inc., Wright Patterson Air Force Base, Ohio, USA)
	Supp. Paper #2	29	State of Development of Sensory Systems for Structural Health Monitoring.		**CAN**	**Dr. Nezih Mrad** (Research Scientist, Defence R&D Canada, Department of National Defence, Ottawa, Canada)
	Supp. Paper #3	30	Physics of Failure Modelling at the Microstructural Level for Prognostics of Creep Failure in an Engine Turbine Blade.		**CAN**	**Dr. Ashok K. Koul, Mr. Ajay Tiku** and **Mr. Saurabh Bhanot** (Life Prediction Technologies Inc., Ottawa, Canada) **Mr. Brent Junkin** (Standard Aero Limited, Winnipeg, Canada)
	Supp. Paper #4	31	Operational Availability Modeling for Risk and Impact Analysis.		**CAN**	**Mr. David J. Hurst** (Manager Accreditation and Audits, Aerospace Engineering and Project Management Division, Department of National Defence, Ottawa, Canada)

Annex C – LIST OF DEFINITIONS

Source Key

A. Def Stan 00-60 Integrated Logistics Support (GBR)	H. Allied Reliability and Maintainability Publication ARMP-7 NATO R&M Terminology
B. MOD Guide to Integrated Logistics Support (GBR)	I. AAP-6 NATO Glossary of Terms and Definitions
C. Def Stan 00-49 R&M MOD Guide to Terminology Definitions (GBR)	J. ISO/IEC 15288:2002(E) Systems Engineering – System Life-Cycle Processes
D. Mil-Hdbk-502 Acquisition Logistics (USA)	K. European Standard NF EN 13306 Terminologie de la maintenance
E. NAVAIR 00-25-403 Guidelines for the Naval Aviation RCM Process (USA)	L. SAE Standard JA1011 (August 1999) Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes
F. Mil-Std-1388-1A (Notice 4, 1993) Logistic Support Analysis (USA)	M. Air Transport Association of America, Inc. "Operator/Manufacturer Scheduled Maintenance Development", ATA MSG3 Revision 2003.1
G. A-LM-505-001/AG-001 Integrated Logistics Support (CAN)	N. MIL-Hdbk-338B " Electronic Reliability Design Handbook", 1 October 1998

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Acceptable Probability of Failure		The probability of a given failure mode occurring during a defined period that a program is willing to accept.					X										
Accessibility		A measure of the relative ease of admission to the various areas of an item for the purpose of operation or maintenance.								X							
Achieved Availability	A_A	The availability of a system with respect to operating time and both corrective and preventive maintenance. It ignores Mean Logistics Delay Time (MLDT) and may be calculated as Mean Time Between Maintenance (MTBM) divided by the sum of MTBM and Mean Maintenance Time (MMT), that is, AA = MTBM/(MTBM+MMT). Editor's Note: See Mean Time Between Maintenance, Mean Logistics Delay Time, and Mean Maintenance Time.															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Acquisition Logistics		A multi-functional technical management discipline associated with the design, development, test, production, fielding, sustainment, and improvement modifications of cost effective systems that achieve the user's peacetime and wartime readiness requirements.				X											

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Acquisition Phases		a) Concept Exploration and Definition Phase – The identification and exploration of alternative solutions or solution concepts to satisfy a validated need. b) Demonstration and Validation Phase – The period when selected candidate solutions are refined through extensive study and analyses; hardware development, if appropriate; test; and evaluations. c) Full Scale Development Phase – The period when the system and the principal items necessary for its support are designed, fabricated, tested, and evaluated. d) Production and Deployment Phase – The period from production approval until the last system is delivered and accepted. e) Operations and Support – The period following fielding of initial systems which is used to ensure systems continue to provide the capabilities required to meet the identified mission need.						X									
Active Maintenance Time		The part of the maintenance time during which active maintenance is carried out on an item, either manually or automatically, excluding logistic delays.											X				
Active Time		That time during which an item is in an operational inventory.														X	
Advanced Maintenance Concept (in RTO AVT-144)		A maintenance/support concept that offers potential improvements in the life-cycle cost and/or capability of military aircraft, or has recently resulted in such improvements.															AVT-144 Technical Team.
Advanced Maintenance Technology (in RTO AVT-144)		A technology usable in maintenance/support that offers potential improvements in the life-cycle cost and/or capability of military aircraft, or has recently resulted in such improvements.															AVT-144 Technical Team.
Age		A measure of exposure to stress computed from the moment an item or component enters service when new or re-enters service after a task designed to restore its initial capability, and can be measured in terms of calendar time, running time, distance traveled, duty cycles, or units of output or throughput.												X			
Age Exploration	AE	A process used to collect specific data to replace estimated or assumed values that were used during a previous RCM analysis.					X										
Age Exploration		A systematic evaluation of an item based on analysis of collected information from in-service experience. It verifies the item's resistance to a deterioration process with respect to increasing age.													X		
Airworthiness Limitations		A section of the Instructions for Continued Airworthiness that contains each mandatory replacement time, structural inspection interval, and related structural inspection task.													X		

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Airworthiness Limitations (cont'd)		This section may also be used to define a threshold for the fatigue related inspections and the need to control corrosion to Level 1 or better. The information contained in the Airworthiness Limitations section may be changed to reflect service and/or test experience or new analysis methods.													X		
Artificial Intelligence	AI	The scientific understanding of the mechanisms underlying thought and intelligent behavior and their embodiment in machines.															Association for the Advancement of Artificial Intelligence, http://www.aaai.org/AITopics/html/overview.html.
Artificial Intelligence	AI	Q: What is artificial intelligence? A: It is the science and engineering of making intelligent machines, especially intelligent computer programs. It is related to the similar task of using computers to understand human intelligence, but AI does not have to confine itself to methods that are biologically observable. Q: Yes, but what is intelligence? A: Intelligence is the computational part of the ability to achieve goals in the world. Varying kinds and degrees of intelligence occur in people, many animals and some machines. Q: Isn't there a solid definition of intelligence that doesn't depend on relating it to human intelligence? A: Not yet. The problem is that we cannot yet characterize in general what kinds of computational procedures we want to call intelligent. We understand some of the mechanisms of intelligence and not others.															McCarthy, J., Stanford University, http://www-formal.stanford.edu/jmc/whatisai/whatisai.html.
Artificial Intelligence	AI	The ability of a digital computer or computer-controlled robot to perform tasks commonly associated with intelligent beings. The term is frequently applied to the project of developing systems endowed with the intellectual processes characteristic of humans, such as the ability to reason, discover meaning, generalize, or learn from past experience.															Encyclopaedia Britannica, http://www.britannica.com/eb/article-9009711/artificial-intelligence.
Attrition		The reduction of the effectiveness of a force caused by loss of personnel and materiel.									X						
Automatic Test		That performance assessment, fault detection, diagnosis, isolation, and prognosis which is performed with a minimum of reliance on human intervention. This may include BIT.															Mil-Std-1309D, "Definition of Terms for Testing Measurement and Diagnostics", 1992.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Automatic Test Equipment	ATE	1) Test, Measurement and Diagnostic Equipment (TMDE) that performs a program to test functional or static parameters, to evaluate the degree of performance degradation, or to perform fault isolation of unit malfunctions. The decision making, control, or evaluative functions are conducted with minimum reliance on human intervention. 2) An equipment that is designed to automatically conduct analysis of functional or static parameters, evaluate the degree of performance degradation and perform isolation of item malfunctions.															Mil-Std-1309D, "Definition of Terms for Testing Measurement and Diagnostics", 1992.
Automatic Test Equipment	ATE	Equipment that is designed to automatically conduct analysis of functional or static parameters and to evaluate the degree of UUT (Unit Under Test) performance degradation; and may be used to perform fault isolation of UUT malfunctions. The decision making, control, or evaluative functions are conducted with minimum reliance on human intervention and usually done under computer control.														X	
Availability		A measure of the degree to which an item is in an operable and committable state at the start of a mission, when the mission is called for at an unknown (random) time.		X		X		X	X								
Availability		The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided. (IEC-50(191))			C					X							
Availability		The ability of an item to be in a state to perform a required function under given conditions at a given instant of time or during a given time interval, assuming that the required external resources are provided. Note 1: This ability depends on the combined aspects of the reliability, the maintainability and the maintenance supportability. Note 2: Required external resources, other than maintenance resources, do not affect the availability of the item.											X				
Availability		A measure of the degree to which an item is in an operable and committable state at the start of a mission when the mission is called for at an unknown (random) time. (Item state at start of a mission includes the combined effects of the readiness-related system R&M parameters, but excludes mission time.)														X	

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Availability		A measure of the degree to which an item is in an operable state and can be committed at the start of a mission when the mission is called for at an unknown (random) point in time. Editor's Note: See GDAAT definitions of Inherent Availability, Achieved Availability, and Operational Availability.															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Availability – Operational	OA	The probability that, when used under stated conditions, a system will operate satisfactorily at any time. OA includes standby, administrative, and logistic delay time.						X	X								
Availability – Operational (Ao)	Ao	The proportion of the defined operational period during which the equipment is available for use without any performance limitations, i.e. Ao = uptime measured over an operational period / (uptime + downtime). Operational availability may be expressed by the formula: Ao = (OT + ST)/(OT + ST + TPM + TCM + ALDT) where: OT = operating time ST = standby time TPM = total preventative maintenance time TCM = total corrective maintenance time ALDT = administration and logistics delay time spent waiting for parts, maintenance personnel or transportation Note: Units will be defined in accordance with Service practice.			X												
Availability Centered Maintenance	ACM	A Contractual Service Agreement (CSA) in which the manufacturer is responsible for maintenance, and will guarantee a certain availability of an asset. Usually, the maintenance program is designed with the help of the RCM process. Editor's Note: See also Performance-Based Logistics (PBL).															GE Power (MB).
Basic Reliability		The ability of an item to perform its required functions without failure or defect for the duration of its life profile. Note: Reliability is deemed to include Durability								X							
Battle Damage Repair		Essential repair, which may be improvised, carried out in a battle environment in order to return damaged or disabled equipment to temporary service.			X												

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Battle Damage Repair – Aircraft (RAF Use)		The maintenance action taken in wartime to maximize the availability of damaged mission capable aircraft.			X												
Bayesian Network (or a Belief Network)		A Bayesian network (or a belief network) is a probabilistic graphical (network) model that represents a set of variables and their probabilistic independencies. For example, a Bayesian network can be used to calculate the probability of a patient having a specific disease, given the absence or presence of certain symptoms, if the probabilistic independencies between symptoms and disease as encoded by the graph hold. The term “Bayesian Networks” was coined by Pearl (1985) to emphasize three aspects: (1) The often subjective nature of the input information; (2) The reliance on Bayes’s conditioning as the basis for updating information; and (3) The distinction between causal and evidential modes of reasoning, which underscores Thomas Bayes’s paper of 1763. In order to fully specify the Bayesian network and thus fully represent the joint probability distribution, it is necessary to specify for each node X the probability distribution for X conditional upon X’s parents (parent nodes). Bayesian networks are used for modelling knowledge and performing probabilistic inference.															http://en.wikipedia.org/wiki/Bayesian_network, based on Pearl, Judea, “Bayesian Networks, A Model of Self-Activated Memory for Evidential Reasoning”, 7th Conference of the Cognitive Science Society, University of California, Irvine, CA, USA, pp. 329-334, August 15-17, 1985.
Bayesian Network		The nodes in a Bayesian network represent propositional variables of interest (e.g. the temperature of a device, the gender of a patient, a feature of an object, the occurrence of an event) and the links represent informational or causal dependencies among the variables. The dependencies are quantified by conditional probabilities for each node given its parents in the network. The network supports the computation of the probabilities of any sub-set of variables given evidence about any other sub-set. Perhaps the most important aspect of a Bayesian networks is that they are direct representations of the world, not of reasoning processes. The arrows in the diagram represent real causal connections and not the flow of information during reasoning (as in rule-based systems and neural networks).															Pearl, J. and Russel, S. “Bayesian Networks”, In M.A. Arbib (Ed.), Handbook of Brain Theory and Neural Networks, Cambridge, MA: MIT Press, pp. 157-160, 2003.
Built-In Test	BIT	An integral capability of the equipment which provides an on-board test capability to detect, diagnose, or isolate system failures. The fault detection and, possibly, isolation capability is used for periodic or continuous monitoring of a system’s operational health, and for observation and, possibly, diagnosis as a prelude to maintenance action.								X						C	
Built-In Test	BIT	A test approach using built-in test equipment or self-test hardware and software that is internally designed into the supported end item to test all or a part of that item.															Mil-Std-1309D, “Definition of Terms for Testing Measurement and Diagnostics”, 1992.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Built-In Test	BIT	An integral capability of the mission equipment which provides an on-board, automated test capability, consisting of software or hardware (or both) components, to detect, diagnose, or isolate product (system) failures. The fault detection and, possibly, isolation capability is used for periodic or continuous monitoring of a system's operational health, and for observation and, possibly, diagnosis as a prelude to maintenance action.								C						X	
Built-In Test Equipment	BITE	Any identifiable device that is a part of the supported end item and is used for testing that supported end item.															Mil-Std-1309D, "Definition of Terms for Testing Measurement and Diagnostics, 1992.
Built-In Test Equipment	BITE	Any device permanently mounted in the equipment and used for the express purpose of testing the equipment, either independently or in association with external test equipment.								X						X	
Cannibalization		The transfer of a serviceable part from one equipment/system to another or from an uninstalled assembly to an equipment/system, to overcome a temporary deficiency in spares. Same as Robbing.			X												
Cannot Duplicate	CND	An operationally observed/recorded system malfunction (for example, by BIT or on-line monitoring means) which maintenance personnel were unable to duplicate.															Mil-Std-1309D, "Definition of Terms for Testing Measurement and Diagnostics, 1992.
Capability		A measure of the degree to which a weapon system is able to perform its intended mission.						X	X								
Capability		The ability to execute a specified course of action. (A capability may or may not be accompanied by an intention.)															Joint Publication 1-02 (JP 1-02), "United States Department of Defense Dictionary of Military and Associated Terms", 31 August 2005.
Capability		Capability is the enduring ability to generate a desired operational outcome or effect, and is relative to the threat, physical environment and the contributions of coalition partners. Capability is not a particular system or equipment. Capability is delivered by Force Elements – Ships, Aircraft, Army formations, other Military Units and Force Enablers – combined into packages by Joint Force Commanders, tailored for particular operations or missions. Each Force Element is delivered by either a single service, or by a joint organisation such as the Joint Helicopter Force.															MOD UK Acquisition Operating Framework, http://www.aof.mod.uk.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Capability		An operational outcome or effect that users of equipment need to achieve.															MOD UK Acquisition Operating Framework, http://www.aof.mod.uk/aofcontent/tactical/randa/content/glossary.htm.
Capability		The ability to achieve a desired effect under specified standards and conditions through combinations of means and ways to perform a set of tasks. It is defined by an operational user and expressed in broad operational terms in the format of a joint or initial capabilities document or a joint Doctrine, Organization, Training, Materiel, Leadership and education, Personnel, and Facilities (DOTMLPF) change recommendation. In the case of materiel proposals/ documents, the definition will progressively evolve to DOTMLPF performance attributes identified in the capability development document and the capability production document.															Chairman of the Joint Chiefs of Staff Instruction CJCSI 3170.01 "Joint Capabilities and Integration System (JCIDS)", 1 May 2007.
Capability-Based Planning	CBP	The process for planning under uncertainty to provide capabilities suitable for a wide range of modern-day challenges and circumstances while working within an economic framework that necessitates choice.															Chairman of the Joint Chiefs of Staff Instruction CJCSI 3170.01 "Joint Capabilities and Integration System (JCIDS)", 1 May 2007.
Case-Based Reasoning		Case-Based Reasoning stores a set of problems and answers in an organized data structure called cases. A case-based reasoning system upon being presented with a problem finds a case in its knowledge base that is most closely related to the new problem and presents its solutions as an output with suitable modifications.															Kristian, H.J., "Case-Based Planning: Viewing Planning as a Memory Task", Academic Press Perspectives In Artificial Intelligence; Vol. 1, p. 277, ISBN 0-12-322060-2, 1989, http://en.wikipedia.org/wiki/Artificial_intelligence#_note-6.
Case-Based Reasoning	CBR	"Case-Based Reasoning (CBR) is a problem-solving paradigm that uses exemplars or previous solutions to solve new problems (Aamodt and Plaza 1994; Kolodner 1993). Three characteristics of CBR account for its growing popularity. First, CBR can reduce search. ... The second characteristic is that CBR permits problem solving even when the underlying domain theory is incomplete. ... Finally, CBR can facilitate knowledge acquisition …"															Althoff, K.-D. Bergmann, R. and Branting, K., AI Magazine 22(1): pp. 116-118, Spring 2001, http://www.aaai.org/AITopics/html/casebased.html.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Causal Bayesian Network		A Bayesian network is a carrier of the conditional independencies of a set of variables, not of their causal connections. However, causal relations can be modelled by the closely related causal Bayesian network. The additional semantics of the causal Bayesian networks specify that if a node X is actively caused to be in a given state x (an operation written as do(x)), then the probability density function changes to the one of the network obtained by cutting the links from X's parents to X, and setting X to the caused value x (Pearl, 2000). Using this semantics, one can predict the impact of external interventions from data obtained prior to intervention.															http://en.wikipedia.org/wiki/Bayesian_network, based on Pearl, J., "Causality: Models, Reasoning, and Inference", Cambridge University Press, ISBN 0-521-77362-8, 2000.
Causal Network		A graphical (network) model of causal relationships and the evolution of the outcomes. The nodes (vertices) represent the application of the relationships (functions, maps), and the links (edges) represent the data inputs (parents, causes) or the data outputs (outcomes), as applicable. Refer to http://mathworld.wolfram.com/CausalNetwork.html for a mathematical definition.															AVT-144 Technical Team.
Causal Network		A causal network, intuitively speaking, is a Bayesian network with the added property that the parents of each node are its direct causes. Editor's Note: See definition of Bayesian Network by the same author.															Pearl, J. and Russel, S., "Bayesian Networks", In M.A. Arbib (Ed.), Handbook of Brain Theory and Neural Networks, Cambridge, MA: MIT Press, pp. 157-160, 2003.
Common Logistics Operating Environment	CLOE	The Common Logistics Operating Environment (CLOE) is the Army Campaign Plan's initiative to synchronize logistics concepts, organizational approaches, information, and a new generation of technologies into a single operational and technical architecture for current and future force structures. The ultimate goal is to enable warfighters and logisticians at all levels to have total situational awareness within a common operating picture for all aspects of logistics, from factory to foxhole.															http://www.army.mil/aps/08/information_papers/transform/Common_Logistics_Operating_Environment.html.
Common Source Database	CSDB	The Common Source Database (CSDB) provides an electronic repository for discrete units of re-usable information, called data modules, to enable the creation, storage, editing and publication of information to be configuration managed, following the CALS principle of creating data once and using many times.		X													
Compliance Test		A test used to show whether or not a characteristic or a property of an item complies with the stated specification.											X				

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Concept, Assessment, Demonstration, Manufacture, In-Service, Disposal	CADMID	The CADMID Acquisition Cycle is a development of the Downey procurement cycle. The objective of this acquisition cycle is to assist with the reduction of risk during the early programme phases so that, at Main Gate, there is a high level of confidence that project targets for time, whole-life cost and performance will be achieved. The basic content of each stage is described in the glossary of definitions at Annex A of Def Stan 00-60.	X														UK Defence Industrial Strategy 2005.
Concurrent Engineering		A systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule and user requirements.								X							
Condition-Based Maintenance	CBM	Editor's Note: See the definitions of PHM and On Condition Task in NAVAIR 00-25-403.					X										
Condition-Based Maintenance		Preventive maintenance based on performance and/or parameter monitoring and the subsequent actions. Note: Performance and parameter monitoring may be scheduled, on request, or continuous.											X				
Condition-Based Maintenance	CBM	CBM is the use of machinery run time data to determine the machinery condition and hence its current fault/failure condition, which can be used to schedule required repair and maintenance prior to breakdown. Prognostics and Health Management (PHM) refers specifically to the phase involved with predicting future behavior, including Remaining Useful Life (RUL). Editor's Note: This definition appears in Chapter 2 of the Reference.															Vachtsevanos, G., Lewis, F., Roemer, M., Hess, A. and Wu, B., "Intelligent Fault Diagnosis and Prognosis for Engineering Systems", John Wiley & Sons Inc., 2006.
Condition-Based Maintenance		Maintenance performed as governed by condition monitoring programmes.															ISO 13372:2004(E) "Condition Monitoring and Diagnostics of Machines – Vocabulary".

