The Management of Reliability and Maintainability and the Choice of Maintenance Concept to Optimize Aircraft Availability and Life Cycle Cost

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ABSTRACT

The motivation to invest continued effort into the subject of aircraft availability springs from the following:

a) *Resources for new acquisitions are steadily falling;*
b) *Cost of maintaining legacy systems are ever-increasing, yet they will need to be retained for periods well past their originally envisioned lives; and*
c) *Combat readiness, based on recent experience, is looming as a big issue for military establishments in many countries.*

To a military commander, safety, reliability and combat readiness of his high-value assets are of prime importance. The same is largely true in the civilian sectors. As a result, one has to err on the conservative side, but the dilemma is that conservatism needs to be well quantified because undue conservatism is wasteful and insufficient conservatism could be fatal. Moreover, early diagnosis of impending failures assists the commander in effective resource management by making possible forestalling actions. To achieve such an objective, three extremely difficult problems need solution:

a) *Diagnostic systems must keep false calls, both positive and negative, to an absolute minimum, for otherwise the costs of maintenance and the fearsome prospect of non-availability of assets when needed will escalate exponentially.*
b) *Data documenting malfunctions and defects will need to be gathered for prognosticating the state of health of the system through robust statistical approaches, yet the data gathering requirements cannot be burdensome.*
c) *Certain modes of failures in aging systems may not be amenable to prognostication through diagnosis and health monitoring; hence they need to be defended against through innovative design strategies.*

Efficient gathering of in-service data is of course a prerequisite to achieve the objectives. However, data gathered in the absence of agreement by the design and manufacturing, operator, and maintenance communities as to what data elements need to gathered and archived, and how exactly the data are going to be used has always been the bane of such efforts. Thus, data gathering efforts must have the following attributes: timeliness, high integrity, standards, security, and, above all, they should not become an unbearable burden to the maintenance community whose duty it is to also keep downtime to an absolute minimum. In the same context, consideration of new technology for data collection, archival, and retrieval may be useful.

The topical areas that will be addressed in this paper are:

- *Design improvement to provide better reliability and maintainability;*
- *Maintenance Strategies and Maintenance Concepts; and*
- *Data evaluation, data assessment and economic decision support.*

All three areas will discuss in the context of means to reduce life cycle cost and improvement of availability.

1.0 INTRODUCTION

Military operators require high levels of mission effectiveness and supportability to ensure that all scheduled missions can be successfully completed. The emphasis must be on safe and reliable aircraft operation under all environmental conditions and with minimal logistic support resources. To achieve this goal tremendous effort has been spent to improve the design for better maintainability and reliability. However, in service experience shows that operational interruptions due to unscheduled maintenance remains a dominant factor during operations and that there are deficiencies in aircraft diagnostics in particular when we are talking about fault isolation capabilities.

To fulfil current and future defence requirements we have to offer a maintainable design combined with integrated support solutions.

The scope of the paper is to provide an overview about maintenance strategies and methods to be used to ensure high level of supportability and maintainability. The second part of the paper will discuss the Integrated Logistic Support methods and tools to be used in design and product support. The last part is focused on information services including diagnostic and health management as the most promising technology to improve aircraft and fleet availability and to reduce life cycle cost.

The content of the paper is prepared according to the guideline of the workshop. In this context the paper is designed to provide an overview and background information rather than a full understanding of the complexity of aircraft availability management.

1.1 Definitions

The definitions in this chapter originate from the European Standard EN 13306 [**1**], unless otherwise indicated. This standard was approved by the CEN in 2001. CEN is the European Committee for Standardization, which was founded in 1961. Cf. [CEN01], [I-CEN05].

Maintenance is understood as 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." As this definition clearly shows, maintenance is a cross-sectional responsibility.

1.2 Technical Aspects

Technical aspects of maintenance must be considered in all phases of an items life cycle. During conception and construction phases engineers have to keep maintainability in mind, which is the "ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can reform a required function, when maintenance is performed under given conditions and using stated procedures and resources."

The desired *reliability*, the "ability ... to perform a required function under given conditions for a given time interval", as well as the *durability*, the "ability ... to perform a required function under given conditions of use and maintenance, until a limiting state is reached" also have to be taken into account.

If an item should be relevant to the safety of a system, *redundancies*, either *active* (i.e. all items performing the same function operate simultaneously), or *standby redundancies* (i.e. one part operates, the others remain inoperative until needed) will have to be planned.

A helpful tool at this stage of the planning process can be *Failure Mode and Effect Analysis (FMEA)*, a technique that tries to predict causes and effects of failures. The knowledge of failure behaviour is essential. While the item is in operation, failure can occur as *wear-out-failure*, whose "probability of occurrence increases with the operating time or the number of operations ... or ... applied stress", as well as *ageing failure*, whose "probability of occurrence increases with the passage of time." Failure can also be *random.*

If information regarding failure behaviour is not available it can be obtained by a variety of testing methods, e.g. accelerated life cycle tests. Since failure behaviour is hardly ever deterministic, it is often modelled using statistical distributions.