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Condition-Based Maintenance	CBM	A maintenance strategy based on equipment operational experience derived from analysis. CBM includes maintenance processes and capabilities derived from real-time or approximate real-time assessments obtained from embedded sensors and/or external tests and measurements using either portable equipment or actual inspection. The objective of CBM is to perform maintenance based on the evidence of need while ensuring safety, reliability, availability, and reduced total ownership cost. CBM is further explained in the "DoD Guide for Achieving Reliability, Availability, and Maintainability (RAM)" (Reference (d)).															US Department of Defense Instruction 4151.22, "Condition Based Maintenance Plus (CBM+) for Materiel Maintenance", 2 December 2007, http://www.dtic.mil/whs/directives/corres/pdf/415122p.pdf.
Condition-Based Maintenance		Continuous monitoring or continuous inspection is the basis of CBM. Condition monitoring is the ongoing surveillance of the operation of a system or process to ensure specified performance and to detect abnormalities that may indicate and impending failure or of a failure that has already occurred. Therefore, condition monitoring enables corrective maintenance to be performed when and "out of specifications" condition exists or preventive maintenance when early system deterioration occurs and a scheduled component replacement, adjustment, or calibration is desired. CBM is ideal when it is not possible to accurately anticipate and predict the expected wear out trends and characteristics of a product or process with age. CBM is also effective when the criticality of a failure warrants the continuous monitoring of a particular product function or component, or process parameter. Different types of condition monitoring techniques and sensing apparatus exist and can be tailored to fit the nature, characteristics, and functionality of the parameter being observed.															"DoD Guide for Achieving Reliability, Availability, and Maintainability (RAM)", August 1, 2005, http://www.acq.osd.mil/sse/docs/RAM_Guide_080305.pdf.
Condition-Based Maintenance Plus	CBM+	A form of proactive equipment maintenance that forecasts incipient failures based on reliability analysis. Editor's Note 1: This definition may not be in official use by the US Army. Editor's Note 2: Do not confuse CBM+ with CBM.															Gorak, M. and Kwinn, Jr., M., "Lead-the-Fleet: Transitioning Army Aviation Maintenance From a Time Based System to a Usage Based System", US Army Operations Research Center of Excellence Technical Report DSE-TR-0406 DTIC #:ADA426343, June 2004.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Condition-Based Maintenance Plus	CBM+	CBM+ is the application and integration of appropriate processes, technologies, and knowledge-based capabilities to improve the reliability and maintenance effectiveness of DoD systems and components. At its core, CBM+ is maintenance performed on evidence of need provided by Reliability Centered Maintenance (RCM) analysis and other enabling processes and technologies characterized in Enclosure 2. CBM+ uses a systems engineering approach to collect data, enable analysis, and support the decision-making processes for system acquisition, sustainment, and operations.															US Department of Defense Instruction 4151.22, “Condition Based Maintenance Plus (CBM+) for Materiel Maintenance”, 2 December 2007.
Condition Monitoring		Continuous monitoring or continuous inspection is the basis of CBM. Condition monitoring is the ongoing surveillance of the operation of a system or process to ensure specified performance and to detect abnormalities that may indicate and impending failure or of a failure that has already occurred. Therefore, condition monitoring enables corrective maintenance to be performed when and “out of specifications” condition exists or preventive maintenance when early system deterioration occurs and a scheduled component replacement, adjustment, or calibration is desired.															“DoD Guide for Achieving Reliability, Availability, and Maintainability (RAM)”, August 1, 2005, http://www.acq.osd.mil/sse/docs/RAM_Guide_080305.pdf.
Condition Monitoring		The detection and collection of information and data that indicate the state of a machine. Note: The machine state deteriorates if faults or failures occur.															ISO 13372:2004(E) “Condition Monitoring and Diagnostics of Machines – Vocabulary”.
Condition Monitoring		The measurement and interpretation of data, condition indication, and determination of maintenance requirements.															Mitchell, P. (RAF), “What the Customer Wants Maintenance-Free and Failure-Free Operating Periods to Improve Overall System Availability and Reliability”, RTO-MP-037, September 2000.
Conditional Probability of Failure		The probability that a failure will occur in a specific period provided that the item concerned has survived to the beginning of that period.					X							X	X		
Configuration Management	CM	The process that identifies functional and physical characteristics of an item during its life cycle, controls changes to those characteristics, provides information on status of change actions and audits the conformance of configuration items to approved configuration baselines.						X	X								Mil-Std-480-B.

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Conformity		Fulfilment by a product, process or service of specifications.											X				
Consumables		Items such as oils, greases, paint, adhesives, cleaning materials, bulk rags etc. that are consumed during their use.	X														
Continuous Acquisition and Life-Cycle Support	CALS	It is an effort to document and utilise technical information, in a digitised format, for weapon system acquisition, design, manufacturing and support. Its intent is to accrue to military services the benefits available from digital technology. Previously the acronym stood for Computer-aided Acquisition and Logistic Support.								X							
Continuous Acquisition and Life-Cycle Support	CALS	Continuous Acquisition and Life-cycle Support is a strategy for improving business efficiency by integrating processes and making them less paper intensive. CALS seeks to apply the best technologies, processes and standards (i.e. E-commerce) to business and technical information passing between the MOD, its contractors, other government departments and organisations.		X													
Continuous Process Improvement	CPI	A DoD initiative to apply process improvement methods such as Lean and Six Sigma to organic maintenance activities. • Description – Continuous process improvement maximizes weapon system readiness while minimizing materiel flows and in-process inventories. • Goal – Optimize reliability and cycle time while striking a reasonable balance with costs across the total life-cycle value chain. • Key Features: – Employs: • Lean for eliminating all types of waste. • Six Sigma(6s) for minimizing process variation. • Theory Of Constraints (TOC) for alleviating process “bottlenecks”. – Focuses on: • Strong involved leadership committing significant time and resources. • Workforce buy-in. • Education and training for all value chain participants. • Clear outcome-focused metrics that are measurable and provable. • Ambitious and continuous improvement goals across the entire value chain.															www.acq.osd.mil/log/mppr/mssg.htm.
Continuous Process Improvement Transformation Review	CPI Transformation Review	A review of weapon systems programs nominated by the Services – understanding the system’s readiness requirements and key leverage points across sustainment value chains that import key cause and effect results on the efficiency and effectiveness the weapon system materiel readiness value chain. Started March 2005.															www.acq.osd.mil/log/mppr/mssg.htm.

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Core (Maintenance Capability)		Core represents the minimum amount of maintenance capability that the DoD Components must maintain in organic depot facilities to ensure that contingency operations are not compromised because of lack of essential depot maintenance support. Core is an organic capability and is not performed in the private sector.				X											
Corrective Maintenance		Same as Unscheduled Maintenance.	X														
Corrective Maintenance		All actions performed as a result of failure, to restore an item to a specified condition. Corrective maintenance can include any or all of the following steps: localization, isolation, disassembly, interchange, reassembly, alignment, and checkout.						X	X							X	
Corrective Maintenance		Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function.											X				
Corrosion Level 1		Corrosion damage that does not require structural reinforcement or replacement. or Corrosion occurring between successive inspections exceeds allowable limit but is local and can be attributed to an event not typical of operator usage of other aircraft in the same fleet (e.g. Mercury spill).													X		
Corrosion Prevention and Control Program	CPCP	A program of maintenance tasks implemented at a threshold designed to control an aircraft structure to Corrosion Level 1 or better.													X		
Cost Effectiveness		A comparative evaluation derived from analyses of alternatives (actions, methods, approaches, equipment, weapon systems, support systems, force combinations, etc.) in terms of the interrelated influences of cost and effectiveness objectives and support costs of the materiel system.	X														
Cost Effectiveness		A measure of the operational capability added by a system as a function of its life-cycle cost.															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Critical Failure		A failure that could result in injury to persons or that prevents an item from performing an essential mission.								X							
Critical Item		An item whose failure could result in a critical failure or that requires special effort during development/production. Note: Examples, that might be tailored for each contract, are listed below: 1) The failure of which would critically affect system safety, cause the system to become unavailable or unable to achieve mission objectives, or cause extensive/expensive maintenance and repair. 2) The failure of which would prevent the acquisition of data to evaluate system safety, availability, mission success, or need for maintenance/repair. 3) An item which has stringent performance requirement(s) in its intended application relative to state-of-the-art techniques for the item. 4) A single point failure which causes system failure. 5) An item which is stressed in excess of specified derating criteria. 6) An item which has a limitation which warrants controlled surveillance under specified conditions. 7) An item which is known to require special handling, transportation, storage, or test precautions. 8) An item which is difficult to produce or manufacture relative to state-of-the-art techniques. 9) An item which has exhibited an unsatisfactory operating history or which does not have sufficient history of its own to provide confidence in its reliability. 10) An item which has past history, nature, function or processing with a deficiency warranting a total traceability. 11) An item that can be produced by one company only. 12) Long lead time items.								X							
Criticality		A relative measure of the consequence and frequency of occurrence of a failure mode.														X	
Criticality Analysis		A procedure that prioritizes each failure mode identified in the FMEA according to the combined influence of its severity and its probability of occurrence.					X										

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Damage (in SHM)		Intentional or unintentional changes to the material and/or geometric properties of the system, including changes to the boundary conditions and system connectivity, which adversely affect the current or future performance of that system. In terms of length scales, all damage begins at the material level and then, under appropriate loading conditions, progresses to component- and system-level damage at various rates. In terms of time scales, damage can accumulate incrementally over long periods of time, such as damage associated with fatigue or corrosion. Damage can also occur on much shorter time scales as a result of scheduled discrete events, such as aircraft landings, and from unscheduled discrete events, such as enemy fire on a military vehicle. Implicit in this definition of damage is the concept that damage is not meaningful without a comparison between two different system states.															Farrar, C. (Los Alamos National Laboratory) et al. in "Damage Prognosis for Aerospace Civil and Mechanical Systems", Daniel J. Inman et al. Editors, Published by Wiley, 2005.
Damage Accumulation Modelling		Damage accumulation, or usage-based modeling utilize highly accelerated operating conditions, or acceleration factors, to predict RUL. Specifically, acceleration factors refer to operating conditions that expedite the occurrence of a failure mode. Acceleration factors can be identified through the physics of failure, experimental failure testing, or prior experience.															Brown, D., Kalgren, P., and Roemer, M. (Impact Technologies), "Electronic Prognostics – A Case Study Using Switched-Mode Power Supplies (SMPS)", IEEE Instrumentation & Measurement Magazine, Vol. 10, Issue 4, pp. 20-26, August 2007.
Damage Prognosis		The estimate of a system's remaining useful life. This estimate is based on the output of predictive models, which develop such estimates by coupling information from usage monitoring, structural health monitoring, past, current and anticipated future environmental and operational conditions, the original design assumptions regarding loading and operational environments, and previous component and system level testing. Editor's Note: See Prognosis.															Farrar, C. (Los Alamos National Laboratory) et al. in "Damage Prognosis for Aerospace Civil and Mechanical Systems", Daniel J. Inman et al. Editors, Published by Wiley, 2005.

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Damage Tolerance (Aircraft Engines)		An element of the life management process that recognizes the potential existence of component imperfections, which are the result of inherent material structure, material processing, component design, manufacturing or usage. Damage tolerance addresses this situation through the incorporation of fracture resistant design, fracture mechanics, process control, and non-destructive inspection.															FAA Advisory Circular (Draft) AC 33.70-Y "Engine Life Limited Parts Requirements", 2007.
Damage Tolerance (Aircraft Structure)		Damage tolerance is the attribute of a structure that permits it to retain its required residual strength for a period of unrepaired usage after the structure has sustained specific levels of fatigue, corrosion, accidental, and/or discrete source damage.															Mil-Std-1530C (USAF) "Aircraft Structural Integrity Program (ASIP)" 1 November 1995 & FAA Advisory Circular, "Damage Tolerance and Fatigue Evaluation of Aircraft Structure", AC 25.571-1C, Dated 29 April 1998.
Damage Tolerant		A qualification standard for aircraft structure. An item is judged to be damage tolerant if it can sustain damage and the remaining structure can withstand reasonable loads without structural failure or excessive structural deformation until the damage is detected.													X		
Data-Based Assessment/ Model (in SHM)		An assessment/model that relies on previous measurements from the system to assess the current damage state, typically by means of some sort of pattern recognition method such as neural networks. Although data-based assessment techniques may be able to indicate a change in the presence of new loading conditions or system configurations, they will perform poorly when trying to classify the nature of the change. Thus, it is not uncommon to use the results from a physics-based model to "train" a data-based assessment technique to recognize damage cases for which no experimental data exists.															Farrar, C. (Los Alamos National Laboratory) et al. in "Damage Prognosis for Aerospace Civil and Mechanical Systems", Daniel J. Inman et al. Editors, Published by Wiley, 2005.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Data Fusion		a) Low level fusion, also called data fusion, combines several sources of raw data to produce new raw data that is expected to be more informative and synthetic than the inputs. b) Intermediate level fusion, also called feature level fusion, combines various features. Those features may come from several raw data sources (several sensors, different moments, etc.) or from the same raw data. c) High level, also called decision fusion combines decisions coming from several experts. By extension, one speaks of decision fusion even if the experts return a confidence (score) and not a decision. To distinguish both cases, one speaks of hard and soft fusion. Methods of decision fusion include voting methods, statistical methods, fuzzy logic-based methods, etc.															Royal Military Academy, Belgium, http://www.sic.rma.ac.be/Research/Fusion/Intro/content.html. .
Data Fusion		Data fusion is a formal framework in which are expressed the means and tools for the alliance of data originating from different sources. (In French: la fusion de données constitue un cadre formel dans lequel s'expriment les moyens et techniques permettant l'alliance des données provenant de sources diverses.) Data fusion aims at obtaining information of greater quality; the exact definition of 'greater quality' will depend upon the application.															Wald, L., "A European Proposal for Terms of Reference in Data Fusion", International Archives of Photo-grammetry and Remote Sensing, Vol. XXXII, Part 7, pp. 651-654, 1998, http://www.datafusion.org/article.php?sid=71.
Data Mining		The non-trivial extraction of implicit, previously unknown, and potentially useful information from data.															Frawley, W., Piatetsky-Shapiro, G. and Matheus, C., "Knowledge Discovery in Databases: An Overview", AI Magazine, pp. 213-228, ISSN 0738-4602, Fall 1992, http://en.wikipedia.org/wiki/Data_mining.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Data Mining		The science of extracting useful information from large data sets or databases.															Hand, D., Mannila, H. and Smyth, P., “Principles of Data Mining”, MIT Press, Cambridge, MA, ISBN 0-262-08290-X, 2001, http://en.wikipedia.org/wiki/Data_mining.
Defect		Any non-conformance of an item with specified requirements, or a condition which experience indicates could result in a non-conformance.	X														
Defect		Any non-conformance of an item with specified requirements, or a condition which experience indicates could result in a non-conformance.								X							
Deferred Maintenance		Corrective maintenance which is not immediately carried out after a fault detection but is delayed in accordance with given maintenance rules.											X				
Degradation		A gradual impairment of the ability to perform.														C	Mil-Std-721.
Degradation		An irreversible process in one or more characteristics of an item with either time, use or an external cause. Note 1: Degradation may lead to failure. Note 2: Degradation is often referred to as wearout.											X				
Degradation		A gradual decrease in an item’s characteristic or ability to perform.														X	
Degraded State		State of an item whereby that item continues to perform a function to acceptable limits but which are lower than the specified values or continues to perform only some of its required functions.											X				
Dependability		A collective item used to describe the availability and its influencing factors: reliability, maintainability and maintenance supportability. Note: Dependability is used only for general descriptions in non-quantitative terms.											X				
Dependability		A measure of the degree to which an item is operable and capable of performing its required function at any (random) time during a specified mission profile, given that the item is available at mission start. (Item state during a mission includes the combined effects of the mission-related system R&M parameters but excludes non-mission time; see Availability.)														X	

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Design Service Goal		The period of time (in flight cycles/hours) established at design and/or certification during which the principal structure will be reasonably free from significant cracking.															FAA Advisory Circular, “Damage Tolerance and Fatigue Evaluation of Aircraft Structure”, AC 25.571-1C, Dated 29 April 1998.
Design Service Life (Aircraft Structure)	DSL	The design service life is the period of time (e.g., years, flight cycles, hours, landings, etc.) established at design, during which the structure is expected to maintain its structural integrity when flown to the design loads/environment spectrum.															Mil-Std-1530C (USAF) “Aircraft Structural Integrity Program (ASIP)”, 1 November 1995.
Diagnosis		A formal definition in maintenance documents has not been found. For AVT-144 purposes, “Diagnosis” will be regarded as synonymous with “Fault Diagnosis” as defined by EN 13306, i.e. actions taken for fault recognition, fault localization and cause identification.															AVT-144 Technical Team.
Diagnosis		The determination of the nature of a diseased condition; the identification of a disease by careful investigation of its symptoms and history.															Oxford English Dictionary.
Diagnosis – Fault		The actions taken for fault recognition, fault localization and cause identification. Note: Fault diagnosis is sometimes called trouble shooting.											X				
Diagnostics		The examination of symptoms and syndromes to determine the nature of faults or failures (kind, situation, extent).															ISO 13372:2004(E) “Condition Monitoring and Diagnostics of Machines – Vocabulary”.
Diagnostics		The detection, isolation and analysis of faults and failures.							X								
Diagnostics		The process of determining the state of a component and the analysis of a symptom to understand its cause.															Def Stan 25-24 Health and Usage Monitoring Capability for Land Platforms (HUMS). Also Defence Standard 00-40 Part 7 Reliability and Maintainability (R&M) Part 7.
Diagnostics		The process of determining the state of a component to perform its function(s).															Hess, A., JSF Project Office PHM Lead, Presentation, 2005.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Diagnostics		The hardware, software, or other documented means used to determine that a malfunction has occurred and to isolate the cause of the malfunction. Also refers to “the action of detecting and isolating failures or faults”.														X	
Disabled State		The state of an item characterized by its inability to perform a required function, for any reason. Editor’s Note: See also External Disabled State, Up State, and Degraded State.											X				
Discard		The removal from service of an item at a specified life limit.													X		
Dormant		A state in which an item is able to but is not required to function. Most often associated with long-term storage and “wooden” rounds. Not to be confused with downtime.														X	
Down State		State of an item characterized either by a fault, or by a possible inability to perform a required function during preventive maintenance. Note 1: This state is related to availability performance. Note 2: A down state is sometimes referred to as an internal disabled state. Note 3: See also Up State, Degraded State, and Disabled State.											X				
Down Time		The time interval during which an item is in a down state.											X				
Down Time – Maintenance		The interval between the time a system/equipment is made available for preventive or corrective maintenance until that maintenance action is successfully completed.								X							
Downing Event		An event which causes an item to become unavailable to begin a mission (i.e. the transition from up-time to down-time).														X	
Downtime		That period of time during which an item is not in a condition to perform a required function. It is the sum of the Total Preventive Maintenance (TPM) time, plus Total Corrective Maintenance (TCM) time plus the total of the Administration and Logistics Delay Time (ALDT) spent waiting for parts, maintenance personnel or transportation.			X												
Downtime		That element of time during which an item is in an operational inventory but is not in condition to perform its required function.														X	
Durability		The ability of an item to perform a required function under given conditions of use and maintenance, until a limiting state is reached.			X								X				BS 4778.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Durability		The ability of an item to perform a required function under given conditions of use and maintenance, until a limiting state is reached. Note: A limiting state of an item may be characterized by the end of the useful life, unsuitability for any economical or technological reasons or other relevant factors.											X				
Durability		Editor's Note: In a note under the definition of Basic Reliability, ARMP-7 states that Reliability is deemed to include Durability. No specific definition of Durability is given in ARMP-7.								X							
Durability		A measure of an item's useful life (a special case of reliability). Often referred to as ruggedness.														X	
Durability (Aircraft Structure)		Durability is the ability of the aircraft structure to resist cracking, corrosion, thermal degradation, delamination, wear, and the effects of foreign object damage for a prescribed period of time.															Mil-Std-1530.
E-Business		See Enterprise Integration (EI).		X													
Economic Life (in RCM)		Economic Life limits are used in RCM for items whose failure modes have only Economic/Operational consequences. An Economic Life Limit is warranted for an item if it is cost-effective to remove it before it fails.					X										
Effectiveness		The extent to which the goals of the system are attained, or the degree to which a system can be elected to achieve a set of specific mission requirements. Also, an output of cost-effectiveness analysis. Editor's Note: See Operational Effectiveness, Measure of Performance, Operational Suitability, and Measure of Suitability from the Same Source.															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Effectiveness – Measure of		Measure designed to correspond to accomplishment of mission objectives and achievement of desired results. (CJCSI 3170.01E) MOEs may be further decomposed into Measures of Performance and Measures of Suitability.															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.