1.3 Administrative Aspects

The administrative aspects of maintenance are extensive. They extend from strategic decisions (e.g. organisational structure of maintenance operations) down to operative decisions (e.g. which documentation of maintenance activities to use). Since this sub area is not of focal interest to this paper, it will not be discussed at this point.

1.4 Managerial Aspects

[CEN01] defines Maintenance Management as "all activities of the management that determine the maintenance objectives, strategies, and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, improvement of methods in the organization including economical aspects."

This definition involves all levels of an organization, and stresses once again the cross-sectional character of maintenance.

Figure 1 illustrates some of the other organisational units that interact with maintenance. While *CEN's* definition does not directly mention legal aspects, those may not be forgotten, and can constitute restrictions, as far as maintenance intervals or replacement policies are concerned.

Quality Assurance	Production	Materials Management
Assets Management	**Maintenance**	Personnel Management
Service	New Development Planning	Controlling

Figure 1: Interfaces of Maintenance.

2.0 UNDERSTANDING OF ENHANCED AVAILABILITY

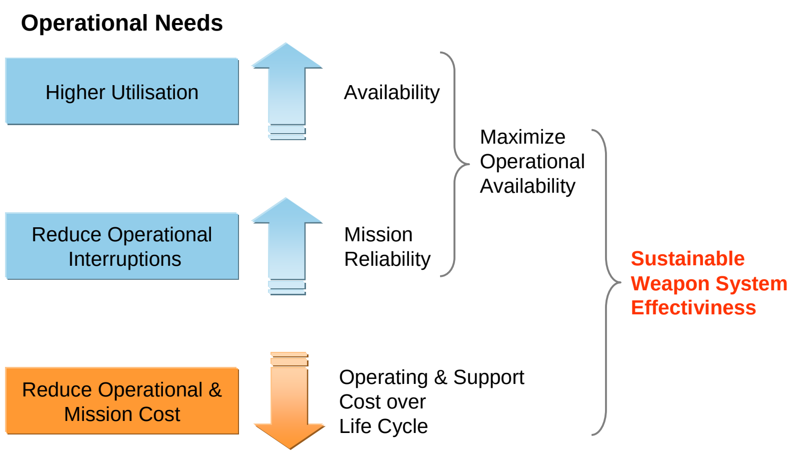


Figure 2: Optimization throughout the Life Cycle.

Each operator is looking for a high utilization rate of the aircraft or fleet which means less downtime due to scheduled maintenance or to minimize operational interruptions due to unscheduled maintenance. These operational requirements are a trade off in the design to maintainability and high reliability to affordable life cycle costs.

Because it is so important to understand the requirements of enhanced availability the following chapter will try to explain the terms Higher Utilization, Reduce Operational Interruptions and Life Cycle Cost in more detail.

Higher Utilization: ➔ maximize the time where the product can be operated.

The related challenges can be grouped as follows:

- Scheduled maintenance should be reduced and optimizes as per aircraft usage.

  - Generally there are different levels of effort imaginable to realise a Usage Monitoring. Low effort on Usage Monitoring results in low costs but a high loss of Remaining Useful Life [RUL]. The benefit of high effort is the maximum exploitation of RUL but at the same time the costs for Usage Monitoring System are higher. Increasing investments for developing and producing a new WS have promoted the tendency to extend the in-serve time of existing WS. The initially planned in-service time is ensured by the experiences of a fatigue test, which is initiated in the design phase. When extending the in-service time the experience of operational usage, which might differ from the assumptions made in the design phase, becomes more and more important. Changing boundary conditions, such as modified parameters of operational usage and modifications of the Weapon System itself, require high accuracy in evaluating individual operational usage.

- More flexibility should be provided for maintenance planning and management.
  - This relates strongly to the maintenance strategies to be selected to ensure high utilization. Trends are showing an increase application of condition based maintenance, predictive based maintenance and maintenance free operating periods, thanks to new technologies e.g. health management capabilities new concepts are becoming mature for operations.

- Precise decision making based on reliable aircraft and fleet information.
  - Integrated maintenance information systems are key enabler to acquire, process, and distribute the information across all maintenance related processes to support a better and reliable decision making.

Reduce Operational Interruptions: ➔ Improve Mission Reliability.

The related challenges can be grouped as follows:

- Assessment of failures & damages should be as fast as possible.
- Improved trouble shooting capabilities rely on improved diagnostic to isolate the failure and link the maintenance action to the relevant maintenance procedure.
- Unscheduled maintenance actions should be avoided during Turn Around Times.
- Reduce Operation and Support Costs.