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Effectiveness – Measures of	MOE	The tools used to measure results achieved in the overall mission and execution of assigned tasks. Measures of effectiveness are a prerequisite to the performance of combat assessment.															Joint Publication 1-02 (JP 1-02), "United States Department of Defense Dictionary of Military and Associated Terms", 31 August 2005.
Effectiveness – Operational		The degree to which an equipment is capable of fulfilling the purpose for which it was procured.			X												
Effectiveness – Operational		The measure of the overall ability of a system to accomplish a mission when used by representative personnel in the environment planned or expected for operational employment of the system considering organization, doctrine, tactics, supportability, survivability, vulnerability, and threat. (CJSCI 3170.01E)															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Engine Health Management	EHM	Activities directed at the pre-emption, postponement and accommodation of gas turbine engine degradation, faults and failures.															AVT-126 Technical Team.
Enterprise Integration	EI	Also known as E-Business, it is the bringing together of People, Processes and Information to work together in a harmonised way and supported by appropriate information systems, through the discipline of CALS and the introduction of E-Commerce.		X													
Enterprise Level Materiel Readiness Metrics		a) Operational: Availability/Mission Capable (MC) rates; cannibalization rates. b) Logistics: Equipment fill rates; maintenance manning rates. c) Resources: Spares funding; depot maintenance funding.															1) Timko, A. et al, "Material Readiness Metrics". 2) Logistics Management Institute Report LG102T4 August 2003 for DUSD(L&MR).
Environmental Stress Screening	ESS	A series of tests conducted under environmental stresses to disclose weak parts and workmanship defects so that corrective action can be taken.														X	
Environment		The aggregate of all external and internal conditions (such as temperature, humidity, radiation, magnetic and electrical fields, shock, vibration, etc.), whether natural, manmade, or self-induced, that influences the form, fit, or function of an item.														X	

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Equipment Fill Rate		The class of metrics indicating the difference between authorized and assigned key weapon systems.															1) Timko, A. et al, “Material Readiness Metrics”. 2) Logistics Management Institute Report LG102T4 August 2003 for DUSD(L&MR).
Evident Failure		A failure mode whose effects become apparent to the operating crew under normal circumstances if the failure mode occurs on its own.												X			
Evolutionary Acquisition		The preferred DoD strategy for rapid acquisition of mature technology for the user according to DoDI 5000.2. An evolutionary approach delivers capability in increments, recognizing up front the need for future capability improvements. There are two approaches to achieving an EA: Spiral Development and Incremental Development as noted below: • Spiral Development: In this process, a desired capability is identified, but the end-state requirements are not known at program initiation. Requirements are refined through demonstration, risk management, and continuous user feedback. Each increment provides the best possible capability, but the requirements for future increments depend on user feedback and technology maturation. According to DoD 5000.1, spiral development is the preferred process for executing an EA strategy. • Incremental Development: In this process, a desired capability is identified, an end-state requirement is known, and that requirement is met over time by developing several increments, each dependent on available mature technology.															US DoD Defense Acquisition University, “Glossary of Defence Acquisition Acronyms and Terms”, Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Evolutionary Acquisition		Evolutionary Acquisition is the preferred DoD strategy for rapid acquisition of mature technology for the user. An evolutionary approach delivers capability in increments, recognizing, up front, the need for future capability improvements. The objective is to balance needs and available capability with resources, and to put capability into the hands of the user quickly. The success of the strategy depends on consistent and continuous definition of requirements, and the maturation of technologies that lead to disciplined development and production of systems that provide increasing capability towards a materiel concept. Evolutionary Acquisition includes Spiral Development and Incremental Development.															DoD 5000.2 Operation of the Defense Acquisition System 12, May 2003, http://akss.dau.mil/dapc/index.html.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Exception Handling (SW)		The ability to deal actively with failures, so avoiding system crashes or erroneous results.															Mitchell, P. (RAF), "What the Customer Wants Maintenance-Free and Failure-Free Operating Periods to Improve Overall System Availability and Reliability", RTO-MP-037, September 2000.
Expert System		The basic components of an expert system are a knowledge base, or KB, and an inference engine. The information to be stored in the KB is obtained by interviewing people who are expert in the area in question. The interviewer, or knowledge engineer, organizes the information elicited from the experts into a collection of rules, typically of an "if-then" structure. Rules of this type are called production rules. The inference engine enables the expert system to draw deductions from the rules in the KB.															Extract from Artificial Intelligence, Encyclopædia Britannica. 2007, Encyclopædia Britannica Online, 1 September 2007, http://www.britannica.com/eb/article-219079.
Expert System		Expert knowledge is a combination of a theoretical understanding of the problem and a collection of heuristic problem-solving rules that experience has shown to be effective in the domain. **Expert systems** are constructed by obtaining this knowledge from a human expert and coding it into a form that a computer may apply to similar problems. This reliance on the knowledge of a human domain expert for the system's problem solving strategies is a major feature of expert systems.															Luger, G.F., "Artificial Intelligence: Structures and Strategies for Complex Problem Solving", 5th Edition (Addison-Wesley; 2005), Chapter 1, http://www.aaai.org/AITopics/html/expert.html#nii.
Expert System		An expert system, **also known as a knowledge based system**, is a computer program that contains some of the subject-specific knowledge, and contains the knowledge and analytical skills of one or more human experts. The most common form of expert systems is a program made up of a set of rules that analyze information (usually supplied by the user of the system) about a specific class of problems, as well as providing mathematical analysis of the problem(s), and, depending upon their design, recommend a course of user action in order to implement corrections. It is a system that utilizes what appear to be reasoning capabilities to reach conclusions. Expert systems are most valuable to organizations that have a high-level of know-how experience and expertise that cannot be easily transferred to other members.															http://en.wikipedia.org/wiki/Expert_system.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Expert System (cont'd)		They are designed to carry the intelligence and information found in the intellect of experts and provide this knowledge to other members of the organization for problem-solving purposes.															http://en.wikipedia.org/wiki/Expert_system.
External Disabled State		That sub-set of the disabled state when the item is in an up state, but lacks required external resources or is disabled due to planned actions other than maintenance.											X				
Facilities		Facilities comprise all the physical infrastructure required to integrate, operate and maintain the equipment.	X														
Facilities		The permanent, semi-permanent, temporary or mobile assets required to support the system through its life cycle. Facilities Management includes the conduct of studies to determine the type of facilities or facility improvements, locations, space needs, environmental requirements and equipment.						X									
Facilities		Includes the permanent, semi-permanent, or temporary real property assets required to operate and support the materiel system, including conducting studies to define types of facilities or facility improvements, locations, space needs, utilities, environmental requirements, real estate requirements, and equipment. One of the traditional elements of Logistics Support (LS).															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Fail Safe (Aircraft Structure)		The attribute of the structure that permits it to retain its required residual strength for a period of unrepaired use after the failure or partial failure of a principal structural element.															FAA Advisory Circular, "Damage Tolerance and Fatigue Evaluation of Aircraft Structure", AC 25.571-1C, Dated 29 April 1998.
Fail Safe Structure		A structure that retains its required residual strength for a period of unrepaired usage after the failure or partial failure of safety-of-flight structure.															Mil-Std-1530C (USAF), "Aircraft Structural Integrity Program (ASIP)", 1 November 1995.
Fail Soft		A non-specific deviation in characteristics of a system that has manifested a number of failures but still provides most of its functional capability.															Mil-Std-1309D, "Definition of Terms for Testing Measurement and Diagnostics", 1992.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Failure		The termination of the ability of an item to perform a required function. Note: Failure is an event as distinguished from fault (1.8), which is a state.															ISO 13372:2004(E), “Condition Monitoring and Diagnostics of Machines – Vocabulary”.
Failure		Change in operating characteristics of an item resulting in degradation of useful performance.															Mil-Std-1309D, “Definition of Terms for Testing Measurement and Diagnostics”, 1992.
Failure		The termination of the ability of an item to perform a required function. Note 1: After failure the item has a fault, which may be complete or partial. Note 2: “Failure” is an event, as distinguished from “Fault”, which is a state.											X				
Failure		The inability of an item to perform within previously specified limits. Failures may be classified as to such aspects as cause, degree, relevancy, chargeability, dependency and responsibility. Editor’s Note: This definition is subtly different from the NAVAIR 00-25-403 definition of “Functional Failure” and the ARMP-7 definition of “Fault”. In these various definitions, the terms “Fault” and “Functional Failure” both imply that the function of the item has been lost. The term “Failure” on its own implies that the performance of the item is outside specification, but leaves open the possibility that the function can still be performed to some useful degree or under some conditions.	X							X					X		
Failure		The event, or inoperable state, in which any item or part of an item does not, or would not, perform as previously specified.														X	
Failure (Aircraft Engines)		The separation of the part into two or more pieces so that the part is no longer whole or complete.															FAA Advisory Circular (Draft) AC 33.70-Y, “Engine Life Limited Parts Requirements”, 2007.
Failure Analysis		The logical, systematic examination of a failed item to identify and analyse the failure mechanism, the failure cause and the consequences of failure. (IEC-50(191))								X			X				
Failure Cause		Why the functional failure occurs.													X		

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Failure Condition		The effect on the aircraft and its occupants, both direct and consequential, caused or contributed to by one or more failures, considering relevant adverse operational or environmental conditions.													X		
Failure Effect		The result of a functional failure.													X		
Failure Effects		The result of a functional failure on surrounding items, the functional capability of the end item, and hazards to personnel and the environment.					X										
Failure Finding Task (RCM)	FF Task	A preventative maintenance task performed at a specified interval to determine whether a hidden failure has occurred.					X										
Failure Finding Task (RCM)		A scheduled task used to determine whether a specific hidden failure has occurred.												X			
Failure Free Operating Period	F-FOP	A period, measured in appropriate units, when the system is meeting its minimum operating capability.															Mitchell, P. (RAF), “What the Customer Wants Maintenance-Free and Failure-Free Operating Periods to Improve Overall System Availability and Reliability”, RTO-MP-037, September 2000.
Failure Free Operating Period	FFOP	A period (measured in a number of days or hours, for example) where the system is running continuously without failure. “Failure Free” means that the equipment is able to operate to its full mission requirement for the period required or specified. There may well be faults, however, that do not affect the operation of the equipment or system; perhaps by re-configuration or redundancy, system operation is unaffected and thereby no functional failure is recorded. “Fault Free”, on the other hand, means that as there are no faults, there can therefore also be no failures. Full and continued operation of the system is ensured – simple and unequivocal. Editor’s Note: See definition of Fault-Free Period of Operation from the same source.															Hockley, C.J. (Royal Military College of Science, Shrivenham, UK), “Design for Success”, Institution of Mechanical Engineers Journal of Aerospace Engineering, Vol. 212, No. 6, pp. 371-378, 1998.
Failure Mechanism		The physical, chemical or other processes which lead or have led to failure.											X				
Failure Mode		The consequences of the mechanism through which the failure occurs, i.e. short, open, fracture, excessive wear.	X							X							

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Failure Mode		A specific physical condition that can result in a particular functional failure.					X										
Failure Mode		A single event, which causes a functional failure.												X			
Failure Mode		The consequence of the mechanism through which the failure occurs, i.e. short, open, fracture, excessive wear.														X	
Failure Mode and Effects Analysis	FMEA	A process used to determine the functions(s) of each item, the functional failures associated with each function, the failure modes that have the potential to cause each functional failure, and the effect and severity of each failure mode.					X										
Failure Mode and Effects Analysis	FMEA	A procedure by which each potential failure mode of a component, equipment or sub-system in a system is analysed to determine the results or effects thereof on the overall system and to classify each potential failure mode according to its severity.								X							
Failure Mode and Effects Analysis	FMEA	A procedure for analyzing each potential failure mode in a product to determine the results or effects thereof on the product. When the analysis is extended to classify each potential failure mode according to its severity and probability of occurrence, it is called a Failure Mode, Effects, and Criticality Analysis (FMECA).														X	
Failure Mode Effects and Criticality Analysis	FMECA	A procedure for analyzing each potential failure mode in a product to determine the results or effects thereof on the product. When the analysis is extended to classify each potential failure mode according to its severity and probability of occurrence, it is called a Failure Mode, Effects, and Criticality Analysis (FMECA).														X	
Failure Mode Effects and Criticality Analysis	FMECA	A process which combines a Failure Mode and Effects Analysis and a Criticality Analysis.					X	C	C								
Failure Modes Effects and Criticality Analysis	FMECA	An analysis to identify potential design weaknesses through systematic, documented consideration of the following: a) All likely ways in which component or equipment can fail. b) Causes for each mode. c) The effects of each failure (which may be different for each mission phase). d) The criticality for each failure both for safety and for mission success.	X														
Failure Modes Effects and Criticality Analysis	FMECA	A qualitative method of reliability analysis which involves a fault modes and effects analysis together with a consideration of the probability of their occurrence and of the ranking of the seriousness of the faults. (IEC-50(191))								X							

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Failure Rate		The number of failures of an item per unit measure of life, expressed in hours, cycles, kilometres, events as applicable to the item. (A-LP-001-000/AM-000)								X							
Failure-Finding Task		A scheduled task used to determine whether a specific hidden failure has occurred.												X			
Fault		The state of an item characterised by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources. A fault is often the result of a failure of the item itself, but may exist without prior failure. (IEC-50(191))	X							X							
Fault		The condition of a component that occurs when one of its components or assemblies degrades or exhibits abnormal behaviour, which may lead to the failure of the machine. Note 1: A fault may be the result of a failure, but can exist without a failure. Note 2: Planned actions or lack of external resources are not a fault.															ISO 13372:2004(E), “Condition Monitoring and Diagnostics of Machines – Vocabulary”.
Fault		1) A physical condition that causes a device, a component, or an element to fail to perform in a required manner; for example, a short circuit or a broken wire, or an intermittent connection. 2) A degradation in performance due to detuning, maladjustment, misalignment, or failure of parts. 3) The immediate cause of failure (e.g. maladjustment, misalignment, defect, etc.).															Mil-Std-1309D, “Definition of Terms for Testing Measurement and Diagnostics”, 1992.
Fault		The state of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources. Note: See also Latent Fault and Partial Fault.											X				
Fault		The immediate cause of failure (e.g. maladjustment, misalignment, defect, etc.).														X	
Fault		An identifiable condition in which one element of a redundant system has failed (no longer available) without impact on the required function output of the system (Maintenance Significant Item – MSI). At the system level, a fault is not considered a functional failure.													X		
Fault Analysis		The logical, systematic examination of an item to identify and analyse the probability, causes and consequences of potential faults.											X				
Fault Detection		A process which discovers the existence of faults.														X	

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Fault Diagnosis		Actions taken for fault recognition, fault localization and cause identification. Note: Fault diagnosis is sometimes called trouble shooting.											X				
Fault Free Period of Operation	FFPO	This is the period during which the system is available and has no faults or failures. The equipment might be available to be operated but not necessarily in an operating mode all the time (useful for a system detached from its main operating base, for example). “Failure Free” means that the equipment is able to operate to its full mission requirement for the period required or specified. There may well be faults, however, that do not affect the operation of the equipment or system; perhaps by re-configuration or redundancy, system operation is unaffected and thereby no functional failure is recorded. “Fault Free”, on the other hand, means that as there are no faults, there can therefore also be no failures. Full and continued operation of the system is ensured – simple and unequivocal. Editor’s Note: See definition of Failure Free Period of Operation from the same source.															Hockley, C.J. (Royal Military College of Science, Shrivenham, UK), “Design for Success”, Institution of Mechanical Engineers Journal of Aerospace Engineering, Vol. 212, No. 6, pp. 371-378, 1998.
Fault Isolation		The process of determining the location of a fault to the extent necessary to effect repair.														X	
Fault Tolerance		The capacity of a system or program to continue operation in the presence of specified faults.															Mil-Std-1309D, “Definition of Terms for Testing Measurement and Diagnostics”, 1992.
Fault Tolerance		The attribute of an item that makes it able to perform a required function in the presence of certain given sub-item faults. (IEC-50(191))								X							
Fault Tolerant System		A system that is designed with redundant elements that can fail without impact on safety or operating capability. Note from main text of MSG-3: In other words, redundant elements of the system may fail (fault), but the system itself has not failed. Individually, and in some combinations, these faults may not be annunciated to the operating crew, but by design the aircraft may be operated indefinitely with the fault(s) while still satisfying all certification and airworthiness requirements. Consequently, this means that the implementation of fault-tolerant system design by the manufacturer enhances the in-service system availability.													X		

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Feature-Based Modelling		Feature-based modeling utilizes in-situ readily available monitoring parameters to predict impending failures. During model development the physics, or root cause of failure, is analyzed. Monitoring parameters are selected based on circuit attributes with a high variability, or sensitivity, to device degradation. Then, faults of varying severity are generated or "seeded" using a Highly Accelerated Stress Test (HAST) procedure. Once faults are generated, the properties of each device are measured and recorded appropriately. Next, the degraded devices are inserted into the system to study changes in monitoring parameters. Finally features, or properties, extracted from the monitoring parameters are used to develop a feature-based probability of failure model.															Brown, D., Kalgren, P. and Roemer, M. (Impact Technologies), "Electronic Prognostics – A Case Study Using Switched-Mode Power Supplies (SMPS)", IEEE Instrumentation & Measurement Magazine, Vol. 10, Issue 4, pp. 20-26, August 2007.
Firm Price		An agreed price which is not subject to variation.	X														
Firmware Item		The combination of a hardware item and an executable software item and/or data residing on that device in read-only form.	X														
Fixed Price		An agreed price which is subject to variation, by means of a formula, for changes in economic conditions.	X														
Full Mission Capable	FMC	The aircraft is capable of doing all assigned missions. The formula for FMC rate is FMC hours/possessed hours.															US Air Force Instruction AFI 21-103, "Equipment Inventory, Status and Utilization Reporting", Attachment 2 Maintenance Status Codes and Condition Status Codes, 14 December 2005.
Full Scale Development		An agreed programme of detailed design engineering, including the manufacture of models or prototypes, of an equipment and any necessary trials, leading to the acceptance of the equipment into service; the production of full manufacturing and support information and documentation; and the provision of draft handbooks.	X														
Function		The normal characteristic actions of an item.													X		
Function (RCM)		An intended purpose of an item as described by a required standard of performance.					X										
Function (RCM)		What the owner or user of a physical asset or system wants it to do.												X			

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Function Check Out		The action taken after maintenance actions to verify that the item is able to perform the required function. Note: Function check is usually carried out after down state.											X				
Functional Baseline		The technical portion of the program requirements (Type A Specifications); provides the basis for contracting and controlling system design.						X	X								
Functional Check		A quantitative check to determine if one or more functions of an item performs within specified limits.													X		
Functional Failure		The inability of an item to perform a specific function within specified limits.					X							C	C		
Functional Failure		A state in which a physical asset or system is unable to perform a specific function to a desired level of performance.					C							X	C		
Functional Failure		The failure of an item to perform its intended function within specified limits.					C							C	X		
Functional Test		An evaluation of a product or item while it is being operated and checked under limited conditions without the aid of its associated equipment in order to determine its fitness for use.														X	
Functional Test		1) A test which determines whether the UUT is functioning properly. The operational environment (such as stimuli and loads) can be either actual or simulated. 2) A test which is intended to exercise and identifiable function of a system. The function is tested independent of the hardware implementing the function.															Mil-Std-1309D, “Definition of Terms for Testing Measurement and Diagnostics”, 1992.
Fuzzy Logic		Some expert systems use fuzzy logic. In standard logic there are only two truth values, true and false. This absolute precision makes vague attributes or situations difficult to characterize. (When, precisely, does a thinning head of hair become a bald head?) Often the rules that human experts use contain vague expressions, and so it is useful for an expert system’s inference engine to employ fuzzy logic.															Extract from “Artificial Intelligence”, Encyclopædia Britannica Online, 1 September 2007, http://www.britannica.com/eb/article-219079.
Hard Time Task (RCM usage)	HT Task	The scheduled removal of an item, or a restorative action at some specified maximum operating limit to prevent functional failure. Note: This is a preventative maintenance task.					X										
Health and Usage Monitoring (System)	HUM(S)	For the purposes of AVT-144, a HUMS will be considered as equivalent to a PHM system as defined in NAVAIR 00-205-403.															AVT-144 Technical Team.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Health and Usage Monitoring System		A platform system that provides health, usage, and status information using data captured automatically from the platform. The system may include elements such as BIT/BITE which diagnose faults, and prognostic analysis of failure.															Def Stan 25-24, "Health and Usage Monitoring Capability for Land Platforms (HUMS)".
Health Management		The capability to make appropriate decisions about maintenance actions based on diagnostics/prognostics information, available resources and operational demand.															Hess, A., JSF Project Office PHM Lead, Presentation, 2005.
Health Monitoring		The automatic acquisition of data necessary to determine the potential failure or degradation of a system.															Def Stan 25-24, "Health and Usage Monitoring Capability for Land Platforms (HUMS)".
Hidden Failure		A functional failure whose effects are not apparent to the operating crew under normal circumstances if the failure mode occurs on its own. Additional Comments: A hidden failure is the one that is the result of loss of some function that is not exercised as part of normal operations or is not evident to the operator and its failure goes undetected without failure of some other function or other occurrence of and event that demands its functionality. The function that must be lost (or demand event) to cause a hidden failure to become evident is referred to as the protected or evident function.					X										
Hidden Failure		A failure mode whose effects do not become apparent to the operating crew under normal circumstances if the failure mode occurs on its own.												X			
Hidden Function		1) A function which is normally active and whose cessation will not be evident to the operating crew during performance of normal duties. 2) A function which is normally inactive and whose readiness to perform, prior to it being needed, will not be evident to the operating crew during performance of normal duties.													X		
Hidden Function (RCM)		A function whose failure on its own does not become apparent to the operating crew under normal circumstances.												X			
Human Engineering		The area of human factors, which applies scientific knowledge to the design of items to achieve effective man-machine integration and utilization including operations, maintenance, support and disposal of the system.								X							
Human Engineering		The application of scientific knowledge to the design of items to achieve effective user-system integration (man-machine interface).														X	

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Human Factors		A body of scientific facts about human characteristics. The term covers all biomedical and psychosocial considerations; it includes, but is not limited to, principles and applications in the areas of human engineering, personnel selection, training, life support, job performance aids, work loads, and human performance evaluation.														X	
Human Factors Integration	HFI	The current term for MANPRINT. A comprehensive management and technical effort to assure total system effectiveness by continuous integration into materiel development and acquisition of all relevant information concerning manpower, personnel, training, human factors engineering, system safety and health hazards. Therefore, it is the recognition of the capabilities and limitations of the personnel who operate, maintain and support an equipment, making this an important consideration when designing or selecting hardware. MANPRINT achieves this objective by focusing attention on user performance as an integral part of total system performance and emphasizing front end planning to achieve an optimum user material system balance during the acquisition process.	X														
Incremental Development		The process in which a desired capability is identified, an end-state requirement is known, and that requirement is met over time by developing several increments, each dependent on available mature technology.															DoD 5000.2 Operation of the Defense Acquisition System 12, May 2003, http://akss.dau.mil/dapc/index.html.
Inherent Availability	A_I	The availability of a system with respect only to operating time and corrective maintenance. A_I ignores standby and delay times associated with preventive maintenance as well as Mean Logistics Delay Time (MLDT) and may be calculated as the ratio of Mean Time Between Failure (MTBF) divided by the sum of MTBF and Mean Time To Repair (MTTR), that is A_I = MTBF/(MTBF+MTTR).															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Inherent Availability	Ai	A measure of availability that includes only the effects of an item design and its application, and does not account for effects of the operational and support environment. Sometimes referred to as "intrinsic" availability.														X	
Inherent Level of Reliability and Safety		That level which is built into the unit and, therefore, inherent in its design. This is the highest level of reliability and safety that can be expected from a unit, system, or aircraft if it receives effective maintenance To achieve higher levels of reliability generally requires modification or redesign.													X		

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Inherent Maintainability		The maintainability potential present in a design, i.e. the maintainability which is dependent solely on the quality of design and assumes perfect quality of manufacture and correct use in the field.								X							
Inherent Reliability		The reliability potential present in a design, i.e. the reliability which is dependent solely on the quality of design and assumes perfect quality of manufacture and correct use in the field.								X							
Inherent Reliability and Maintainability Value		A measure of reliability or maintainability that includes only the effects of an item's design and application, and assumes an ideal operating and support environment.														X	
Inspection		Check for conformity (fulfilment by a product, process or service of specifications) by measuring, observing, testing or gauging the relevant characteristics of an item. Note: Generally inspection can be carried out before, during or after other maintenance activity.											X				
Inspection		The process of systematically examining, checking and testing aircraft structural members, components and systems, to detect actual or potential unserviceable conditions.								X							
Inspection – Detailed	DET	An intensive examination of a specific item, installation or assembly to detect damage, failure or irregularity. Available lighting is normally supplemented with a direct source of good lighting at an intensity deemed appropriate. Inspection aids such as mirrors, magnifying lenses, etc., may be necessary. Surface cleaning and elaborate access procedures may be required.													X		
Inspection – General Visual	GVI	A visual examination of an interior or exterior area, installation or assembly to detect obvious damage, failure or irregularity. This level of inspection is made from within touching distance unless otherwise specified. A mirror may be necessary to enhance visual access to all exposed surfaces in the inspection area. This level of inspection is made under normally available lighting conditions such as daylight, hangar lighting, flashlight or drop-light and may require removal or opening of access panels or doors. Stands, ladders or platforms may be required to gain proximity to the area being checked.													X		
Inspection – Special Detailed	SDI	An intensive examination of a specific item, installation, or assembly to detect damage, failure or irregularity. The examination is likely to make extensive use of specialized Inspection Techniques and/or equipment. Intricate cleaning and substantial access or disassembly procedure may be required.													X		

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Inspection – Zonal		A collective term comprising selected general visual inspections and visual checks that is applied to each zone, defined by access and area, to check system and powerplant installations and structure for security and general condition.													X		
Integrated Diagnostics		A structured process which maximizes the effectiveness of diagnostics by integrating pertinent elements, such as testability, automatic and manual testing, training, maintenance aiding, and technical information as a means for providing a cost effective capability to unambiguously detect and isolate all faults known or expected in items and to satisfy system mission requirements. Products of this process are hardware, software, documentation, and trained personnel.														X	
Integrated Logistic Support	ILS	A disciplined management approach, affecting the Central Customer, Customer 2, the IPT and industry, aimed at optimizing equipment Life-Cycle Costs (LCC). It includes elements for influencing equipment design and determining support requirements to achieve supportable and supported equipment. ILS provides the disciplines for ensuring that supportability and cost factors are identified and considered from concept and throughout the life of an equipment, with the aim of optimizing the LCC. While ILS and R&M are distinct disciplines, they must be closely co-ordinated. The overall Project Management Plan shall recognise the working relationship between ILS and R&M activities and ensure that the outputs from the R&M activities, required as inputs to ILS, are identified and scheduled to be available in time to allow the support considerations to influence the design and trade-off analysis.	X														
Integrated Logistics Support	ILS	A methodology developed to identify and optimise Whole Life Costs (WLC) of system ownership, which uses a structured analysis of supportability throughout a project's life – developed in response to escalating costs and financial constraints of equipment ownership encountered by the MOD. The Chief of Defence Procurement (CDP) mandated its application on 22 November 1993 (see CDP 115/9). Application of ILS has also been mandated by the Defence Logistics Organisation (DLO) through the Support Solutions Envelope (SSE) and it is MOD Policy that the principles of ILS are to be applied to every project throughout its entire life.		X													

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Integrated Logistics Support (cont'd)	ILS	By analysing the equipment support requirements in a structured manner it is possible to identify and then reduce major cost drivers for In-Service support. Using ILS will improve supportability, reduce WLC and improve availability.		X													
Integrated Logistics Support	ILS	A disciplined, unified, and iterative approach to the management and technical activities necessary to: a) Cause support considerations to influence both requirements and design. b) Define the support requirements that are optimally related to the design and to each other. c) Acquire that required support. d) Provide the required support over the life cycle of the equipment at lowest possible cost.							X								
Integrated Logistics Support	ILS	A unified and iterative approach to the management and technical activities needed to: • Influence operational and materiel requirements, system specifications, and ultimate design or selection (in the case of commercial and NDI (Non-Developmental Items). • Define the support requirements best related to system design and to each other. • Develop and acquire the required support. • Provide required operational phase support for best value. • Seek performance, readiness and LCC improvements during all phases of the Program in order to meet requirements. • Repeatedly examine support requirements throughout the in-service life of the System.															Dipl. Ing. Matthias Buderath (EADS Military Air Systems), 2006.
Integrated Logistics Support Elements	ILS Elemen ts	The disciplines and elements of ILS, as defined by the ILS Defence Standard(Def Stan) 00-60, are listed below: • Logistic Support Analysis (LSA). • Maintenance Planning. • Supply Support. • Obsolescence. • Manpower and Human Factors. • Whole Life Costs. • Support and Test Equipment (S&TE). • Reliability and Maintainability (R&M), Safety, Testability and other design disciplines. • Facilities. • Training and Training Equipment. • Technical Documentation. • Packaging, Handling, Storage and Transportation (PHS&T).	X	X													

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Integrated Logistics Support Elements (cont'd)	ILS Elements	• Software Support. • Configuration Management. • Disposal.	X	X													
Integrated Product and Process Development	IPPD	IPPD is the DoD management technique that simultaneously integrates all essential acquisition activities through the use of multi-disciplinary teams to optimize design, manufacturing, and supportability processes. One of the key IPPD tenets is multi-disciplinary teamwork through Integrated Product Teams. IPPD facilitates meeting cost and performance objectives from product concept through production, including field support. The 10 tenets of IPPD can be summarized into the following 5 principles: • Customer Focus. • Concurrent Development of Products and Processes. • Early and Continuous Life-Cycle Planning. • Proactive Identification and Management of Risk. • Maximum Flexibility for Optimization and Use of Contractor Approaches.															DoD Acquisition Guidebook Chapter 11.8, http://akss.dau.mil/dapc/index.html.
Integrated Product Team	IPT	Integrated Product Teams (IPTs) are the means through which IPPD is implemented. They are its fundamental building blocks. These cross-functional teams are formed for the specific purpose of delivering a product for an external or internal customer.				X											
Integrated Product Team	IPT	A concurrent engineering team made up of individuals representing all relevant disciplines associated with a product's design, manufacturing, and marketing. All members work together using shared knowledge and capabilities to develop and manufacture a product in which requirements are balanced. The individuals must be committed to a common purpose, work to a unified set of requirements, and hold themselves accountable for decisions made and actions taken.														X	
Integrated Project Team	IPT	The body responsible for managing a project from Concept to Disposal. Its main tasks include developing the SRD, devising equipment solutions to meet that requirement, and managing the acquisition and in-service support of the equipment. The SMART Acquisition IPT is characterised by its 'cradle to grave' responsibility, its inclusion of all the skills necessary to manage its project, and its effective and empowered leader.	X														
Integrated Systems Health Management	ISHM	Efficient asset management through advanced design, monitoring, prognostics and maintenance practices.															AVT-126 Technical Team.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Integrated Vehicle Health Management	IVHM	Integrated Vehicle Health Management enables the health of a vehicle to be monitored and assessed. Sensors distributed throughout the vehicle collect data on the condition of components and sub-systems, while on-board processors assess their health and predict possible deterioration and future life. This data and resulting information can be used to improve maintenance, extend the life of both the whole vehicle and individual components, improve vehicle readiness and availability, and reduce operating costs. For any operator, use of IVHM can provide long-term cost benefits and advantages over competitors. IVHM is suited to high-technology, high-value vehicles such as aircraft, shipping, high-speed trains and high-performance cars, but can be applied to any vehicle or complex system. It will take existing concepts of Maintenance and Repair and Overhaul (MRO) one step further. It differs from those concepts in that it looks at the whole vehicle, regularly sensing and evaluating the vehicle operation and updating a ground-based operations control centre to enable better decisions on the operation schedule and effectiveness of a fleet of vehicles.															Cranfield University, IVHM Centre of Excellence, UK, http://www.cranfield.ac.uk/news/pressreleases/2007/page8835.jsp.
Interactive Electronic Technical Publication	IETP	An Interactive Electronic Technical Publication provides a technical publication which is prepared and delivered in digital format, designed for display in a standardized form on visual display unit. It consists of the Final Publication Data Base, with all the necessary links implemented and the output formatting instructions incorporated. IETP-Linear (IETP-L). A linear structured IETP (i.e. not formed from a hierarchically structured data base) which provides interactive display of information, through the use of SGML tagging and hypertext links. IETP-Database (IETP-D). A hierarchically structured IETP which is specifically authored into and built from a relational or object oriented data base, to provide interactive display of information. IETP-Integrated (IETP-I). An integrated IETP which is designed to present data from several processes / data base sources, such as; expert systems, diagnostics, and computer-based training for the interactive provision of information. WEB-HTML – A representation of the document instances, converted to Hypertext Mark-up Language (HTML) to enable viewing through native web browsers. Note: These are the four discrete types detailed in AECMA S1000D.	X	C													

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Interoperability		The ability of systems, units, or forces to provide services to, and accept services from, other systems, units, or forces and to use the services so exchanged to enable them to operate effectively together.	X			X											
Interoperability		The ability of Alliance forces and, when appropriate, forces of Partner and other Nations to train, exercise and operate effectively together in the execution of assigned missions and tasks. (4/10/2000)									X						
Interval (Initial – Repeat)		Initial Interval – Interval between the start of service-life and the first task accomplishment. Repeat – The interval (after the initial interval) between successive accomplishments of a specific maintenance task.													X		
Intrinsic Availability		The probability that the system/equipment is operating satisfactorily at any point in time when used under stated conditions, where the time considered is operating time and repair time (active). Thus, intrinsic availability excludes from consideration all free time, storage time, administrative delay time and logistic delay time.								X							
Item		Any level of hardware assembly (i.e. system, sub-system, module, accessory, component, unit, part, etc.).													X		
Joint Advanced Health and Usage Monitoring System	JAHUMS	A joint US Navy and Army program to support a dynamic change in maintenance philosophy for DoD helicopters.															Haas, D.J. (NSWC, Carderock) and Baker, T. (USAAMCOM(AATD), Fort Eustis), "JAHUMS ACTD", Briefing to the OSD MTSSG, 19 October 2004.
Key Equipment		A key equipment is a system or item of equipment which is essential for operations and for which availability must be maintained. With large, complex equipment, it is probable that surging to meet realistic emergency timescales will be difficult to achieve. In such instances, major sub-assemblies should be considered key equipments and the methodology applied on that basis.	X														
Knowledge-Based System		See Expert System.															
Latent Fault		An existing fault that has not yet been detected.											X				

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Lead-the-Fleet	LTF	A systems approach to proactively solving sustainment issues based on equipment condition and planned usage. Additional Notes: The program is critical to (the US Army's) Aviation Logistics Transformation and to the Army's successful transition to Condition-Based Maintenance and 2-Level Maintenance. It grew out of pilot projects during 1986 – 1995 that generated $100M in O&S costs savings. The program was re-instituted in 2002. The referenced report analyzes the current program and recommends improvements.															Gorak, M. and Kwinn, Jr., M., "Lead-the-Fleet: Transitioning Army Aviation Maintenance From a Time Based System to a Usage Based System", US Army Operations Research Center of Excellence Technical Report DSE-TR-0406 DTIC #:ADA426343, June 2004.
Lean		Lean production is aimed at the elimination of waste in every area of production including customer relations, product design, supplier networks and factory management. Its goal is to incorporate less human effort, less inventory, less time to develop products, and less space to become highly responsive to customer demand while producing top quality products in the most efficient and economical manner possible.															The Production System Design Laboratory (PSD), Massachusetts Institute of Technology IMIT), http://LEAN2.MIT.EDU.
Lean		SAE J4000 is a tool to identify and measure best practice in the implementation of lean operation in a manufacturing organization. Implementation of lean operation is defined as the process of eliminating waste exhibited in an organization's value stream.															SAE J4000: Identification and Measurement of Best Practice in Implementation of Lean Operation (August 1999).
Level of Repair Analysis	LORA	A systematic procedure to determine the cost of alternative maintenance options, taking into account such variables as spares support, ground equipment and manpower cost. An element of the ILS process.	X					C	C								
Life Cycle		Time interval that commences with the initiation of the concept and terminates with the disposal of the item.											X				
Life-Cycle Cost	LCC	A total cost reflecting not only the acquisition and development costs but also the operational and support costs throughout the life of the equipment. It is not possible to give an accurate mathematical definition as these vary between life-cycle models. However, the definition of a particular model to be used in calculating LCC should be agreed by all parties before accepting the results.	X														

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Life-Cycle Cost	LCC	The sum total of the direct, indirect, recurring, non-recurring and other related costs incurred, or estimated to be incurred, in the design, development, production, operations, maintenance, support and disposal of a major system over its anticipated useful life span.								X							
Life-Cycle Cost		All of the costs generated during the life cycle of the item. Note: For a user or an owner, the total life-cycle cost may include costs pertaining to acquisition, operation maintenance and disposal.											X				
Life-Cycle Model		A framework of processes and activities concerned with the life cycle, which also acts as a common reference for communication and understanding.										X					
Life-Cycle Phases		The identifiable stages in the life of a product from the development of the first concept to removing the product from service and disposing of it. Within the Department of Defense, four phases are formally defined: Concept Exploration; Program Definition and Risk Reduction; Engineering and Manufacturing Development; and Production, Deployment, and Operational Support. Although not defined as a phase, Demilitarization and Disposal is defined as those activities conducted at the end of a product's useful life. Within the commercial sector, various ways of dividing the life cycle into phases are used. One way is: Customer Need Analysis, Design and Development, Production and Construction, Operation and Maintenance, and Retirement and Phase-out.														X	
Life Limit (Aircraft Engines)		An operational service exposure limit characterized by the application of a finite number of flights or flight cycles. It is equal to the minimum number of flight cycles required to initiate a crack equal to approximately 0.30 inches in length.															FAA Advisory Circular (Draft) AC 33.70-Y, "Engine Life Limited Parts Requirements", 2007.
Life Limited Item	LLI	An item that has a limited and predictable useful life and could be considered for replacement on a pre-planned basis for reliability, safety or economic reasons.	X							X							
Life Management (Aircraft Engines)		A series of interrelated engineering, manufacturing, and service support activities that ensure that life-limited engine parts are removed from service prior to the development of a hazardous condition.															FAA Advisory Circular (Draft) AC 33.70-Y, "Engine Life Limited Parts Requirements", 2007.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Life Policy		The policy whereby items are deemed to have a limited life, and which determines the replacement of the items on a pre-planned basis for durability, reliability, safety or economic reasons. The period of limited life can include periods of storage as well as Service use.			X												
Line of Maintenance		An echelon in an organisation where specified levels of maintenance are to be carried out on an item. Note 1: Examples of maintenance echelons are: field, repair shop, manufacturer. Note 2: The maintenance echelon is characterised by the skill of the personnel, the facilities available, the location, etc.								X							
Line of Maintenance		Position in an organization where specified levels of maintenance are to be carried out on an item. Note 1: Examples of line of maintenance are: field, repair shop, manufacturer. Note 2: The lines of maintenance are characterized by the skill of the personnel, the facilities available, the location, etc. Note 3: The levels of maintenance are characterized by the complexity of the maintenance task.											X				
Line Replaceable Item (UK RAF Use)	LRI	Any functional item which can be removed from the equipment as part of a single maintenance action.			X												
Line Replaceable Unit	LRU	A unit designed to be removed upon failure from a larger entity (product or item) in the operational environment, normally at the organizational level.														X	
Line Replaceable Unit (NATO ARMP-7 Use)	LRU	A unit designated to be removed upon failure from a larger entity (equipment, system) in the operational environment.								X							
Line Replaceable Unit (UK Army Use)	LRU	An assembly or unit, normally incorporating sub-assemblies or modules mounted together and designed for ease of replacement (normally at the Service operating unit) as an entity and which can be provisioned separately.			X												
Logistic Delay		The accumulated time during which maintenance cannot be carried out due to the necessity to acquire maintenance resources, excluding any administrative delay.											X				

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Logistics		The science of planning and carrying out the movement and maintenance of forces. In its most comprehensive sense, those aspects of military operations which deal with: a) Design and development, acquisition, storage, movement, distribution, maintenance, evacuation and disposition of materiel. b) Movement, evacuation and hospitalisation of personnel. c) Acquisition or construction, maintenance, operation and disposition of facilities. d) Acquisition of furnishing of services.								X	X						
Logistics Support Analysis	LSA	The selective application of scientific and engineering analyses, during the system engineering and design process to assist in complying with supportability and other ILS objectives.	X														
Logistics Support Analysis	LSA	A supportability analysis that is conducted iteratively, as an integral part of the design process, with the aim of influencing the design by stimulating trade-off decisions to optimise WLC. An element of the ILS process.		X													
Logistics Support Analysis	LSA	A disciplined approach to the activities necessary to: a) Cause support considerations to be integrated into system and equipment design. b) Develop support requirements that are consistently related to design and to each other. c) Acquire the required support. d) Provide the required support during the operational phase at minimum cost.						X	C								
Logistics Support Analysis	LSA	The selective application of scientific and engineering efforts undertaken during the acquisition process, to assist in causing support considerations to influence design; defining support requirements that are related optimally to design and to each other; acquiring the required support; and providing the required support during the in-service phase at the lowest possible cost.						C	X								
Logistics Support Analysis	LSA	The selective application of scientific and engineering efforts undertaken during the acquisition process, as part of the system engineering and design process, to assist in complying with supportability and other ILS objectives.						X									

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Logistics Support Analysis		The selective application of scientific and engineering efforts undertaken during the acquisition process, as part of the system engineering process, to assist in: a) Causing support considerations to influence design. b) Defining support requirements that are related optimally to design and to each other. c) Acquiring the required support. d) Providing the required support during the operational phase at minimum cost. During the later production and in-service phase LSA is conducted on a repetitive basis in order to meet life-cycle costs, readiness and supportability objectives. (ALP 10)								X							
Logistics Support Analysis Candidate Items	LSA CI	LSA CI are those parts of a system which may impact on support or supportability considerations (i.e. – maintenance, supply, S&TE, R&M, safety, testability, facilities, manpower and human factors, training, documentation, PHS&T and disposal).		X													
Logistics Support Analysis Record	LSAR	That portion of LSA documentation consisting of detailed data pertaining to the identification of logistic support resource requirements of an equipment.	X														
Long Lead Time Items	LLTI	The materials or component parts of an equipment which, because of the time taken to procure them, need to be ordered in advance of the main item in order to meet a stated delivery date for the main item.	X														
Low Cycle Fatigue (Aircraft Engines)	LCF	The process of progressive and permanent local structural deterioration occurring in a material subject to cyclic variations in stress and strain of sufficient magnitude and number of repetitions. The process will culminate in a detectable crack initiation typically within 10E+05 cycles. A detectable crack initiation is defined as 0.030 inches in length by 0.015 inches in depth.															FAA Advisory Circular (Draft) AC 33.70-Y, “Engine Life Limited Parts Requirements”, 2007.
Lowest Replaceable Assembly (UK RN Use)	LRA	A sub-assembly, sub-unit or item consisting of a number of components mounted together (e.g. on a sub-chassis in or on the outside of a unit) which can be removed for repair or replacement.			X												
Lubrication and Servicing		Any act of lubricating or servicing for the purpose of maintaining inherent design capabilities.													X		

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Lubrication Task (RCM)	L Task	The periodic application of a lubricant to items that require lubrication for proper operation or to prevent premature functional failures. Note: The replenishment or reapplication of Corrosion Preventive Compounds (CPC) can in most cases be regarded as a Servicing or a Lubrication task.					X										
Maintainability		The ability of an item under stated conditions of use, to be retained in or restored to a specified condition when maintenance is performed by personnel having specified skill levels under stated conditions and using prescribed procedures and resources.	X														
Maintainability		The ability of a machine or part of a system to be retained in, or restored to, a state in which it can perform the required function(s).															ISO 13372:2004(E), “Condition Monitoring and Diagnostics of Machines – Vocabulary”.
Maintainability		The ability of a system to be repaired and restored to service when maintenance is conducted by personnel using specified skill levels and prescribed procedures and resources.															“Designing and Assessing Supportability in DOD Weapon Systems: A Guide to Increased Reliability and Reduced Logistics Footprint”, Office of the Secretary of Defense, 24 October 2003.
Maintainability		The measure of the ability of an item to be retained in, or restored to, specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each specified level of maintenance and repair.				X		X	X								
Maintainability		The probability that a given maintenance action, for an item under given conditions of use, can be carried out within a stated time interval, when the maintenance is performed under stated conditions and using stated procedures and resources. The term “Maintainability” is also used to denote the maintainability performance quantified by this probability. (IEC-50 (191))								X							
Maintainability		The ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources.											X				