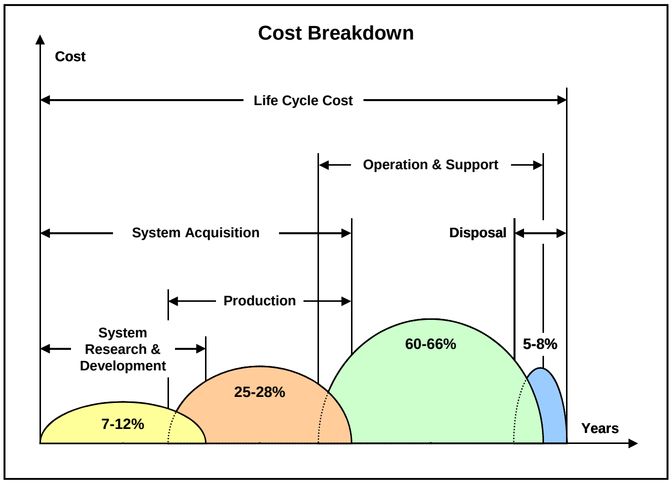


Figure 3: Current Cost Breakdown of Product Support in the Development Phase.

The following conclusion can be determined from **Figure 4**. The Customer spends for the Acquisition (Research & Development Phase + Production Phase) 40% of the total Life Cycle Cost of the acquired Weapon System. The rest 60% of the cost occur in the Operation and Support Phase. But it is exactly during the Research & Development Phase, when these costs are being fixed, by determining the reliability and maintainability which are mandatory to the Operation & Support cost.

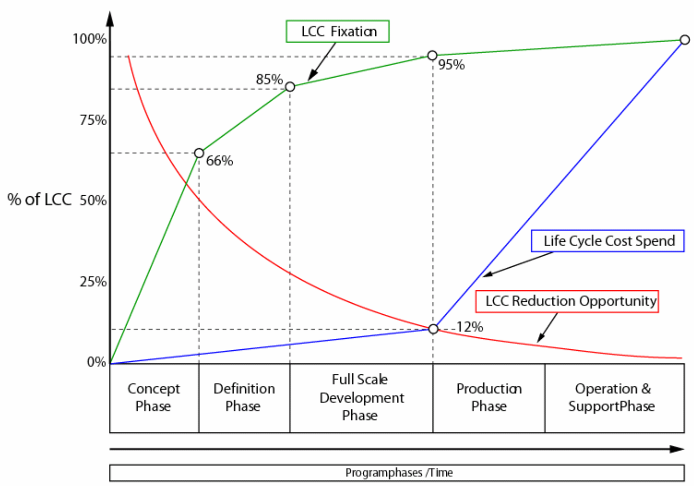


Figure 4: Opportunity (early impact of decisions of LCC) to reduce cost as per Phases.

It is obvious that the customer wants not only to acquire the best performance for its weapon System, but the optimum balance between performance & supportability (which will determine the availability of the Weapon System).

A Cost Efficient System depends on the efficiency of the Weapon System and what this Efficient System costs in its entire Life Cycle.

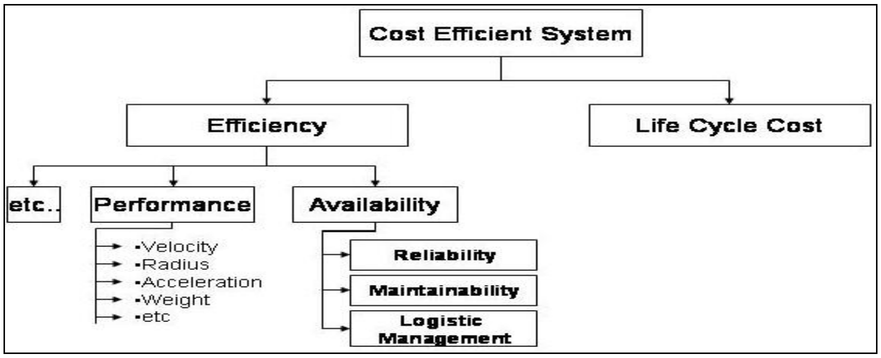


Figure 5: Cost Efficiency.

Not seeing the Operating & Support Cost in its real cost relevance is for sure the responsibility of poor management that will be surprised by high Operation & Support costs, and a reduced availability of the Weapon System what will lead to a System that may have great performance, but low availability that at least will lead to an inefficient system, that also is not cost efficient.