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Maintainability		The relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair. Also, the probability that an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.														X	
Maintainability – Inherent		See Inherent Maintainability.								X							
Maintenance		The combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.											X				
Maintenance		All actions necessary for retaining an item in or restoring it to a specified condition.														X	
Maintenance – 1st Line		Maintenance performed on or near the flight line.															AVT-144 Technical Team.
Maintenance – 2nd Line		Maintenance performed at the operating base but away from the flight line or off the aircraft.															AVT-144 Technical Team.
Maintenance – 3rd Line		Maintenance performed at a military base requiring resources not available at 2nd Line.															AVT-144 Technical Team.
Maintenance – 4th Line		Maintenance performed at a contractor's facilities.															AVT-144 Technical Team.
Maintenance – Corrective		See Corrective Maintenance.															
Maintenance – Depot Level		Maintenance performed at a military base or contractor's facilities requiring resources not available at Intermediate Level.															AVT-144 Technical Team.
Maintenance – Depth A (RN and RAF Term)		Maintenance directly concerned with day-to-day preparation. It may include such operations as functional testing, replenishment, servicing, re-arming, role changing, minor modification, fault diagnosis and corrective maintenance by replacement, adjustment or minor repair.			X												
Maintenance – Depth B (RN and RAF Term)		Maintenance that is required on items and assemblies that are temporarily unserviceable, in an unacceptable condition, require servicing or preventive maintenance. This may include scheduled maintenance, embodiment of prescribed modifications, bay maintenance of assemblies and corrective maintenance beyond depth A; but within generally provisioned resources.			X												

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Maintenance – Depth C (RN and RAF Term)		Maintenance that is the repair, partial reconditioning and modification requiring special skills, special equipment or relatively infrequently used capabilities that are not economic to provide generally, but which is short of complete strip, reconditioning and reassembly.			X												
Maintenance – Depth D (RN and RAF Term)		Maintenance that is full reconditioning, major conversion or such repair that involves work of this depth/level.			X												
Maintenance – Flight Line Level		Maintenance performed on or near the flight line.															AVT-144 Technical Team.
Maintenance – Intermediate Level		Maintenance performed at the operating base but away from the flight line or off the aircraft.															AVT-144 Technical Team.
Maintenance – Organisational Level		Maintenance performed at the operating base.															AVT-144 Technical Team.
Maintenance – Predetermined		See Pre-Determined Maintenance.															
Maintenance – Predictive		See Predictive Maintenance.															
Maintenance – Preventive		See Preventive Maintenance.															
Maintenance – Proactive		See Proactive Maintenance.															
Maintenance – Scheduled		See Scheduled Maintenance.															
Maintenance – Unscheduled		See Unscheduled Maintenance.															
Maintenance (Materiel)		1) All action taken to retain materiel in a serviceable condition or to restore it to serviceability. It includes inspection, testing, servicing, classification as to serviceability, repair, rebuilding, and reclamation. 2) All supply and repair action taken to keep a force in condition to carry out its mission. 3) The routine recurring work required to keep a facility (plant, building, structure, ground facility, utility system, or other real property) in such condition that it may be continuously used at its original or designed capacity and efficiency for its intended purpose.			C					X	X						Joint Publication 1-02 (JP 1-02), "United States Department of Defense Dictionary of Military and Associated Terms", 31 August 2005.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Maintenance Concept		A narrative description identifying the broad, planned approach to be employed in sustaining the system/equipment at a defined level of readiness or in a specified condition in support of the operational requirement. Provides the basis for the maintenance plan.						X	X								
Maintenance Concept		A description of the planned general scheme for maintenance and support of an item in the operational environment. The maintenance concept provides the practical basis for design, layout and packaging of the system and its test equipment and establishes the scope of maintenance responsibility for each level (echelon) of maintenance and the personnel resources (maintenance manning and skill levels) required to maintain the system.								X							
Maintenance Critical Part (Aircraft Structure)		A structural component whose failure will not cause a safety-of-flight condition but is sized by durability requirements and would not be economical to repair or replace.															Mil-Std-1530C (USAF) “Aircraft Structural Integrity Program (ASIP)”, 1 November 1995.
Maintenance Down Time		The interval between the time a system/equipment is made available for preventive or corrective maintenance until that maintenance action is successfully completed.								X							
Maintenance Effectiveness		The ratio between the maintenance performance target and the actual result.											X				

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Maintenance Free Operating Period	MFOP	A period of operation during which the system must be able to carry out all its assigned missions without any maintenance action and without the operator being restricted in any way due to system faults or limitation. Note: As at 1999, the M-FOP concept was being developed by the Society of British Aerospace Companies (SBAC) Foresight Action Initiative. It was intended as a potential alternative or complement to MTBF as a metric for the specification of reliability requirements. It shifts the focus from a purely statistical metric of reliability to one that might be more useful from a practical operational standpoint. A status update on this work is needed. Editor's Note: See also Failure Free Operating Period and Fault Free Period of Operation.															Mitchell, P. (RAF), "What the Customer Wants Maintenance-Free and Failure-Free Operating Periods to Improve Overall System Availability and Reliability", RTO-MP-037, September 2000. Hockley, C.J. (Royal Military College of Science, Shrivenham, UK), "Design for Success", Institution of Mechanical Engineers Journal of Aerospace Engineering, Vol. 212, No. 6, pp. 371-378, 1998. Staff Target (Air) ST(A). Definition used in the ST(A) for the replacement for the Tornado aircraft. (See Hockley 1998)
Maintenance Free Operating Period	MFOP	A period during which the equipment shall operate without failure and without the need for any maintenance; however, faults and minor planned contractually agreed maintenance are permissible.															Hockley, C.J. (Royal Military College of Science, Shrivenham, UK), "Maintenance Free Periods of Operation – The Holy Grail?", NATO RTO AVT-144 Workshop, Lithuania, October 2006, Paper 4.8. M-FOP definition agreed by MOD CODERM Track 1 Sub-Group on 6 August 1999.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Maintenance Levels		The basic levels of maintenance into which all maintenance activities are divided. The scope of maintenance performed within each level can only be equal with the personnel, equipment, technical data and facilities available.	X														
Maintenance Planning		The planning and analysis required to define the maintenance resources required to support a system throughout its life cycle. This includes the definition of maintenance tasks, levels of maintenance and repair, and LCC.						X	X								
Maintenance Planning		The process conducted to evolve and establish maintenance concepts and requirements for a material system. One of the principle elements of ILS.	X	C													
Maintenance Recovery Period	MRP	The time spent carrying out maintenance after an M-FOP has elapsed. The maintenance done should be enough to ensure that the equipment can start another M-FOP cycle.															Hockley, C.J. (Royal Military College of Science, Shrivenham, UK), "Maintenance Free Periods of Operation – The Holy Grail?", NATO RTO AVT-144 Workshop, Lithuania, October 2006. MRP definition agreed by MOD CODERM Track 1 Sub-Group on 6 August 1999.
Maintenance Recovery Period	MRP	A period during which all maintenance actions necessary to recover a weapon system to a state whereby it can complete the next M-FOP. The length and content of the MRP would be directly related to the length of the previous M-FOP and the required length of the subsequent M-FOP.															Mitchell, P. (RAF), "What the Customer Wants Maintenance-Free and Failure-Free Operating Periods to Improve Overall System Availability and Reliability", RTO-MP-037, September 2000.
Maintenance Significant Item	MSI	Those items identified by the manufacturer whose failure: a) Could affect safety (on ground or in flight); and/or b) Is undetectable during operations; and/or c) Could have significant operational impact; and/or d) Could have significant economic impact.													X		
Maintenance Support		The resources, services and management necessary to carry out maintenance.											X				

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Maintenance Support Efficiency		The ratio between the planned or expected resources necessary to fulfil the required maintenance task and the resources actually used.											X				
Maintenance Supportability		The ability of a maintenance organization of having the right maintenance support at the necessary place to perform the required maintenance activity at a given instant of time or during a given time interval.											X				
Maintenance Task		A composite of related activities (perceptions, decisions and responses) performed for an immediate purpose, written in operator/ maintainer language, e.g. change tyre. Editor's Note: See Def-Stan 00-60 definition of Task Classifications.	X														
Maintenance Task		The maintenance effort necessary for retaining an item in, or changing/restoring it to a specified condition.														X	
Maintenance Tasks		An action or set of actions required to achieve a desired outcome which restores an item to or maintains an item in serviceable condition, including inspection and determination of condition.													X		
Maintenance Time		The time interval during which a maintenance is carried out on an item either manually or automatically, including technical and logistic delays. Note: Maintenance may be carried out while the item is performing a required function.											X				
Maintenance Transformation		• Real-Time Status of Equipment Material Condition. • Integrated Supply/Maintenance via Serialized Item Management. • Total Asset Visibility. System components: maintenance history; configuration control; RCM data analysis; UID/SIM data bases; battlespace network; condition monitoring and reliability analysis; embedded sensors; linked to warfighters; predictive maintenance; reduced footprints; integrated data bus; maintenance; portable maintenance aids; interactive training and tech support; integrated logistics information; IETMs; troubleshooting and repair; data transfer; anticipatory materiel; on-board diagnostics and prognostics; sense and respond logistics; pedigree management; CBM+; RFID; preventive maintenance.															www.acq.osd.mil/log/mppr/mssg.htm, 2007.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Manpower and Personnel Integration	MANPRINT	A comprehensive management and technical effort to assure total system effectiveness by continuous integration into materiel development and acquisition of all relevant information concerning manpower, personnel, training, human factors engineering, system safety and health hazards. Therefore, it is the recognition of the capabilities and limitations of the personnel who operate, maintain and support an equipment, making this an important consideration when designing or selecting hardware. MANPRINT achieves this objective by focusing attention on user performance as an integral part of total system performance and emphasizing front end planning to achieve an optimum user material system balance during the acquisition process. Current term is HFI.	X														
Markov Chain		A stochastic process on a discrete time basis that has finite or a denumerable number of infinite states and in which the probabilities of occurrence of future states depend only on the present state and not on the history of prior states. A stochastic process is one which can be modelled by a family of random variables (R(t). Editor's Note: Markov Chains are a complex concept. For more detailed information, further references should be sought.								X							
Materiel		All items (including ships, tanks, self-propelled weapons, aircraft, etc., and related spares, repair parts, and support equipment, but excluding real property, installations, and utilities) necessary to equip, operate, maintain, and support military activities without distinction as to its application for administrative or combat purposes. Note: See also Equipment and Personal Property.			C					C							Joint Publication JP 1-02, "Dictionary of Military and Associated Terms", USA.
Materiel Readiness		The availability of materiel required by a military organization to support its wartime activities or contingencies, disaster relief (flood, earthquake, etc.), or other emergencies.															Joint Publication JP 1-02, "Dictionary of Military and Associated Terms", USA.
Mean Operating Time Between Failures		The mathematical expectation of the operating time between failures.											X				
Mean Time Between Critical Failures	MTBCF	Similar to Mean Time Between Failures except that only critical failures are counted. It is a measure of expected time between critical failures.								X							

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Mean Time Between Failures	MTBF	The total functional life of a population of an item divided by the total number or failures within the population – for a particular interval. The definition holds for time, rounds, miles, events, or other measures of life units.						X	X	C							
Mean Time Between Failures		The mathematical expectation of the time between failures.											X				
Mean Time To Failure	MTTF	A measure of the expected life till failure. Similar to Mean Time Between Failure but applies to non-repairable systems. It can be estimated by dividing the total number of failures within a population into the total number of life units of the population during a stated period under stated conditions.								X							
Mean Time To Repair	MTTR	The total elapsed time (clock hours) for corrective maintenance divided by the total number of corrective maintenance actions during a given period of time.						X	X	C							
Measure of Effectiveness	MOE	A measure designed to correspond to accomplishment of mission objectives and achievement of desired results. (CJCSI 3170.01E) MOEs may be further decomposed into Measures of Performance and Measures of Suitability.															US DoD Defense Acquisition University, “Glossary of Defence Acquisition Acronyms and Terms”, Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Measure of Performance		A measure of a system’s performance expressed as speed, payload, range, time on station, frequency, or other distinctly quantifiable performance features. Several MOPs and/or Measures of Suitability may be related to the achievement of a particular Measure of Effectiveness (MOE). Editor’s Note: See Measure of Suitability, Operational Suitability, and Measure of Effectiveness.															US DoD Defense Acquisition University, “Glossary of Defence Acquisition Acronyms and Terms”, Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Measure of Suitability		A measure of an item's ability to be supported in its intended operational environment. MOSs typically relate to readiness or operational availability, and hence reliability, maintainability, and the item's support structure. Several MOSs and/or Measures of Performance may be related to the achievement of a particular Measure of Effectiveness (MOE). Editor's Note: See Measure of Effectiveness and Operational Suitability.															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Micro-Electro-Mechanical-Systems	MEMS	The integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. While the electronics are fabricated using Integrated Circuit (IC) process sequences (e.g. CMOS, Bipolar, or BICMOS processes), the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices. Sensors gather information from the environment through measuring mechanical, thermal, biological, chemical, optical, and magnetic phenomena. The electronics then process the information. Because MEMS devices are manufactured using batch fabrication techniques similar to those used for integrated circuits, unprecedented levels of functionality, reliability, and sophistication can be placed on a small silicon chip at a relatively low cost.															MEMS Exchange, http://www.memsnet.org/mems/what-is.html.
Milestone Decision Authority	MDA	The designated individual with overall responsibility for a program. The MDA shall have the authority to approve entry of an acquisition program into the next stage of the acquisition process, and shall be accountable for cost, schedule, and performance reporting to higher authority, including Congressional reporting.															DoD Directive 5000.1, "The Defense Acquisition System", 12 May 2003, http://akss.dau.mil/dapc/index.html.
Militarily Useful Capability		A capability that achieves military objectives through operational effectiveness, suitability, and availability, which is interoperable with related systems and processes, transportable, and sustainable when and where needed, and at costs known to be affordable over the long term.															Chairman of the Joint Chiefs of Staff Instruction CJCSI 3170.01, "Joint Capabilities and Integration System (JCIDS)", 1 May 2007.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Minimum Essential Systems Sublist (USAF Air Mobility Command)	MESL	The systems and sub-systems that must be operational for the aircraft to do its assigned missions.															Balaban, H.S. (Institute for Defense Analysis), Brigantic, R.T. et al. (HQ Air Mobility Command), "A Simulation Approach for Estimating Aircraft Mission Capable Rates for the USAF", Proceedings 2000 Winter Simulation Conference.
Mission		1) A clear, concise statement of the task of the command and its purpose. 2) One or more aircraft ordered to accomplish one particular task. (1/8/82)									X						
Mission Capable Rate	MCR	The percentage of possessed hours for aircraft that are Full Mission Capable (FMC) or Partial Mission Capable (PMC) for specific measurement periods (e.g. monthly or annual). Editor's Note: The MCR and related statistics apply only to aircraft in the USAF's primary Aircraft Inventory (PAI). The PAI excludes aircraft that are undergoing maintenance or other work by units other than the operational unit or base. For example aircraft undergoing depot maintenance are excluded, while aircraft undergoing isochronal or home station checks are included.															US Air Force Instruction AFI 21-101, "Aircraft and Equipment Maintenance Management", 29 June 2006, Section 1.15.3 Primary Maintenance Metrics.
Mission Critical System		A system whose operational effectiveness and operational suitability are essential to successful completion or to aggregate residual combat capability. If this system fails, the mission likely will not be completed. Such a system can be an auxiliary or supporting system, as well as a primary mission system.															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Mission Profile		A time-phased description of the events and environments an item experiences from initiation to completion of a specified mission, to include the criteria of mission success or critical failures.	X														
Mission Profile		A time-phased description of the events and environments an item experiences from initiation to completion of a specified mission. It identifies the tasks, events, durations, operating conditions and environments for each phase of a mission.								X						C	

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Mission Profile		A time-phased description of the events and environments experienced by an item during a given mission. The description includes the criteria for mission success and critical failures.								C						X	
Mission Reliability		The ability of an item to perform its required mission critical functions for the duration of a specified mission or life profile. Editor's Note: See also Def-Stan 00-60 definition of Reliability and Basic Reliability.	X														
Mission Reliability		The probability that a system will perform its required mission-critical functions for the duration of a specified mission under conditions stated in the mission profile.															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Mission Reliability		The probability that, having started a mission successfully, the weapon system will complete the mission without failure.						X	X								
Mission Reliability		The measure of the ability of an item to perform its required function for the duration of a specified mission profile. Mission reliability defines the probability that the system will not fail to complete the mission, considering all possible redundant modes of operation.														X	
Mission Reliability		The probability that an item will perform its required functions for the duration of a specified mission profile. Editor's Note: See ARMP-7 Mission Profile.						C	C	X							
Model-Based Reasoning	MBR	The use of explicit models to aid intelligent reasoning processes in achieving set goals within such domains as diagnosis, explanation, and training.															Vachtsevanos, G., Lewis, F., Roemer, M., Hess, A., and Wu, B., "Intelligent Fault Diagnosis and Prognosis for Engineering Systems (Chapter 5)", John Wiley & Sons Inc., 2006.
Modification		An authorized alteration of a design or equipment.	X														

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Modification		The combination of all technical, administrative and managerial actions intended to change the function of an item. Note 1: Modification does not mean replacement by an equivalent item. Note 2: Modification is not a maintenance action but has to do with changing the required function of an item to a new required function. The changes may have an influence on the dependability or on the performance. Note 3: Modification may be allocated to the maintenance organization.											X				
Monitoring		Activity, performed either manually or automatically, intended to observe the actual state of an item. Note 1: Monitoring is distinguished from inspection in that it is used to evaluate any changes in the parameters of the item with time. Note 2: Monitoring may be continuous, over time interval or after a given number of operations. Note 3: Monitoring is usually carried out in the operating state. Editor's Note: See also EN 13306 and ISO 13372 definitions of CBM.											X				
Monte Carlo Computer Simulation Techniques		A method utilising random sampling to obtain inputs for computer simulation trials and obtaining approximate solutions in terms of a range of values each of which has a calculated probability of being the solution to the problem. Note: This is a complex concept. For more detailed information further references should be sought.								X							
Multiple Failure		An event that occurs if a protected function fails while its protective device or protective system is in a failed state. Editor's Note: See also Protective Device or System.												X			
Net-centric		Relating to or representing the attributes of a net-centric environment. A net-centric environment is a robust, globally interconnected network environment (including infrastructure, systems, processes, and people) in which data is shared timely and seamlessly among users, applications, and platforms. A net-centric environment enables substantially improved military situational awareness and significantly shortened decision-making cycles.															Chairman of the Joint Chiefs of Staff Instruction CJCSI 3170.01, "Joint Capabilities and Integration System (JCIDS)", 1 May 2007.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Non-Destructive Evaluation	NDE	Same as NDI.															AVT-144 Technical Team.
Non-Destructive Inspection	NDI	This term usually means the inspection of a structural component in any aircraft system without causing permanent damage or degradation of the component or any other component. The inspection may be performed with or without the help of inspection equipment, and includes unaided visual inspection. For the purposes of AVT-144, the terms “Non-Destructive Evaluation (NDE)” and “Non-Destructive Test (NDT}”, will be considered synonymous with NDI, unless stated otherwise.															AVT-144 Technical Team.
Non-Destructive Inspection	NDI	Any method used for inspecting an item without physically, chemically, or otherwise destroying or changing the design characteristics of the item. However, it may be necessary to remove paint or other external coatings to use the NDI method. A wide range of technology is usually described as non-destructive inspection, evaluation, or testing (collectively referred to as Non-Destructive Evaluation or NDE). The core of NDE is commonly thought to contain ultrasonic, visual, radiographic, eddy current, liquid penetrant, and magnetic particle inspection methods. Other methodologies, include acoustic emission, use of laser interference, microwaves, magnetic resonance imaging, thermal imaging, and so forth.														X	
Non-Destructive Inspection	NDI	The examination of a material to determine geometry, damage or composition, by using technology that does not affect its future usefulness: involves a high degree of human interaction; local focussed inspections; requires access to area of interest; time-based monitoring – applied at predetermined intervals; portable and applied to numerous areas. Editor’s Note: See also Roach Definition of SHM.															Roach, D., Rackow, K., DeLong, W., Yepez, S., Reedy, D. and White, S., “Use of Composite Materials, Health Monitoring and Self Healing Concepts to Refurbish Our Civil and Military Infrastructure”, Sandia National Laboratories Report SAND2007-5547, September 2007.
Non-Destructive Test	NDT	Same as NDI.															AVT-144 Technical Team.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Non-Developmental System/Item	NDI	A generic term that covers equipment available which will meet an approved operational requirement with little or no development effort required by defence organizations. Normally, these sources are commercial products or equipment developed and in use by defence organizations of other Nations. In most cases the equipment has to be adapted, modified or improved to meet the requirements set.	X														
Non-Mission Capable Rate	NMCR	See Mission Capable Rate.															See MCR.
Non-Operating Time		The amount of time that a system/equipment is not operating but assumed to be operable. Non-Operating Time refers only to systems not committed to a specific mission.								X							
Non-Significant Function	NSF	A function whose failure will have no adverse safety, environmental, operational, or economic effects.					X										
N-Version Programming (SW)		A software form of redundancy, involving voting between differently, often independently, developed software units.															Mitchell, P. (RAF), "What the Customer Wants Maintenance-Free and Failure-Free Operating Periods to Improve Overall System Availability and Reliability", RTO-MP-037, September 2000.
Objective (in a specification)		The desired value required in a supportability metric in a system specification.				X											
On Condition Task (RCM)	OC Task	A periodic or continuous inspection designed to detect a potential failure condition and allow correction prior to functional failure. Note: The complexity of on condition tasks ranges from simple visual inspections to complex NDI requiring specialized equipment including imbedded PHM systems. An on condition task is a preventative maintenance task. It contains only the inspection phase of the maintenance evolution. An on condition task allows and item to be left in service until a potential failure is detected, thereby maximizing its useful life while minimizing repair costs and the number of spares required. Also, since an on condition task is normally the least intrusive of the PM task options, the likelihood of inducing damage/ failures is reduced.					X										