3.0 MAINTENANCE STRATEGIES

3.1 Maintenance Strategy Planning

Maintenance strategy planning (*MSP*) cannot be discussed detached from investment planning. By determining which items to procure and determining the operating time, it sets the basic parameters for *MSP*. The economic life time is determined by investment policies. In most cases it is be possible to prolong the life of an item by maintenance measures, but technological progress or legal restrictions (often environmental) render the item obsolete. Also, it may be more cost-effective to replace an item, as compared to successively replacing many parts of that item. On the other hand, it would be too costly to replace an item each time a failure occurs. A proposed compromise is the classification of failures into two categories:

- Failures, that are so grave they raise the question of whether to replace the item by a new one.
- Failures, that are corrected by maintenance means.

MSP then encompasses all preventive and corrective maintenance activities, whose costs do not exceed the costs of a replacement item. To identify a useful maintenance strategy, STRAUSS proposes a mathematical model [**2**] that sufficiently represents the actual item to be maintained. He first differentiates economical and technical characteristics of the item. This is done for three reasons:

- Wear will at first result in a change of the actual technical state of the item.
- This change in the technical state may lead to a change in an item's economic properties.
- Only if these correlations are properly understood and modelled is it possible to determine economically reasonable technical maintenance activities.

Then, meaningful condition features are developed, which allow to distinguish different conditions (both economic and technical). In the proposed model, these condition features are expressed by vectors. Technical vectors are matched to economic vectors, to describe the influence of one on the other. Wear is modelled using statistical functions since it is assumed that in most cases the technical state of an item is not directly observable. Maintenance activities are represented by altering the relevant elements of the concerned vectors.

ROKOHL [**2**] takes a slightly different perspective. He presents the investment process as a rotation process of investing, de-investing and reinvesting. The maintenance process is seen to be starting with investing, and ending with de-investing. During the reinvestment phase, when assets generate capital flow, maintenance compensates for an items decrease in value caused by wear. The consideration of maintenance aspects during the procurement process and the determination of the optimum point of time to replace an item are responsibilities of maintenance managers.

According to ROKOHL, maintenance and investment are alike in two characteristics: investment, as well as maintenance activities, commit capital and share a renewal characteristic.

The actual maintenance strategy planning process is subdivided into four phases: *Inducement, Selection, Optimization and Supervision*:

- *Inducement*: Planning and execution of maintenance activities are induced by an item's diminishing value, caused by wear or aging. Information is gathered, to facilitate an exact formulation of the planning problem at hand. Appraisal factors, as well as precise formulation of objectives, are established.
- *Selection (Finding and evaluating)*: All suitable strategies are considered. Using the established appraisal factors, the number of possible strategies is reduced, leaving only the most promising ones.
- *Optimization*: This phase is largely determined by the choice of optimization method. Because of the complexity of the planning problem at hand, strictly mathematical analysis is seldom feasible. ROKOHL suggests the use of operations research methods and simulation.
- *Supervision*: Actual states and planned states on an item are matched. Deviations are analyzed, and results are used to improve strategies by starting a next round of strategy planning. Often cost-benefit analysis is put to use.

Regardless of which approach is put to use: the result of maintenance strategy planning activities will be a decision in favour of a specific maintenance strategy that, given an organisation's current circumstances, seems optimal.

In the following, possible maintenance types and strategies will be presented.

3.2 Classifications

Maintenance Strategies have to entail instructions concerning three questions:

- Maintenance Type.
- Point in time, at which maintenance activities are to be carried out.
- Extent, to which maintenance activities are to be carried out.

STURM discusses three maintenance strategy types:

- *Damage Based Maintenance* is a failure strategy. No preventive maintenance activities are carried out (As a result, the point in time of maintenance activities is random). An item's failure usually results in down time for a larger system. Therefore, a quick decision has to be taken, whether an item is to be repaired completely (i.e. after the correction the item's conditions equals that of a new item), or to be repaired by a minimum amount (i.e. item is able to carry out required function for a limited period of time). *Damage Based Maintenance* uses up the entire wear reserve, which is advantageous. On the other hand, it is nearly impossible to plan and coordinate maintenance activities. Also, consequential damage may occur in connected items.

- *Time Based Maintenance* is planned and preventive. Maintenance is carried out after fixed time intervals T_N. Should a failure occur, only minimum repairs are carried out. Alternatively, the previously planned maintenance activities are carried out, and a new maintenance cycle is started (This may not be possible for certain items, whose maintenance schedules are determined by external factors, such as seasons). This maintenance approach allows for very good planning and high reliability. Unfortunately, only part of the wear reserve is used, and partly unnecessary measures are costly.
- *Condition Based Maintenance* tries to combine the advantages of the two previous approaches. All available methods are used to obtain information to determine the technical state of an item (These may include, among others, inspections, monitoring and compliance tests. This is done at regular intervals or online). Results are compared to desired states, and decisions are made, if maintenance is necessary or not. In conclusion this enables the user to maximize the use of the wear reserve, while maintaining a high reliability. Still, knowledge of the technical state may be faulty due to ineffective or inaccurate indicators.

The expense that accompanies the detection of these actual conditions is largely influenced by the type of detection used. *Subjective detection*, which relies on human senses, generally uses little time and is not very cost-intensive. One detriment, however, is the dependency of results on the inspector's experience.

Objective detection, which uses instruments to measure values or parameters, is independent of this experience, but costs may be considerably higher. If continuous detection is needed, inspection devices will have to be fixed to the item that has to be inspected. Measured values can be input into a diagnosis system that can ensure a high reliability of monitoring. Discontinuous detection will frequently require the inspected item to be off-line. As compared to continuous condition detection, more maintenance personnel is needed.

Once values and parameters have been obtained, an item's condition has to be evaluated. In a simple approach, the item may be deemed "operative" (i.e. no further maintenance measures are necessary) or "inoperative" (i.e. corrective maintenance has to be carried out). In a superior approach, the remaining wear reserve is predicted. To do so, the given condition feature, the limiting value as well as the rate of change are used to extrapolate the remaining service life.

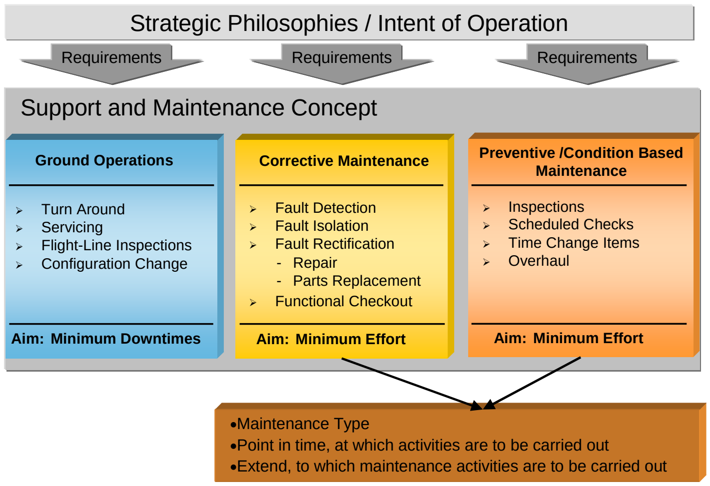


Figure 6: Maintenance Strategies and Concepts.

Preventive Maintenance is performed before an item reaches a disabled state or fails. This can be done based on an item's condition (Condition Based Maintenance), or in accordance with established intervals of time or established number of operating cycles, without previous condition investigation (Predetermined Maintenance).

Corrective Maintenance is carried out after a fault has been observed, and intends to put an item back into a state, in which it can perform the desired function. This can be done right away (Immediate), or it can be delayed until a later point in time (Deferred). Predictive Maintenance, which is Condition Based Maintenance that derives a forecast of an item's degradation from the analysis of significant parameters.

Strictly Periodic Maintenance Strategies dictate preventive complete maintenance after a fixed operating time τp since last preventive maintenance measures. Thus, there are fixed dates for maintenance activities. Should a failure occur, minimum or complete repairs are carried out.

Flexibly Periodic Maintenance Strategies plan prophylactic complete maintenance after reaching a certain up time τp since the last preventive or corrective (complete) maintenance. If an item fails, it is restored to its original state. Then a decision is made, if the next maintenance date is to be scheduled (τp) after the last prophylactic or corrective maintenance activity.

Diagnostics Strategies use preventive diagnostics and maintenance activities depending on these diagnostic findings. Diagnostic activities may be periodic or continuous. Prophylactic maintenance is carried out after reaching a certain up time τp since the last preventive or corrective (complete) maintenance. Consequently dates are fixed, but the extend of may depend upon the diagnostics findings.