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
On-Condition Task (RCM)		A scheduled task used to detect a potential failure. Any on-condition task (or predictive or condition-based or condition monitoring task) that is selected shall satisfy the following additional criteria: 1) There shall exist a clearly defined potential failure. 2) There shall exist an identifiable P-F interval (or failure development period). 3) The task interval shall be less than the shortest likely P-F interval. 4) It shall be physically possible to do the task at intervals less than the P-F interval. 5) The shortest time between the discovery of a potential failure and the occurrence of the functional failure (the P-F interval minus the task interval) shall be long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode.												X			
One-Time Change (RCM)		Any action taken to change the physical configuration of an asset or system (redesign or modification), to change the method used by an operator or maintainer to perform a specific task, to change the operating context of the system, or to change the capability of an operator or maintainer (training).												X			
Operability		The trade-off between availability and operational reliability to minimize operational cost. Operability = Availability*OpReliability/DirectOpCost.															AVT-144 Technical Team (MB).
Operating and Support Costs	O&S Costs	The cost of operation, maintenance and follow-on logistics support of the end item and its associated support systems.	X														
Operating and Maintenance Costs	O&M Costs	The cost of operation, maintenance and follow-on logistics support of the end item and its associated support systems.						X	X								
Operating Time		The time during which the system or equipment is turned on and actively performing at least one of its functions.								X							
Operating Time		The time interval during which an item is performing its required function.											X				
Operational Availability	Ao	See Availability – Operational (Ao).			X					X							

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Operational Availability	A_O	The degree (expressed as a decimal between 0 and 1, or the percentage equivalent) to which one can expect a piece of equipment or weapon system to work properly when it is required, that is, the percent of time the equipment or weapon system is available for use. A_O represents system "uptime" and considers the effect of reliability, maintainability, and mean logistics delay time. A_O may be calculated by dividing Mean Time Between Maintenance by the sum of the Mean Time Between Maintenance, Mean Maintenance Time, and Mean Logistics Delay Time (MLDT), that is, A_O = MTBM / (MTBM + MMT + MLDT). It is the quantitative link between readiness objectives and supportability. Note: See Mean Time Between Maintenance, Mean Maintenance Time, and Mean Logistics Delay Time.															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Operational Availability	OA	The probability that, when used under stated conditions, a system will operate satisfactorily at any time. OA includes standby, administrative, and logistic delay time.						X	X								
Operational Capability		The measure of the results of the mission, given the condition of the systems during the mission (dependability).															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Operational Check		A task to determine that an item is fulfilling its intended purpose. Does not require quantitative tolerances. This is a failure finding task.													X		
Operational Effectiveness		The measure of the overall ability of a system to accomplish a mission when used by representative personnel in the environment planned or expected for operational employment of the system considering organization, doctrine, tactics, supportability, survivability, vulnerability, and threat. (CJSCI 3170.01E)															US DoD Defense Acquisition University, "Glossary of Defence Acquisition Acronyms and Terms", Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Operational Effects		Those failure effects which interfere with the completion of the aircraft mission. These failures cause delays, cancelations, ground or flight interruptions, high drag coefficients, altitude restrictions, etc.													X		

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Operational Readiness		An evaluation of the operational capability and effectiveness of a unit or any portion thereof.									X						
Operational Readiness		The capability of a unit/formation, ship, weapon system, or equipment to perform the missions or functions for which it is organized or designed. May be used in a general sense or to express a level or degree of readiness.															Joint Publication 1-02 (JP 1-02), “United States Department of Defense Dictionary of Military and Associated Terms”, 31 August 2005.
Operational Readiness		The ability of a military unit to respond to its operation plan(s) upon receipt of an operations order. (A function of assigned strength, item availability, status, or supply, training, etc.)														X	
Operational Scenario		An outline projecting a course of action under representative operational conditions for an operational system.						X									
Operational Scenario (for AVT-144 purposes)		A specific combination of mission profiles, sortie rates for each mission profile, geographic location, climate, and enemy action.															AVT-144 Technical Team.
Operational Suitability		The degree to which a system can be placed and sustained satisfactorily in field use with consideration being given to availability, compatibility, transportability, interoperability, reliability, wartime usage rates, maintainability, safety, human factors, habitability, manpower, logistics supportability, natural environmental effects and impacts, documentation, and training requirements. (CJCSI 3170.01E)															US DoD Defense Acquisition University, “Glossary of Defence Acquisition Acronyms and Terms”, Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Other Action (in RCM)		A term used in RCM to indicate that some action (other than PM) is either required or desired to most effectively deal with the consequences of a failure mode.					X										
Other Structure		Structure which is judged not to be a Structural Significant Item (SSI). Other Structure is defined both externally and internally within zonal boundaries.													X		
Overhaul		The effort, usually performed at depot level, when a complete disassembly inspection, rework and reassembly, of an item is required to restore the item to a `like new’ condition.								X							

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Overhaul		A comprehensive set of examinations and actions carried out, in order to maintain the required level of availability and safety of an item. Note 1: Overhaul may be performed at prescribed intervals of time or number of operation. Note 2: Overhaul may require a complete or partial dismantling of the item.											X				
P to F Interval		The interval between the point at which a potential failure becomes detectable and the point at which it degrades into a functional failure.					C							C	X		
Packaging, Handling, Storage and Transportation	PHS&T	The resources, processes, procedures, design considerations and methods to ensure that all systems, equipment and support items are preserved, packaged, handled and transported properly (including: environmental considerations and equipment preservation requirements for short- and long-term storage, and transportability). One of the principle elements of ILS.	X														
Packaging, Handling, Storage and Transportation	PHS&T	The resources, procedures, design considerations and methods necessary to ensure that all system equipment and support items are packaged, handled, stored and transported properly and in conformance with appropriate legislation, particularly for hazardous materials. This includes environmental limitations, equipment preservation requirements for short- and long-term storage and transport requirements.		X				C	C								
Partial Fault		Fault characterized by the fact that an item can only perform some but not all of the required functions. Note: In some cases it may be possible to use the item with reduced performance.											X				
Partial Mission Capable	PMC	A material condition of an aircraft or training device indicating it can perform at least one, but not all, assigned missions.															US Air Force Instruction AFI 21-103, "Equipment Inventory, Status and Utilization Reporting", 14 December 2005, Attachment 2 Maintenance Status Codes and Condition Status Codes.
Performance-Based Acquisition	PBA	Same as PBL.															AVT-144 Technical Team.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Performance-Based Contracting	PBC	Same as PBL.															AVT-144 Technical Team.
Performance-Based Logistics	PBL	A method of contracting for in-service support with organic or commercial organisations in which the required outcomes are expressed quantitatively in supportability metrics. Also known as PBA and PBC.															AVT-144 Technical Team.
Performance-Based Logistics	PBL	Performance-Based Logistics is the acquisition of support as an integrated, affordable, performance package designed to optimize system readiness and meet performance goals for a weapon system through long-term support arrangements with clear lines of authority and responsibility. Performance-based strategies focus on achievement of performance outcomes, not the transactional products or services that enable those outcomes.															JSF Program Office (JSFPO), "Performance Based Agreement Planning", Briefing, May 2005. Quotation in Hawkins, S.T., Major, USAF, "Logging the JSF: Acquisition Logistics and Fleet Management for Modern Fighters", School of Advanced Air and Space Studies Air University, Thesis, 2005.
PF Interval	PF	The interval between Potential Failure and Functional Failure.					X							C	C		
P-F Interval		The interval between the point at which a potential failure becomes detectable and the point at which it degrades into a functional failure (also known as Failure Development Period and Lead Time to Failure).					C							X	C		
Physics-Based Assessment/ Model (in SHM)		An assessment/model that uses mathematical equations that theoretically predict the system behaviour by simulating the actual physical processes that govern the system response. These assessments/models are especially useful for predicting system response to new loading conditions and/or new system configurations (damage states). However, physics-based assessment techniques are typically computationally intensive.															Farrar, C. (Los Alamos National Laboratory) et al., "Damage Prognosis for Aerospace Civil and Mechanical Systems", Daniel J. Inman et al. Editors, Published by Wiley, 2005.
Potential Failure (RCM)		An identifiable condition that indicates that a functional failure is either about to occur or is in the process of occurring.					C							X	C		
Potential Failure (RCM)		A definable and detectable condition that indicates that a functional failure will occur.					X							C	C		

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Potential Failure (RCM)		A defined identifiable condition that indicates that a degradation process is taking place that will lead to a functional failure.					C							C	X		
Potential Failure Interval (RCM)		See P-F Interval.															
Power by the Hour Contracting		A method of performance-based contracting for system acquisition and in-service support in which most of the support, including the provisioning of repair parts and spares, is the responsibility of a commercial prime contractor. Payment is based mainly on the actual usage and availability of the weapon system.															AVT-144 Technical Team. The term "Power by the Hour" is a Rolls Royce trademark.
Pre-Determined Maintenance		Preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation.											X				
Predictive Cause and Effect Modeling		• Description: Development of a cross-cutting model that can assist DoD in identifying the readiness implications of alternative levels of funding for materiel readiness. • Goals: – Identify the critical budget funding categories, by weapon system and major component, that relate to materiel readiness. – Translate operational/mission requirements into weapon system availability goals for SORTS weapon systems. – Develop a system evaluator, reliability evaluator and spares optimization process that can assist in reducing the cost of required weapon system materiel readiness. • Key Features: – Identify critical degraders that contribute most to weapon system "down time". – Identify and evaluate alternative options for achieving required readiness at reduced costs by examining the implications of improvements in the following areas for critical degraders: cycle times and reliability; scheduled maintenance; spares optimization across echelons and indentures; and policies for expedited shipments and global component sharing.															www.acq.osd.mil/log/mppr/mssg.htm.
Predictive Maintenance		Maintenance emphasizing prediction of failure and taking action based on the condition of the equipment to prevent failure or degradation.															ISO 13372:2004(E), "Condition Monitoring and Diagnostics of Machines – Vocabulary".

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Predictive Maintenance		Condition-based maintenance carried out following a forecast derived from the analysis and evaluation of the significant parameters of the degradation of the item. Note: Performance and parameter monitoring may be scheduled, on request, or continuous. Editor's Note: EN 13306 defines CBM as Preventive Maintenance based on performance and/or parameter monitoring and the subsequent actions.											X				
Prescriptive Action		A process to decide what to do about the symptom and doing it.															AVT-126 Technical Team.
Preventive Maintenance		All action performed in an attempt to retain equipment in specified condition by providing systematic inspection, detection and prevention of incipient failures.	X					X	X							X	
Preventive Maintenance		Maintenance performed according to a fixed schedule, or according to a prescribed criterion that detects or prevents degradation of a functional structure, system or component, in order to sustain or extend its useful life.															ISO 13372:2004(E), "Condition Monitoring and Diagnostics of Machines – Vocabulary".
Preventive Maintenance	PM	Actions performed prior to functional failure (multiple failures or demand requirements for hidden failures) to achieve the desired level of safety and reliability for an item. Note: Preventive Maintenance includes the following types of tasks: Servicing, Lubrication, On Condition, Hard Time, Failure Finding.					X										
Preventive Maintenance		Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item. Same as Scheduled Maintenance.								X							
Preventive Maintenance		Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.											X				
Principal Structural Element	PSE	An element that contributes significantly to the carrying of flight, ground, or pressurization loads, and whose integrity is essential in maintaining the overall structural integrity of the airplane. Editor's Note: See also Structural Significant Item.															FAA Advisory Circular, "Damage Tolerance and Fatigue Evaluation of Aircraft Structure", AC 25.571-1C, Dated 29 April 1998.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Principal Structural Element	PSE	Any element which contributes significantly to carrying flight, ground, pressure, or control loads, and whose consequence of failure is catastrophic.													X		Definition in Section 2-4-1 of MSG-3.
Private Finance Initiative (GBR)		A term used in the context of a leasing arrangement for four C-17 transport aircraft for the RAF. The aircraft could be used by the lessor when not required by the RAF.															www.mod.uk/dpa.
Proactive Maintenance		Type of maintenance emphasizing the routine detection and correction of root cause conditions that would otherwise lead to failure. Examples: High lubricant contamination, misalignment and unbalance.															ISO 13372:2004(E), “Condition Monitoring and Diagnostics of Machines – Vocabulary”.
Process		A set of interrelated or interacting activities which transforms inputs into outputs.										X					
Procurement		That part of the acquisition process concerned with managing the development and manufacture of a system to an agreed systems definition, and whole life cost.	X														
Producibility		The degree to which “Design for Manufacturing” concepts have been used to influence system and product design to facilitate timely, affordable, and optimum-quality manufacture, assembly, and delivery of system to the field. Producibility is closely linked to other elements of availability and to costs. Items that feature design for manufacturability are also normally easier to maintain, have better accessibility features, and have lower life-cycle costs.															“Designing and Assessing Supportability in DOD Weapon Systems: A Guide to Increased Reliability and Reduced Logistics Footprint”, Office of the Secretary of Defense, 24 October 2003.
Product Baseline		Specifications (Type C) that establish the detailed design documentation for each configuration item.							X								
Product Data Management Systems	PDM Systems	PDM systems hold and manage such material as product specifications, plans, geometric models, CAD drawings and images. PDM tools provide comprehensive whole-life management capabilities for all data associated with a product, covering inception, design, manufacture, maintenance and disposal. Typical data includes: project data, notes and documents, test specifications and test analysis reports, cost spreadsheets, numerical control programs, maintenance procedures, spares data and logistic support information.		X													

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Prognosis – Damage		Damage Prognosis is the estimate of a system's remaining useful life. This estimate is based on the output of predictive models, which develop such estimates by coupling information from usage monitoring, structural health monitoring, past, current and anticipated future environmental and operational conditions, the original design assumptions regarding loading and operational environments, and previous component and system level testing.															Farrar, C. (Los Alamos National Laboratory) et al., "Damage Prognosis for Aerospace Civil and Mechanical Systems", Daniel J. Inman et al. Editors, Published by Wiley, 2005.
Prognostic and Health Management Systems	PHM Systems	Diagnostic or prognostic devices and systems that are used to monitor equipment condition and provide indications to the operator or maintainer. These systems may also initiate automatic actions to deal with the condition(s) sensed or predicted. Notes from NAVAIR 00-25-403: Basing performance of maintenance tasks on PHM systems is sometimes referred to as Condition-Based Maintenance. PHM or CBM programs must be based on a well-developed RCM analysis. State of the art PHM systems are capable of detecting potential failure conditions down to the component or sub-element level. They are also able to monitor the progression of chosen failure mode indicators, e.g. heat, vibration, etc., to predict when functional failures will occur.					X										
Prognostics		The analysis of the symptoms of faults to predict future condition and remaining useful life.															ISO 13372:2004(E), "Condition Monitoring and Diagnostics of Machines – Vocabulary".
Prognostics		The use of test, performance, or other related data in the evaluation of a system or equipment for determining the potential of impending faults.															Mil-Std-1309D, "Definition of Terms for Testing Measurement and Diagnostics", 1992.
Prognostics		The process of predicting a future state (of reliability) based on current and historic conditions. Prognostics and Health Management (PHM) is a method that permits the reliability of a system to be evaluated in its actual life-cycle conditions, to determine the advent of failure, and mitigate the system risks.															Vichare, N.M. and Pecht, M.G., "Prognostics and Health Management of Electronics", IEEE Transactions on Components and Packaging Technologies, Vol. 29, Issue 1, pp. 222-229, March 2006.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Prognostics		The determination of where the cause or condition is leading and in what time frame.															AVT-126 Technical Team.
Prognostics		Predictive diagnostics, which includes determining the remaining life or time span of proper operation of a component.															Hess, A., JSF Project Office PHM Lead, Presentation, 2005.
Prognostics		A technique which allows data to be collected and analysed on the operational status of an entity so that predictions can be made as to when failures are likely to occur. Prognostics can be considered as a sub-set of testability, but the storage of data and the instantaneous analysis of data can be highly complex, so it is usually only applied to critical performance attributes.															Def Stan 25-24, "Health and Usage Monitoring Capability for Land Platforms (HUMS)". Also Def Stan 00-42 Part 4 Reliability and Maintainability (R&M) Assurance Guide Part 4 Testability.
Prognostics		The capability to provide early detection of the precursor and/or incipient fault condition (very "small" fault) of a component, and to have the technology and means to manage and predict the progression of this fault condition to component failure. The early-detected fault condition is monitored and safely managed from a small fault as it progresses until it warrants maintenance action or replacement. Impacts on other components and secondary damage are also continually monitored and considered during this fault progression process. Through this early detection and the monitoring of fault progression management, the health of the component is known at any point in time, and the future failure event can be predicted in time to prevent it.															Engel, S.J., Gilmartin, B.J., Bongort, K. and Hess, A., "Prognostics, The Real Issues Involved With Predicting Life Remaining", IEEE Aerospace Conference, pp. 457-469, 2000.
Prognostics and Health Management	PHM	Predictive diagnostics, which includes determining the remaining life or time span of proper operation of a component, and the capability to make appropriate decisions about maintenance actions based on diagnostics/prognostics information, available resources and operational demand.															Hess, A., JSF Project Office PHM Lead, Presentation, 2005. This is a composite of his separate definitions for prognostics and health management.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Prognostics and Health Management	PHM	CBM is the use of machinery run time data to determine the machinery condition and hence its current fault/failure condition, which can be used to schedule required repair and maintenance prior to breakdown. Prognostics and Health Management (PHM) refers specifically to the phase involved with predicting future behavior, including Remaining Useful Life (RUL). Editor's Note: This definition appears in Chapter 2 of the Reference.															Vachtsevanos, G., Lewis, F., Roemer, M., Hess, A. and Wu, B., "Intelligent Fault Diagnosis and Prognosis for Engineering Systems", John Wiley & Sons Inc., 2006.
Prognostics and Health Management	PHM	A method that permits the reliability of a system to be evaluated in its actual life-cycle conditions, to determine the advent of failure, and mitigate the system risks.															Vichare, N.M. and Pecht, M.G., "Prognostics and Health Management of Electronics", IEEE Transactions on Components and Packaging Technologies, Vol. 29, Issue 1, pp. 222-229, March 2006.
Program Manager	PM	The designated individual with responsibility for and authority to accomplish program objectives for development, production, and sustainment to meet the user's operational needs. The PM shall be accountable for credible cost, schedule, and performance reporting to the MDA.															DoD Directive 5000.1, "The Defense Acquisition System", 12 May 2003, http://akss.dau.mil/dapc/index.html.
Project Management		The planning, control and co-ordination of all aspects of a project, and the motivation of all those involved in it, in order to achieve the project objectives.	X														
Protective Device (RCM)		Any device or system that has a function to avoid, eliminate or reduce the consequences of an event or the failure of some other function.												C	X		
Protective Device or System (RCM)		A device or system which is intended to avoid, eliminate, or minimize the consequences of failure of some other system. Editor's Note: See also Multiple Failure.												X	C		
Public Private Partnerships (GBR)		Public private partnerships (PPPs) are arrangements typified by joint working between the public and private sector. In the broadest sense, PPPs can cover all types of collaboration across the interface between the public and private sectors to deliver policies, services and infrastructure.															http://www.hm-treasury.gov.uk/ppp_index.htm, and http://www.partnershipsuk.org.uk/PUK-Defence.aspx.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Quality Assurance		All those planned and systematic actions necessary to provide adequate confidence that a product or service will satisfy given requirements for quality.	X														
Quality Control		The operational techniques and activities that are used to fulfil requirements for quality.	X														
Radio Frequency Identification	RFID	The remote identification of spares and repair parts using active or passive radio transmitters secured to the item or its packaging. This technology has in some cases been extended to include remote monitoring of the environment and condition of items.															AVT-144 Technical Team.
Reactive Maintenance		A maintenance concept in which corrective maintenance is only performed after an item has failed, i.e. there is no preventive maintenance. Note: Also known as Run-to-Failure (RTF) or Fix-When-Fail maintenance.															Dipl. Ing. Matthias Buderath (EADS Military Air Systems), 2006.
Readiness		Readiness is a measure of an organization's capability to perform assigned mission responsibilities when called upon to do so. A combination of Ao and mission frequencies (e.g. sortie rates), for both surge and sustained operations is a measure of equipment readiness. Equipment readiness predictions are a tool for assessing the operational suitability of a product before its introduction into service. Equipment readiness needs will vary from system to system, and from peacetime to wartime.				X											
Readiness		The ability of US military forces to fight and meet the demands of the national military strategy. Readiness is the synthesis of two distinct but interrelated levels. a) Unit readiness – The ability to provide capabilities required by the combatant commanders to execute their assigned missions. This is derived from the ability of each unit to deliver the outputs for which it was designed. b) Joint readiness – The combatant commander's ability to integrate and synchronize ready combat and support forces to execute his or her assigned missions.															Joint Publication JP 1-02, "Dictionary of Military and Associated Terms", USA.
Readiness		In English, "Readiness" is a generic term covering "Readiness State" and "Readiness Time". Preferred terms: readiness state; readiness time. (4/10/2000)									X						

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Readiness (cont'd)		Readiness State – The measure of the capability of forces at a given point in time to execute their assigned missions. Related terms: operational readiness; readiness; readiness time. (4/10/2000) Readiness Time – The time within which a unit can be made ready to perform the tasks for which it has been organized, equipped and trained. This time is amplified or measured by indicators of the unit's current personnel, materiel and training state. It does not include transit time. Related terms – Notice to move; operational readiness; readiness; readiness state. (1/10/2003)									X						
Readiness – Operational		The capability of a unit/formation, ship, weapon system, or equipment to perform the missions or functions for which it is organized or designed. May be used in a general sense or to express a level or degree of readiness.															Joint Publication 1-02 (JP 1-02), "United States Department of Defense Dictionary of Military and Associated Terms", 31 August 2005.
Readiness Drivers		Those system characteristics which have the largest effect on a systems readiness values. These may be design (hardware or software), support or operational characteristics.	X					X									
Readiness, Operational (Operational Readiness)		An evaluation of the operational capability and effectiveness of a unit or any portion thereof.									X						
Readiness, Operational (Operational Readiness)		The ability of a military unit to respond to its operation plan(s) upon receipt of an operations order. (A function of assigned strength, item availability, status, or supply, training, etc.)														X	
Readiness, System (System Readiness)		A measure or measures of the ability to undertake and sustain a specified set of missions at planned peacetime and wartime utilization rates. Additional Notes: System readiness means to take explicit account of the effects of system design (reliability and maintainability), the characteristics and performance of the support system, and the quantity and location of support resources. Examples of typical readiness measures are sortie rate, mission capable rate, operational availability and asset ready rate.	X					X	X								