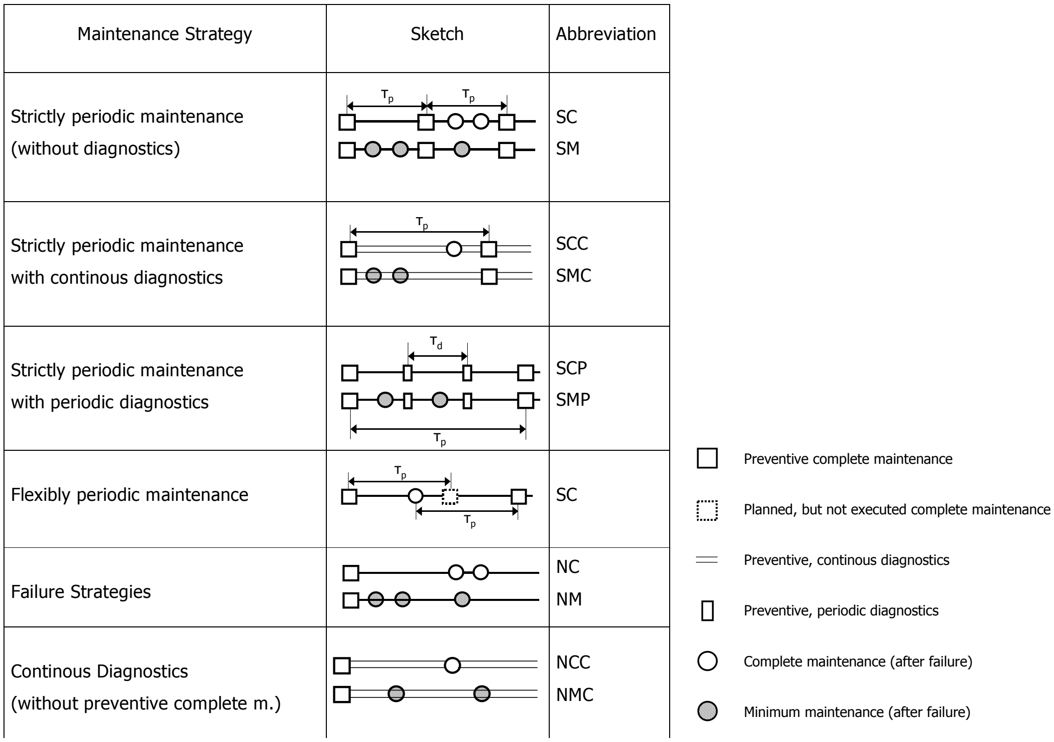


Figure 7: Maintenance strategy types.

Table 1: Nomenclature of Figure 5.

Type of preventive measures	Extend of regeneration	Type of diagnostics
S strictly periodic	C complete	P Periodic
F flexibly periodic	M minimum	C Continuous
N no preventive measures		- no diagnostics

All of the above mentioned strategies are useful, given the right circumstances. This far, maintenance types and strategies have been presented. To put these to use effectively, comprehensive concepts have to be found to incorporate all useful strategies.

3.3 Reliability Centred Maintenance (RCM)

Reliability Centred Maintenance is one of the most recent maintenance programs. **Figure 8** illustrates the maintenance strategies it tries to optimally combine.

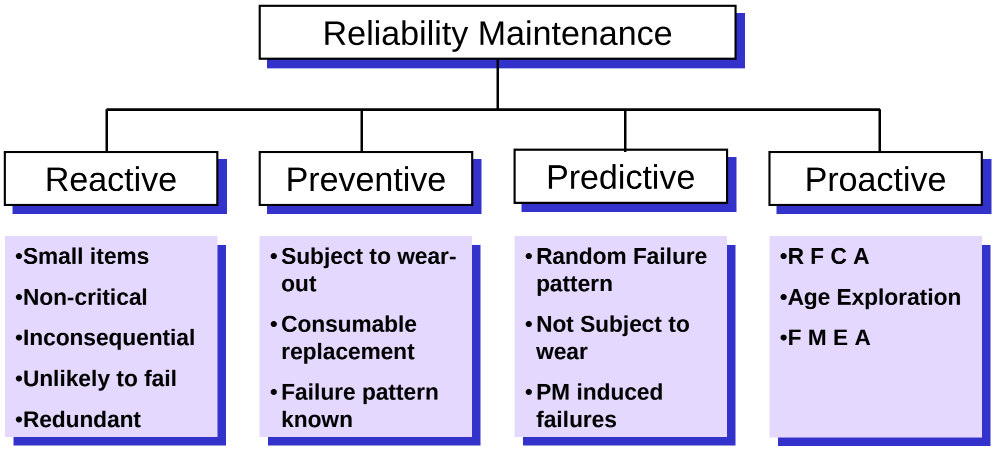


Figure 8: Components of an RCM Program.

RCM was first introduced in 1978. It tried to compensate the major shortcoming of *Preventive Maintenance(PM)*: two of the basic assumptions of *Preventive Maintenance* had been proven false for a majority of equipment: there was no strong correlation between age and failure rate, and statistical modeling of failure behaviour was imperfect in most cases.

The principles of *RCM* were first put to use by industries that cannot afford failures, like aircraft, space and defense. This imperative leads to four key objectives of *RCM*:

- Inherent safety and reliability levels of equipment have to be ensured, to protect users (and customers).
- When deterioration occurs, equipment has to be restored to these inherent levels by maintenance activities.
- Should the inherent reliability prove inadequate, information has to be gathered to enable design improvements.
- All this has to be done at minimum total cost, i.e. maintenance costs and economic consequences of a failure have to be taken into account.

The approach to the installation of a *RCM* program requires an analysis that takes five major steps:

- Step 1. System and system boundaries have to be identified, incorporating resources and constraints.
- Step 2. Sub-systems and their components are identified to the required level.
- Step 3. Functions of components are examined (primary vs. support, continuous vs. intermittent).
- Step 4. Failure and failure modes are defined (hidden failures, potential failures).
- Step 5. Consequences of these failures are identified, focussing of safety, availability and cost.

It is easy to see that these steps will impact on all the phases of any equipment's life cycle. To achieve and maintain a high level of reliability, *RCM* utilizes three types of maintenance tasks:

- Time-directed tasks (PM), which are scheduled.
- Condition-directed tasks (PdM), which are performed when needed.

- Failure-finding tasks (part of Proactive Maintenance), which try to find failed hidden functions.

If none of these tasks are applied, which may be the case if maintenance activities cannot prevent failure, *Run-to-Failure* is chosen, a thinkable option for certain equipment. Maintenance tasks are only applied of they aid in preventing failures or lessen failure consequences. If this is not possible, the design limitations have to be acknowledged.

At this time, the four components - Reactive, Preventive, Predictive and Proactive Maintenance of RCM are inspected.

Reactive Maintenance only dictates maintenance activities only after a functional failure occurred. It is also referred to as Run-to-Failure (RTF) or fix-when-fail maintenance. This technique should only be applied for small, non-critical or redundant parts. Also, a high percentage of unscheduled maintenance activities and high spare part inventories have to be accepted.

Preventive Maintenance, also called time-driven or interval-based maintenance, relies on a regular schedule to inspect, clean replace or repair parts. For this technique, it is consequential that the failure characteristics of the maintained system are known. This knowledge may derive from two sources, either from experience or from failure distribution statistics. In both cases inspection intervals should become shorter as the anticipated failure draws nearer.

If there is no information concerning the failure characteristics, a so-called conservative approach can be used, where equipment is monitored weekly, biweekly or monthly, which in most cases is excessive.

As mentioned before, a PM approach should only be used for parts that are subjected to wear, and to parts whose failure patterns are known. For some parts a Weibull distribution can be used to model that failure behaviour. That these failure patterns do not apply to other equipment does not mean that said equipment does not age or is not subjected to wear. But it does mean that failure behaviour is not significantly determined by age. In those cases, PM should not be used.

Predictive Testing & Inspection (PT&I) uses information about an item’s condition to schedule maintenance. It is also labelled Predictive Maintenance or Condition Monitoring. This information can be gathered using a range of non-intrusive testing techniques and performance metrics of the equipment. The data has to be analyzed, which may be done through trend analysis, pattern recognition or correlation of multiple technologies.

By continuously monitoring a system’s condition, it is possible schedule and coordinate maintenance tasks before failure occurs. Since not all components qualify for condition monitoring, it is futile to use PT&I as the only maintenance technique.

Proactive Maintenance is a new technique. Its ultimate goal is to fix equipment forever, or in other words, to make maintenance unnecessary. To do so, it uses several techniques, which will briefly be presented:

- In a first step, maintenance and maintainability are accounted for when purchasing new equipment. Thus, specifications for new or rebuilt equipment will contain requirements for capabilities to easily obtain condition data while the system is operating (on-line monitoring). In addition, failure histories of equipment families are documented and used, along with LCC).
- Should a failure occur, the cause of the failure is determined Root-Cause Failure Analysis(RCFA), to avoid fixing just the symptoms of a malfunction. Instead, emphasis is placed on determining the cause

of the problem as quickly as possible whilst keeping in mind economical aspects. Then the cause of the problem is corrected. The whole process is documented, to help avoiding this failure cause in the future. RCFA is an essential module of the "fix forever" mentality.

- In some cases it will be necessary to replace a component with a new, superior component. Then, Reliability Engineering is used to redesign, modify or improve the existing component. The extent of this redesign may vary, from using new materials to the construction of an entirely different engineering solution to a given problem.
- Reliability calculations are proposed. Mean Time Between Failures (MTBF), failure rate and availability should be available to maintenance and operations staff.

Many elements of RCM only became possible in the last decade, through the higher availability of cheap and reliable information technology. As technical progress in sensors and engineering sciences continues, RCM will continue to increase in effectiveness and, ultimately, in importance for organizations.

3.4 Availability Centred Maintenance (ACM)

Availability Centred Maintenance ACM is a further development of Reliability Centred Maintenance (RCM). It was introduced by GE Power to take into account some of the deeper Customer – Manufacturer relationships that had evolved.

Manufacturers no longer simply supply products, but rather offer closed service packages. In these Contractual Service Agreements (CSA), the manufacturer will generally guarantee a certain availability of an asset. In that case the responsibility for maintaining the item lies with the manufacturer. It is not uncommon to outsource maintenance activities. In consequence, maintenance becomes "a three person game that is extremely difficult to manage. Availability can be seen not as result on three parameters; maintainability, reliability and logistics. But availability can also be seen as the criterion through which the best combination of maintainability, reliability and logistics can be determined.