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Readiness-Based Materiel Condition Reporting (DODI 3110.5)		• Description: Development of materiel readiness guidance (via DODI 3110.5) that supports the Defence Readiness Reporting System (DRRS) policy objectives with: – A strategy for tying the requirement for weapon system materiel readiness to DoD planning guidance mission outcomes. – A method for objectively quantifying that requirement in a way that encourages value chain alignment and integration. • Goals: – Identify new reporting requirements to support readiness-based capabilities planning. – Support the Defence Readiness Reporting System (DRRS) with readiness-based materiel condition data. – Establish a requirement to report readiness by weapon system core missions. • Key Features: – Each Service establishes availability goals for major weapon systems. – Goals are used to influence resource requirements, weapon system procurements, spare parts inventories, and other resources.															www.acq.osd.mil/log/mppr/mssg.htm.
Rebuilding		That action following the dismantling of an item and the repair or replacement of those sub-items that are approaching the end of their useful life and/or should be regularly replaced. Note 1: Rebuilding differs from overhaul in that the actions may include modifications and/or improvements. Note 2: The objective of rebuilding is normally to provide an item with a useful life which may be greater than the life of the original item.											X				
Reconfigur-ation (Reliability Context)		The recovery, automatic or otherwise, of a system after a failure without the need for the system to go off-line.															
Recovery Blocks and Self-Healing (Software)		The backwards error recovery carried out by periodically saving the system state and reverting to it when necessary.															Mitchell, P. (RAF), “What the Customer Wants Maintenance-Free and Failure-Free Operating Periods to Improve Overall System Availability and Reliability”, RTO-MP-037, September 2000.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Redundancy		Fault tolerance, using either hardware, software, or data duplication in various forms. Note: Can achieve significant reliability gains but at the cost of potential increased complexity, weight, volume and power consumption.															Mitchell, P. (RAF), "What the Customer Wants Maintenance-Free and Failure-Free Operating Periods to Improve Overall System Availability and Reliability", RTO-MP-037, September 2000.
Redundancy		In an item, the existence of more than one means at a given instant of time for performing a required function.											X				
Redundancy		The existence of more than one means for accomplishing a given function. Each means of accomplishing the function need not necessarily be identical. The two basic types of redundancy are active and standby. Active Redundancy – Redundancy in which all redundant items operate simultaneously. Standby Redundancy – Redundancy in which some or all of the redundant items are not operating continuously but are activated only upon failure of the primary item performing the function(s).														X	
Redundancy, active		That redundancy wherein all means for performing a required function are intended to operate simultaneously.											X				
Redundancy, standby		That redundancy wherein a part of the means for performing a required function is intended to operate, while the remaining part(s) of the means are inoperative until needed.											X				
Redundant Functional Elements		Two or more independent physical elements of a system/item providing the same function.													X		
Reliability		The ability of an item to perform a required function under stated conditions for a stated period of time. Note 1: The term reliability is also used as a reliability characteristic denoting a probability of success, or a success ratio: a) Mission Reliability. The ability of an item to perform its required mission critical functions for the duration of a specified mission or life profile. b) Basic Reliability. The ability of an item to perform its required functions without failure for the duration of a specified mission profile. Note 2: Throughout Def-Stan 00-60, and unless stated to the contrary, Reliability is deemed to include Durability.	X		C												

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Reliability		The probability that a machine will perform its required functions without failure for a specified time period when used under specified conditions.															ISO 13372:2004(E), “Condition Monitoring and Diagnostics of Machines – Vocabulary”.
Reliability		The ability of a system to perform as designed in an operational environment over time without failure.															“Designing and Assessing Supportability in DOD Weapon Systems: A Guide to Increased Reliability and Reduced Logistics Footprint”, Office of the Secretary of Defense, 24 October 2003.
Reliability		The ability of a system to perform a required function under stated conditions for a specified period of time. Note: The term “Reliability” is also used as a reliability characteristic, denoting a probability of success or a success ratio.								X	X		C				
Reliability		The ability of an item to perform a required function under given conditions for a given time interval. Note: The term “Reliability” is also used as a measure of reliability performance and may also be defined as a probability.											X				
Reliability		1) The duration or probability of failure-free performance under stated conditions. 2) The probability that an item can perform its intended function for a specified interval under stated conditions. (For non-redundant items this is equivalent to definition 1. For redundant items this is equivalent to definition of mission reliability.)				X		X	X							X	Mil-Std-1309D, “Definition of Terms for Testing Measurement and Diagnostics, 1992.
Reliability – Basic		The ability of an item to perform its required functions without failure or defect for the duration of its life profile. Note: Reliability is deemed to include Durability.								X							
Reliability – Inherent		The reliability potential present in a design, i.e. the reliability which is dependent solely on the quality of design and assumes perfect quality of manufacture and correct use in the field.								X							

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Reliability – Mission		The ability of an item to perform its required mission critical functions for the duration of a specified mission or life profile. Editor's Note: See also Def-Stan 00-60 definition of Reliability and Basic Reliability.	X														
Reliability – Mission		The probability that an item will perform its required functions for the duration of a specified mission profile. Editor's Note: See ARMP-7 Mission Profile.						C	C	X							
Reliability and Maintainability	R&M	The probability of equipment working correctly when required, and the ease of putting it right, once a failure has occurred. The R&M of equipment are two of the key drivers of its support costs and also encompass the areas of: availability, safety, testability and durability.		X													
Reliability Centered Maintenance	RCM	A systematic approach for identifying preventative maintenance tasks for an equipment end item in accordance with a specified set of procedures and for establishing intervals between maintenance tasks.	X					X	X								NATO spelling is Reliability Centred Maintenance.
Reliability Centered Maintenance	RCM	RCM is a logical, structured process used to determine the optimal failure management strategies for any system based on system reliability characteristics and the intended operating context. RCM defines what must be done to a system to achieve the desired levels of safety, reliability, environmental soundness, and operational readiness, at best cost. RCM is to be applied continuously throughout the life cycle of any system.															US Department of Defense Instruction 4151.22, "Condition Based Maintenance Plus (CBM+) for Materiel Maintenance", 2 December 2007.
Reliability Centered Maintenance	RCM	RCM is the optimum mix of reactive, time- or interval-based, condition-based, and proactive maintenance practices.															Pride, A., Associate Director Systems Reliability, Smithsonian Institution, "Reliability-Centered Maintenance (RCM)", www.wbdg.org/design/rcm.php.
Reliability Centered Maintenance	RCM	Reliability Centered Maintenance (RCM) is an analytical process to determine the appropriate failure management strategies, including PM requirements and other actions that are warranted to ensure safe operations and cost-wise readiness. This process of developing PM requirements, with an auditable documentation package, is based on the reliability of the various components, the severity of the consequences related to safety and mission if failure occurs, and the cost effectiveness of the task.					X										

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Reliability Centered Maintenance	RCM	RCM is a specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any physical asset in a given operating context. Any RCM process shall ensure that all of the following seven questions are answered satisfactorily and are answered in the sequence shown as follows: 1) What are the functions and associated desired standards of performance of the asset in its present operating context (functions)? 2) In what ways can it fail to fulfil its functions (functional failures)? 3) What causes each functional failure (failure modes)? 4) What happens when each failure occurs (failure effects)? 5) In what way does each failure matter (failure consequences)? 6) What should be done to predict or prevent each failure (proactive tasks and task intervals)? 7) What should be done if a suitable proactive task cannot be found (default actions)?												X			
Reliability Centered Maintenance Program Metrics		Examples of parameters used in quantifying improvements in the efficiency of a maintenance program due to the application of RCM: availability, readiness, Mean Time Between Failures (MTBF), Total Ownership Cost (TOC), Direct Maintenance Man-hours per Flight Hour (DMMH/FH), and Mean Time Between Removal (MTBR).					X										
Reliability Centered Maintenance Tasks		The main RCM tasks are: RCM plan, hardware partitioning, FMECA, significant function selection, RCM task evaluation, RCM task selection, implementation, feedback.					X										
Reliability Centred Maintenance	RCM	A method for establishing a scheduled (preventive) maintenance programme which will efficiently and effectively achieve the inherent reliability and safety levels of equipment. It is methodology which can be applied to the development of a preventive maintenance programme and results in improved component reliability and minimised overall programme costs. The intended end result is improved overall equipment safety, availability and economic operation.			X					X							NATO spelling is Reliability Centred Maintenance.
Reliability Growth		The improvement in reliability that results when design, material, or part deficiencies are revealed by testing and eliminated or mitigated through corrective action.														X	

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Reliability Growth		The positive improvement of the reliability of an equipment through the systematic and permanent removal of failure mechanisms. Note: Achievement of reliability growth is dependent upon the extent to which testing and other improvement techniques have been used during development and production to "force out" design and fabrication flaws, and on the rigor with which these flaws are analyzed and corrected.														X	
Repair		That part of Corrective Maintenance in which manual actions are performed on an item.			X												
Repair		The physical action taken to restore the required function of a faulty item. Editor's Note: See also Temporary Repair.											X				
Repair Parts		Those support items that are an integral part of the end item or system which are coded as non-repairable. Note: Repairable items are termed Spares – see definition.						X	X								
Reprovisioning		Reprovisioning is the routine replenishment of stocks as well as the enhancement of existing stock levels to support the introduction of new equipment after the agreed IP support period.	X														
Restoration		That work necessary to return the item to a specific standard. Restoration may vary from cleaning or replacement of single parts up to a complete overhaul.													X		
Re-Test OK	RTOK	A unit that was identified as malfunctioning in a particular manner at one maintenance level, but that specific malfunction could not be duplicated at a higher maintenance level facility.															Mil-Std-1309D, "Definition of Terms for Testing Measurement and Diagnostics", 1992.
Reversionary Modes (SW)		The ability of software to back-up when a failure occurs and take a different path, thus bypassing failure.															Mitchell, P. (RAF), "What the Customer Wants Maintenance-Free and Failure-Free Operating Periods to Improve Overall System Availability and Reliability", RTO-MP-037, September 2000.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Robbing		The transfer of a serviceable part from one equipment/system to another or from an uninstalled assembly to an equipment/system, to overcome a temporary deficiency in spares.			X												
Routine Maintenance		Regular or repeated elementary maintenance activities which usually do not require special qualifications, authorization(s) or tools. Note: Routine maintenance may include for example cleaning, tightening of connections, checking liquid level, lubrication, etc.											X				
Run-to-Failure		A failure management policy that permits a specific failure mode to occur without any attempt to anticipate or prevent it.												X			
Safe Life (Aircraft Engines)		A LCF-based (Low Cycle Fatigue-based) process in which components are designed, manufactured, substantiated, and maintained to have a specified service life or life limit, which is stated in operating flight cycles, operating hours, or both. The “safe life approach” requires that parts be removed from service prior to the development of an unsafe condition (i.e. crack initiation). Editor’s Note: See also Life Limit per AC 33.70-Y.															FAA Advisory Circular (Draft) AC 33.70-Y, “Engine Life Limited Parts Requirements”, 2007.
Safe Life (Aircraft Structure)		That number of events such as flights, landings, or flight hours, during which there is a low probability that the strength will degrade below its design ultimate value due to fatigue cracking.															FAA Advisory Circular, “Damage Tolerance and Fatigue Evaluation of Aircraft Structure”, AC 25.571-1C, Dated 29 April 1998.
Safe Life (in RCM)		A Safe Life item must survive to an age below which no failures are expected to occur. Safe life limits are imposed in RCM on only those items whose failure modes have safety/environmental consequences.					X										
Safe Life Structure		Structure which is not practical to design or qualify as damage tolerant. Its reliability is protected by discard limits which remove items from service before fatigue cracking is expected.													X		
Safety		The likelihood of a product to maintain throughout its life cycle an acceptable level of risk that may cause an injury to personnel or major damage to the product or its environment.								X							
Safety (Adverse Effect)		Safety shall be considered as adversely affected if the consequences of the failure condition would prevent the continued safe flight and landing of the aircraft and/or might cause serious or fatal injury to human occupants.													X		

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Safety/ Emergency Systems or Equipment		A device or system that: 1) Enhances the evacuation of the aircraft in an emergency; or 2) If it does not function when required, results in a Failure Condition that might have an adverse effect on safety.													X		
Scheduled		Performed at fixed, predetermined intervals, including “continuous monitoring” (where the interval is effectively zero).												X			
Scheduled Discard		A scheduled task that entails discarding an item at or before a specified age limit regardless of its condition at the time.												X			
Scheduled Maintenance Check		Any of the maintenance opportunities which are pre-packaged and are accomplished on a regular basis.													X		
Scheduled Maintenance		Preventative Maintenance performed at prescribed points in the item’s life.						X	X								
Scheduled Maintenance		Preventive maintenance carried out in accordance with an established time schedule or established number of units of use. Note: In English, scheduled maintenance is sometimes called planned maintenance.											X				
Scheduled Maintenance		Periodic prescribed inspection and servicing of products or items accomplished on the basis of calendar, mileage or hours of operation. Included in Preventive Maintenance.														X	
Scheduled Restoration		A scheduled task that restores the capability of an item at or before a specified interval (age limit), regardless of its condition at the time, to a level that provides a tolerable probability of survival to the end of another specified interval.												X			
Secondary Failure		A failure of an item, caused either directly or indirectly by a failure or a fault of another item. (IEC-50 (191))								X							
Servicing		The performance of any act needed to keep an item in operating condition, (i.e. lubricating, fueling, oiling, cleaning, etc.), but not including preventive maintenance of parts or corrective maintenance tasks.														X	
Servicing Task (RCM)	S Task	The replenishment of consumable materials that are depleted during normal operations. Note: The replenishment or reapplication of Corrosion Preventive Compounds (CPC) can in most cases be regarded as a Servicing or a Lubrication task.					X										

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Shelf Life		The period of time during which an item of materiel, having a limited storage life, is considered to remain serviceable while stored under specified conditions.	X														
Significant Function	SF	A function whose failure will have adverse effect with regard to safety, environment, operations, and economics.					X										
Single Point Failure		A failure of an item that causes the system to fail and for which no redundancy or alternative operational procedure exists.														X	
Smart Acquisition (GBR)		A key element of the UK 1998 Strategic Defence Review (SDR) was a re-examination of the procurement process from both an organisational and a procedural perspective. The Smart Procurement Initiative (SPI) was launched with the aim of establishing a closer customer/supplier relationship and delivering equipment 'faster, cheaper and better'. The SPI was re-launched as Smart Acquisition in October 2000. Smart Acquisition was intended to refine and develop the SPI concept and to "stress the point that the MOD is concerned not only with buying equipment, but with acquiring the means to support it throughout its in-service life."															UK, Library of the House of Commons Research Paper 3/74 3, October 2004.
Sneak Circuit Analysis		An analytical procedure for identifying latent paths that cause occurrence of unwanted functions or inhibit desired functions, assuming all components are operating properly.														X	
Soft Fault		1) A fault causing a degraded performance of the UUT. 2) A condition manifested only under certain conditions of UUT operation. When those conditions change the fault disappears.															Mil-Std-1309D, "Definition of Terms for Testing Measurement and Diagnostics", 1992.
Software Reliability		Software reliability is defined as the probability that software will not cause a system failure over a specified time under specified conditions. This probability is a function of the inputs to and use of the system, as well as the presence of latent software faults. The system inputs determine whether any latent faults will be encountered during system operation.														X	
Software Support		All activities concerned with supporting the operation of software, and with sustaining the ability of software to satisfy the required system performance and functionality during its operational life.	X														
Software Support Significant Item		Any configured software item that is potentially the subject of a software support task.	X														
Software		A computer program or data entity, and the associated design or descriptive documentation.	X														

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Spare Part		Item intended to replace a corresponding item in order to restore the original required function of the item. Note 1: The original item may be subsequently repaired. Note 2: An item that is dedicated and/or exchangeable for a specific item is often referred to as replacement item.											X				
Spares		Those support items that are an integral part of the end item or system which are coded as repairable.						X	X								
Specification		The documents that prescribe the requirements of the product or service together with the descriptive means and criteria to assess conformity.			X												
Spiral Development		In this process, a desired capability is identified, but the end-state requirements are not known at program initiation. Those requirements are refined through demonstration and risk management; there is continuous user feedback; and each increment provides the user the best possible capability. The requirements for future increments depend on feedback from users and technology maturation.															DoD 5000.2, "Operation of the Defense Acquisition System", 12 May 2003, http://akss.dau.mil/dapc/index.html.
Stage (of a System Life-Cycle)		A period within the life-cycle of a system that relates to the state of the system description or the system itself. Note: Stages relate to major progress and achievement milestones of the system through its life-cycle. Stages may be overlapping.										X					
Standardization		The process by which member Nations of an alliance achieve the closest practicable co-operation among forces; the most efficient use of research, development and production resources; and agree to adopt on the broadest possible basis the use of: a) Common or compatible operational, administrative and logistics procedures. b) Common or compatible technical procedures and criteria. c) Common, compatible or interchangeable supplies, components, weapons or equipment. d) Common or compatible tactical doctrine with corresponding organizational compatibility.	X					X	X								

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Structural Health Monitoring	SHM	Use of NDI principles coupled with in-situ sensing to allow for rapid, remote, and even real-time condition assessments; goal is to reduce operational costs and increase life of structures: allows for greater vigilance in key areas – addresses damage tolerance needs; overcomes accessibility limitations, complex geometries, depth of hidden damage; eliminates costly and potentially damaging disassembly; minimizes human factors with automated sensor deployment and data analysis; supports adoption of condition-based maintenance. Editor's Note: See also Roach Definition of NDI.															Roach, D., Rackow, K., DeLong, W., Yepez, S., Reedy, D. and White, S., "Use of Composite Materials, Health Monitoring and Self Healing Concepts to Refurbish Our Civil and Military Infrastructure", Sandia National Laboratories Report SAND2007-5547, September 2007.
Structural Health Monitoring	SHM	The process of damage detection for aerospace, civil, and mechanical engineering infrastructure. SHM involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage – sensitive features from these measurements, and the statistical analysis of these features to determine the current state of the system. For long-term SHM, the output of this process is periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable aging and degradation resulting from operational environments.															Farrar, C. (Los Alamos National Laboratory) et al., "Damage Prognosis for Aerospace Civil and Mechanical Systems", Daniel J. Inman et al. Editors, Published by Wiley, 2005.
Structural Integrity		The condition which exists when a structure is sound and unimpaired in providing the desired level of structural safety, performance, durability, and supportability.															Mil-Std-1530C (USAF), "Aircraft Structural Integrity Program (ASIP)", 1 November 1995.
Structural Significant Item	SSI	Any detail, element or assembly, which contributes significantly to carrying flight, ground, pressure or control loads and whose failure could affect the structural integrity necessary for the safety of the aircraft. Notes from text of MSG-3: An SSI may or may not include a Principal Structural Element (PSE), but all PSE are considered to be SSI. Structure which is judged not to be an SSI is referred to as "Other Structure". Editor's Note: See also Principal Structural Element.													X		
Sudden Failure		Failure that could not be anticipated by prior examination or monitoring.											X				

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Supply Management		Within the context of support management, the responsibility to equipment managers for supply advice and ensuring the provision, receipt, maintenance of stock levels and issue of materiel associated with an equipment or system throughout its life cycle in accordance with staff policies for that equipment.	X														
Supply Support		All management actions, procedures and techniques used to determine requirements to acquire, catalogue, receive, store, transfer, issue, and dispose of secondary items. This includes provisioning for initial support and replenishment supply support.							X								
Support and Test Equipment	S&TE	The equipment (mobile or fixed) required to support the operation and maintenance of an equipment. This includes associated multi-use end items, maintenance equipment, tools, metrology and calibration equipment, test equipment and automatic test equipment.		X													
Support and Test Equipment		The identification of, planning for, and acquisition of all the equipment required to support the operation of a weapon system. This includes ground-handling and maintenance equipment, tools, metrology and calibration equipment, test equipment and automatic test equipment for on and off system maintenance and computer software associated with the test equipment. It also includes the acquisition of logistics support and test equipment.							X								
Support Concept		A complete system level description of a support system, consisting of an integrated set of ILS element concepts, which meets the functional support requirements and is in harmony with the design and operational concepts.	X					X	X								
Support Equipment		All equipment (mobile or fixed) required to support the operation and maintenance of a materiel system. This includes associated multi-use end items, ground handling and maintenance equipment, tools, metrology and calibration equipment, communications resources, test equipment and automatic test equipment, with diagnostic software for both on and off equipment maintenance. It includes the acquisition of logistics support for the support and test equipment itself. One of the principle elements of ILS.	X														Mil-Std-1309D, "Definition of Terms for Testing Measurement and Diagnostics", 1992.
Supportability		The degree to which system design characteristics and planned logistic resources, including manpower, meet the system peacetime and wartime availability requirements.	X														
Supportability		The degree to which system design characteristics and planned logistic resources, including manpower, meet the system peacetime and wartime utilization requirements.			X				X								Old definition in Mil-Std-1388-1A.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Supportability		A key component of availability. It includes design, technical support data, and maintenance procedures to facilitate detection, isolation, and timely repair and/or replacement of system anomalies. This includes factors such as diagnostics, prognostics, real-time maintenance data collection, and human system integration considerations. (CJCSI 3170.01E)															US DoD Defense Acquisition University, “Glossary of Defence Acquisition Acronyms and Terms”, Twelfth Edition, July 2005, http://www.dau.mil/pubs/glossary/12th_Glossary_2005.pdf.
Supportability		Supportability is the degree to which system design characteristics and planned logistics resources meet system peacetime and wartime requirements. Supportability is the capability of a total system design to support operations and readiness needs throughout the system’s service life at an affordable cost. It provides a means of assessing the suitability of a total system design for a set of operational needs within the intended operations and support environment (including cost constraints). Supportability characteristics include many performance measures of the individual elements of a total system. For example: Repair Cycle Time is a support system performance characteristic independent of the hardware system. Mean Time Between Failure and Mean Time to Repair are reliability and maintainability characteristics, respectively, of the system hardware, but their ability to impact operational support of the total system makes them also supportability characteristics.				X											
Supportability		The inherent quality of a system – including design, technical support data, and maintenance procedures – to facilitate detection, isolation, and timely repair/replacement of system anomalies. This includes factors such as diagnostics, prognostics, real-time maintenance data collection, ‘design for support’ and ‘support the design’ aspects, corrosion protection and mitigation, reduced logistics footprint, and other factors that contribute to optimum environment for developing and sustaining a stable, operational system.															“Designing and Assessing Supportability in DOD Weapon Systems: A Guide to Increased Reliability and Reduced Logistics Footprint”, Office of the Secretary of Defense, 24 October 2003.
Supportability		A measure of the degree to which all resources required to operate and maintain the system/equipment can be provided in sufficient quantity. Supportability encompasses all elements of ILS, as defined in DoDI 5000.2.						X									
Supportability		A measure of the degree to which all resources required to operate and maintain the system/equipment can be provided in sufficient quantity and time.								X							

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Supportability (Aircraft Structure)		Supportability means that thermal, environmental, and mechanical deterioration of materials and structures fabricated using the selected manufacturing processes and joining methods have been identified and that acceptable quality and cost-effective preventive methods and/or in-service repair methods are either available or can be developed in a timely manner.															Mil-Std-1530C (USAF), “Aircraft Structural Integrity Program (ASIP)”, 1 November 1995.
Supportability Factors		Qualitative and quantitative indicators of supportability.						X	X								
Survivability		The ability of a weapon system to survive in a hostile environment.						X	X								
Sustainability		The capability of a system to deliver the required availability level over a complete mission.	X														
Sustainability		The Integral of Availability (i.e. the capability of a system to deliver the required availability level over a complete mission).		X													
Sustainability (Operational)		The capability of an item or system, and its inherent support structure, to perform its intended missions over a sustained period of time.				X											
Sustainment		Sustainment includes supply, maintenance, transportation, sustaining engineering, data management, configuration management, manpower, personnel, training, habitability, survivability, environment, safety (including explosives safety), occupational health, protection of critical program information, anti-tamper provisions, and Information Technology (IT), including National Security Systems (NSS), supportability and interoperability functions. Effective sustainment of weapon systems begins with the design and development of reliable and maintainable systems through the continuous application of a robust systems engineering methodology. As a part of this process, the PM shall employ human factors engineering to design systems that require minimal manpower; provide effective training; can be operated and maintained by users; and are suitable (habitable and safe with minimal environmental and occupational health hazards) and survivable (for both the crew and equipment).															DoD Instruction 5000.2, “Operation of the Defense Acquisition System”, Under Secretary for Defense (Acquisition, Technology and Logistics), 12 May 2003, https://akss.dau.mil/dag/DoD5002/Subject.asp.
Symptomatics		Awareness of current condition and identification of a symptom or anomaly.															AVT-126 Technical Team.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
System		A combination of interacting elements organized to achieve one or more stated purposes. Note: A system may be considered as a product or as the services it provides. In practice the interpretation of its meaning is frequently clarified by the use of an associative noun, e.g. aircraft system. Alternatively, the word system may be substituted simply by a context dependent synonym, e.g. aircraft, though this may then obscure a system principles perspective.										X					
System		A composite of equipment and skills, and techniques capable of performing or supporting an operational role, or both. A complete system includes all equipment, related facilities, material, software, services, and personnel required for its operation and support to the degree that it can be considered self-sufficient in its intended operational environment.														X	
System		A system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behavior and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected. (Rechtin, 2000)															Definition of the International Council on Systems Engineering (INCOSE), http://www.incose.org/practice/fellowsconsensus.aspx.
System		Partial Systems – These have independent purpose, but are only viable in the context of a containing system. For instance, an air-launched missile has an independent purpose, but is only viable if integrated with an aircraft platform. Sub-Systems – Systems which only have a purpose as part of a containing system. For example, an engine only has a purpose – providing the power to move a platform – if incorporated into that platform.															"Defence Industrial Strategy", UK Defence White Paper, 2005.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
System (cont'd)		System – One which has a purpose and is viable in its own right. An example, from an equipment perspective, is a fast-jet combat aircraft. We will generally talk about platform systems – in the military sense, as the single viable equipment units, usually capable of independent movement – though examples include satellites, as well as vehicles, aircraft, ships and submarines. Network systems also exist, however; a Wide Area Network fits this definition of a system. Editor's Note: See also UK DIS 2005 definition of System of Systems.															"Defence Industrial Strategy", UK Defence White Paper, 2005.
System Effectiveness		The ability of a weapon system to perform its intended function. Effectiveness can be described in terms of the following factors: Capability, System Readiness, Mission Reliability, and Survivability.							X								
System Effectiveness		System effectiveness reflects the balance achieved between the technical effectiveness and the process efficiency of the system. In this context, process efficiency is constituted by the system operational, maintenance and logistics processes. System effectiveness reflects a holistic view of the real mission capability delivered to the field.															"Designing and Assessing Supportability in DOD Weapon Systems: A Guide to Increased Reliability and Reduced Logistics Footprint", Office of the Secretary of Defense, 24 October 2003.
System Effectiveness		a) For repairable systems and items: the probability that a system can successfully meet an operational demand within a given time when operated under specified conditions. b) For "one-shot" devices and non-repairable items: the probability that the system will operate successfully when called upon to do so under specified conditions.														X	
System Element		A member of a set of elements that constitutes as system. Note: A system element is a discrete part of a system that can be implemented to fulfil specified requirements.										X					
System Life-Cycle		The evolution with time of a system-of-interest from conception through to retirement.										X					

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
System of Systems	SOS	System of Systems (SOS): these contain systems which have purpose and are viable independent of the SOS, but which can when acting together perform functions unachievable by the individual systems acting alone. For instance, the future aircraft carrier, combining its aircraft carrier group with its own sensors, communications and command systems and weaponry and interacting with wider networks, represents a SOS. Editor's Note: See also UK DIS 2005 definition of System.															"Defence Industrial Strategy", UK Defence White Paper, 2005.
System Readiness		See Readiness and System.	X					X	X								
System Readiness		A measure or measures of the ability to undertake and sustain a specified set of missions at planned peacetime and wartime utilization rates. System readiness means to take explicit account of the effects of system design (reliability and maintainability), the characteristics and performance of the support system, and the quantity and location of support resources. Examples of typical readiness measures are sortie rate, mission capable rate, operational availability and asset ready rate.	X					X	X								
Systems Engineering		Systems engineering is an interdisciplinary approach to evolve and verify an integrated and life-cycle balanced set of product and processes solutions that satisfy stated customer needs. A total system design would include product hardware, software, and planned logistics resources. This structured, or process, approach integrates the essential elements and design decisions of three interrelated design efforts. The result is a balanced, total system solution to the operational need and other program objectives. The systems engineering process is used within the Department of Defense to translate operational users' needs into requirements and requirements into designs which meet program performance, cost, and schedule requirements. Figure 4-3 in Mil-Hdbk-502 provides an overview of the process.				X											
Systems Engineering		The application of scientific and engineering efforts to transform an operational need into a description of a system configuration which best satisfies the operational need according to the measures of effectiveness; integrate related technical parameters and ensure compatibility of all physical, functional, and technical project interfaces in a manner that optimizes the total system definition and design to provide a reasonable balance between performance, acquisition cost and LCC; and integrate the efforts of all engineering disciplines and specialities into the total engineering effort.						X	X								

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Systems Engineering		Systems Engineering is an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle. This process is usually comprised of the following seven tasks: State the problem, Investigate alternatives, Model the system, Integrate, Launch the system, Assess performance, and Re-evaluate. These functions can be summarized with the acronym SIMILAR: State, Investigate, Model, Integrate, Launch, Assess and Re-evaluate. It is important to note that the Systems Engineering Process is not sequential. The functions are performed in a parallel and iterative manner.															Consensus Definition of the International Council on Systems Engineering (INCOSE), 2 October 2008, http://www.incose.org/practice/whatissystemseng.aspx.
Systems Operational Effectiveness Framework	SOE	The Systems Operational Effectiveness Framework shows the linkage between overall operational effectiveness and weapon system and product support effectiveness.															"Designing and Assessing Supportability in DOD Weapon Systems: A Guide to Increased Reliability and Reduced Logistics Footprint", Office of the Secretary of Defense, 24 October 2003.
Technical Documentation		The information necessary to operate, maintain, repair, support and dispose of equipment throughout its life. It includes paper, fiche, drawings, Computer-Aided Design (CAD) data, electronic text, non-textual data, e.g. graphics, video, etc., for: a) Illustrated parts lists. b) System description and operation. c) System servicing and maintenance. d) Diagnostic support. e) Repair information. f) Supporting flow, system and wiring diagrams. g) Software documentation. h) Logistic support analysis reports.		X													
Technology		A technology is a particular practical or industrial art.															Oxford English Dictionary.
Technology Demonstrator Programme		A research programme to produce hardware which bridges the gap between research and development and demonstrates the technical feasibility of using new technology to meet a specific operational requirement.	X														

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Temporary Repair		The physical actions taken to allow a faulty item to perform its required function for a limited interval and until a repair is carried out.											X				
Test		A procedure or action taken to determine under real or simulated conditions the capabilities, limitations, characteristics, effectiveness, reliability or suitability of a material, device, system or method.															Mil-Std-1309D, “Definition of Terms for Testing Measurement and Diagnostics”, 1992.
Test Analyse and Fix	TAAF	A synonym for reliability growth in which the three main elements (test, analyze deficiencies, and take corrective action) for achieving reliability growth are identified.														X	
Testability		A design characteristic which allows the status (operable, inoperable, or degraded) of an item and the location of any fault within the item to be confidently determined in a timely fashion.			C			X	X							X	Mil-Std-1309D, “Definition of Terms for Testing Measurement and Diagnostics”, 1992.
Testing Process		A series of tests conducted to disclose deficiencies or to verify that corrective actions will prevent recurrence and to determine compliance with specified R&M requirements.								X							
Threshold (in a Specification)		The minimum required value of a supportability metric in a system specification.				X											
Threshold Period		A period during which no occurrences of the failure can reasonably be expected to occur after the item enters into service. Note: See also Interval – Initial.													X		
Through Life Capability Management (Capability Management)	TLCM	Through Life Capability Management (Capability Management) translates the requirements of Defence policy into an approved programme that delivers the required capabilities, through-life, across all Defence Lines of Development (DLoDs).															MOD UK Acquisition Operating Framework, http://www.aof.mod.uk/.
Through Life Management Plan	TLMP	A plan designed to take a project through its entire life, across the CADMID cycle, meeting Customer requirements and providing visibility to all stakeholders of the planned through life management process.		X													
Through Life Support Standard	TLSS	A new UK standard on ILS under development to replace Def Stan 00-60.															

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Total Life-Cycle Systems Management (US DoD)	TLCSM	A policy of the Office of Secretary of Defense, USA, introduced in 2001, whereby the project manager of a weapon system is charged with the accomplishment of program objectives for the total life cycle, including sustainment.															"Designing and Assessing Supportability in DOD Weapon Systems: A Guide to Increased Reliability and Reduced Logistics Footprint", Office of the Secretary of Defense, 24 October 2003.
Total Life-Cycle Systems Management (US DoD)	TLCSM	The TLCSM approach to major systems decision making is a way to account for some of the total ownership categories that are difficult to address. The TLCSM approach, which is principally a Program Manager responsibility, requires programs to base major decisions on system-wide analyses and the Lifecycle consequences of those decisions on system performance and affordability. Examples of these analyses are the business cases and cost estimates that support the acquisition (i.e. affordability assessments, analyses of alternatives, cost-performance trades, and iterative establishment of program cost goals). The refined, detailed, and discrete Lifecycle cost estimates used within the program office should support internal, program office decision making such as the evaluation of engineering changes or in competitive source selections.															DoD Acquisition Guidebook Chapter 11.7, http://akss.dau.mil/dapc/index.html.
Total Quality Management	TQM	The management application of methods and human resources to control all processes with the objective of achieving continuous improvement in quality. Continuous improvement is the hallmark of TQM. It is achieved by focusing on customer needs and on the processes used to create products. The quality and reliability of delivered products provide the indicators of the adequacy of the processes that create them. TQM demands teamwork, commitment, motivation and professional discipline. It relies on people and involves everyone.															Department of Defense (DoD) Total Quality Management (TQM) Master Plan, August 1988.
Total Systems Approach (US DoD)		The PM shall be the single point of accountability for accomplishing program objectives for total life-cycle systems management, including sustainment. The PM shall apply human systems integration to optimize total system performance (hardware, software, and human), operational effectiveness, and suitability, survivability, safety, and affordability. PMs shall consider supportability, life-cycle costs, performance, and schedule comparable in making program decisions. Planning for Operation and Support and the estimation of total ownership costs shall begin as early as possible.															DoD Directive 5000.1, "The Defense Acquisition System", 12 May 2003, http://akss.dau.mil/dapc/index.html.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Total Systems Approach (US DoD) (cont'd)		Supportability, a key component of performance, shall be considered throughout the system life cycle. Acquisition programs shall be managed through the application of a systems engineering approach that optimizes total system performance and minimizes total ownership costs. A modular, open-systems approach shall be employed, where feasible.															DoD Directive 5000.1, "The Defense Acquisition System", 12 May 2003, http://akss.dau.mil/dapc/index.html.
Trade Space		The range in a supportability metric in a system specification between the Threshold and the Objective.				X											DoD 5000.2, "Operation of the Defense Acquisition System", 12 May 2003, http://akss.dau.mil/dapc/index.html.
Trade-Off		The determination of the optimum balance between system characteristics (cost, schedule, performance and supportability).	X					X	X								
Trade-Off		As a Systems Engineering Term – A decision-making activity that selects from alternative solutions on the basis of overall benefit to the system MOD.															MOD UK Acquisition Operating Framework, Version 2.0.2, June 2008, Glossary, http://www.aof.mod.uk/aofcontent/tactical/randa/content/glossary.htm.
Transportability		The inherent capability of materiel to be moved with available and projected transportation assets to meet schedules established in mobility plans, and the impact of system equipment and support items on the strategic mobility of operating military forces.	X														
Transportability		The inherent capability of an item or system to be moved efficiently over railways, highways, waterways, oceans, or airways either by carrier, towing, or self-propulsion.				X											
Turn Round Time		The element of maintenance time needed to replenish consumables and check out an item for recommitment.			X												
Unique Identification	UID	• Description: An effort to establish globally-unique and unambiguous parts identifiers. • Goals: – Use data elements to track DoD parts. – Ensure data integrity and quality throughout the item's life cycle. – Support multi-faceted business applications and users. – Facilitate Serialized Item Management (SIM) per DODD 4151.18.															www.acq.osd.mil/log/mppr/mssg.htm.

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Unique Identification (cont'd)	UID	• Key Features: – Data integration across DoD, government, and industry systems as envisioned by the DoD Business Enterprise Architecture. – Improved item management and accountability. – Improved asset visibility and life-cycle management. – Clean audit opinions on the property, plant, and equipment and operating materials and supplies portions of DoD financial statements.															www.acq.osd.mil/log/mppr/mssg.htm.
Unscheduled Maintenance		All actions required in addition to normal servicing schedules to maintain a specified condition. Such actions can include any or all of the following steps: a) Localization. b) Isolation. c) Disassembly. d) Interchange. e) Reassembly. f) Alignment. g) Checkout.	X					C	C								
Unscheduled Maintenance		Corrective maintenance performed in response to a suspected failure.														C	
Up State		A state of an item characterized by the fact that it can perform a required function, assuming that the external resources, if required, are provided. Note 1: In English this state relates to availability performance and is sometimes known as available state. Note 2: See also Down State, Degraded State, and Disabled State.											X				
Up Time		The time interval during which an item is in an up state.											X				
Uptime		That period of time during which an item is in a condition to perform a required function. It is the sum of the Operating Time (OT) plus the Standby Time (ST).			X												
Uptime		That element of ACTIVE TIME during which an item is in condition to perform its required functions. (Increases availability and dependability).														X	
Usage		How, or how long equipment has been used. Can include associated factors that may infer the severity of use, e.g. environment, frequency of peak values, etc.															Def Stan 25-24, "Health and Usage Monitoring Capability for Land Platforms (HUMS)".

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Usage Monitoring		The automatic acquisition of data from a system necessary to identify how that system is being used and in what environments.															Def Stan 25-24, "Health and Usage Monitoring Capability for Land Platforms (HUMS)".
Usage Monitoring		The process of measuring responses of, and in some cases, the inputs to, a structure while it is in operation.															Farrar, C. (Los Alamos National Laboratory) et al., "Damage Prognosis for Aerospace Civil and Mechanical Systems", Daniel J. Inman et al. Editors, Published by Wiley, 2005.
Useful Life		Under given conditions, the time interval beginning at a given instant of time and ending when the failure rate becomes unacceptable, or when the item is considered unrepairable as a result of a fault or for other relevant factors.											X				
Validation (UK MOD)		The Validation process is conducted to provide objective evidence that the services (capability), provided by the system when in use, comply with the needs of the stakeholders as defined in the User Requirements Document (URD), and contained in the agreement to acquire the system. Where variances are identified, these are recorded and guide corrective actions. Since validation is a comparative assessment against needs, it also results in confirmation that the stakeholders', and in particular the users', needs were correctly identified and requested; again variances lead to corrective actions.															MOD UK Acquisition Operating Framework, http://www.aof.mod.uk/aofcontent/tactical/randa/content/glossary.htm.
Validation (System)		Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled. Note: Validation in a system life-cycle context is the set of activities ensuring and gaining confidence that a system is able to accomplish its intended use, goals and objectives.										X					

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Verification		The contractor effort to: 1) Determine the accuracy of and update the analytical (predicted) data. 2) Identify design deficiencies. 3) Gain progressive assurance that the required performance of the item can be achieved and demonstrated in subsequent phases. This effort is monitored by the procuring activity from date of award of the contract, through hardware development from components to the Configuration Item (CI).														X	
Verification (UK MOD)		As a Systems Engineering Term – The processes which provide assurance that an integrated system satisfies its System Requirements Document (SRD) requirements. Through assessment of the system product, verification demonstrates that its behaviour and characteristics comply with its specified design requirements. Verification provides the information required to effect the remedial actions that correct failings in the realised system or the processes that act on it.															MOD UK Acquisition Operating Framework, http://www.aof.mod.uk/aofcontent/tactical/randa/content/glossary.htm.
Verification (System)		Confirmation, though the provision of objective evidence, that specified requirements have been fulfilled. Note: Verification in a system life-cycle context is a set of activities that compares a product of the system life-cycle against the required characteristics for that product. This may include, but is not limited to, specified requirements, design description and the system itself.										X					
Visual Check		An observation to determine that an item is fulfilling its intended purpose. Does not require quantitative tolerances. This is a failure finding task.													X		
Wear Out		An increase in the conditional probability of failure with age.					X										
Wear Out Failure		A failure whose probability of occurrence increases with the passage of time, as a result of processes inherent in the item.								X							
Wear Out Failure		A failure whose probability of occurrence increases with the operating time or the number of operations of the item or its applied stresses.											X				
Whole Life Cost	WLC	The life of a system covers the entire spectrum of activity commencing with the identification of the need for the equipment and culminating in its disposal. The objectives of ILS are to ensure that all support requirements are identified and put in place in a manner which contributes to the optimisation of overall WLC, by influencing design, identifying cost effective support solutions and the employment of appropriate modelling techniques.		X													

Term	Abbrev	Definition / Description	A	B	C	D	E	F	G	H	I	J	K	L	M	N	Other Source (Specify)
Widespread Fatigue Damage	WFD	WFD in a structure is characterized by the simultaneous presence of cracks at multiple structural details that are of sufficient size and density whereby the structure will no longer meet its damage tolerance requirement (i.e. to maintain its required residual strength after partial structural failure).															FAA Advisory Circular, “Damage Tolerance and Fatigue Evaluation of Aircraft Structure”, AC 25.571-1C, Dated 29 April 1998 and Mil-Std-1530C (USAF), “Aircraft Structural Integrity Program (ASIP)”, 1 November 2005.

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Corrosion prevention	Maintenance	Usage monitoring

14. Abstract

This report identifies maintenance/support management and equipment technologies which can improve aircraft platform availability. It contains information from a Workshop of invited specialists held in October 2006 (RTO-MP-AVT-144) and separate research by the AVT-144 Technical Team. Aircraft availability is a key component of military capability and an important measure of the readiness and effectiveness of a force. For military effect, high availability on the flight line must be accompanied by continued availability throughout a mission profile, i.e. mission reliability. During deployments and expeditions, a higher than average availability is usually desired. To maximise availability it is necessary to minimise the need for maintenance and the associated downtime. Attrition due to battle damage must also be minimised. The design and management of an aircraft and its maintenance/support occurs in the context of many competing priorities for the available development and operating funds. Therefore, it is important that a systematic approach is followed to achieve an acceptable balance between availability and other force requirements. The report describes how advanced systems engineering and business management processes and advanced aircraft and support equipment technologies can be applied in an integrated manner to achieve this goal.

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