The following seven steps in the ACM procedure are proposed:

- Analysis of the Process & Instrumentation Diagram and equipment specifications.
- Analysis of the operating conditions.
- Collection of reliability data for the equipment.
- Analysis of reliability data for the equipment.
- Definition of the maintenance tasks relating to the equipment.
- Random simulation of risks and ranking of Availability Importance (AI) of each component.
- Definition of optimum spare parts list and location to achieve the required level of availability.

4.0 INTEGRATED LOGISTICS SUPPORT (ILS)

4.1 General

The prime mission of the Air Forces is the defence of their Nations. The ability to achieve this mission is directly related to Availability to Air Force Systems. Air Force Systems must be operational, available at any time a mission demand occurs.

The Availability of an Aircraft System is dependant upon Reliability (or the probability that the system will continue to operate and complete a specific mission, Reliability is an Aircraft Up-Time measure) and the Maintainability (or the ability to shorter the Downtime for maintenance and repair).

An important part of the Acquisition Phase (Development and Production) is the planning, programming, development, acquisition, and delivery of the support resources to ensure the supportability and readiness of an Aircraft weapon system. The ILS is the management and technical process that provides integration of all phases of supportability.

It is obvious that Logistic Support problems can limit an Aircraft's availability. Air Forces carefully monitor statistics on those Systems which are not operationally ready, because of maintenance or supplying difficulties.

They recognize the importance of having the Planning, Maintenance Data, Spares parts, Technical Publications, Test Equipment, and trained Personnel etc necessary to maintain the Aircraft properly. This reduces the resulting maintenance Downtime and increases the Availability.

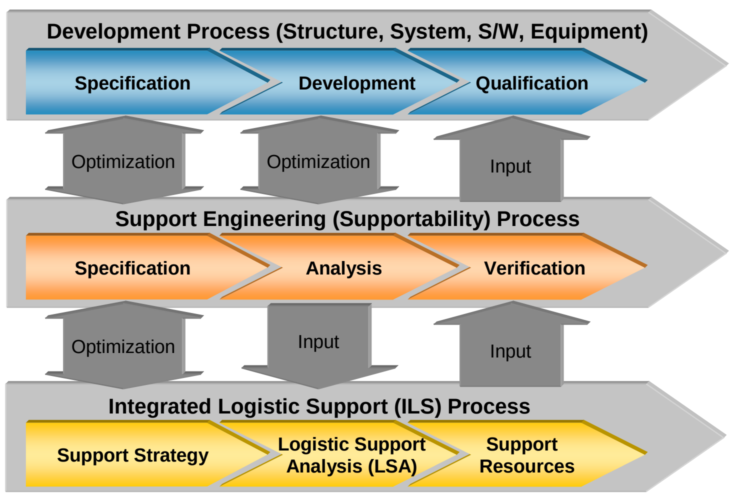


Figure 9: Integrated Logistic Support.

The ILS is defined as 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.

The ILS is the management process to facilitate development and integration of the individual support elements to design and development (or acquire), produce and support Systems. The ILS considerations are addressed early in the Pre-Development and the Development Phases and continue in varying degrees throughout the entire Life Cycle of the system.

Logistic Support must receive proper emphasis and effort during the planning and design of Air A/C weapon systems. It is crucial that Reliability and Maintainability constraints be considered during the design process. In view of this Logistic Support requirement and Analysis must be applied during the System Engineering process, to bring together (integrated) Design / Development and Logistic Support concepts, and as a consequence application of the Integrated Logistics Support concept, since the early Phases of a Programme. The objective: a Design that is supportable instead of supporting a determined Design. The result: a Weapon System that is designed for Supportability and ready to meet mission requirements.

Additionally to the Design Interface, the Support System also includes Planning, Maintenance /Support Analysis and Data, Spares parts ,Handling ,Storage and Transportation, Technical Publications, Test Equipment, trained Personnel, Training Equipment, Facilities etc . All of these logistic areas are referred to as Integrated Logistics Support Element (I.L.S.E.) and must be managed throughout the Life Cycle of the aircraft. The Life cycle of an A/C system includes system Design and Development, Production and Deployment, Operation and Support. Generally speaking 60 to 70% of Life Cycle costs are spent in Operation and Support. For every 1€ cost spent in acquiring an Aircraft system, approximately 2 times equivalent cost are spent in Logistic Support. In view of the tremendous support costs, Reliability, Maintainability, Logistics Supportability must be designed into the weapons system. More specifically, at the time weapon systems are being designed, attention must be given to supportability impacts of the design. Further, the support requirements are developed simultaneously with the A/C system. As Reliability is designed into a weapons system fewer spares, repair parts, facilities and technical manuals will be required. Incorporating consideration for maintainability into the design, such as standardization and interchange ability of parts, accessibility and simplicity reduces the number of personnel and the level of skills required to carry out maintenance.

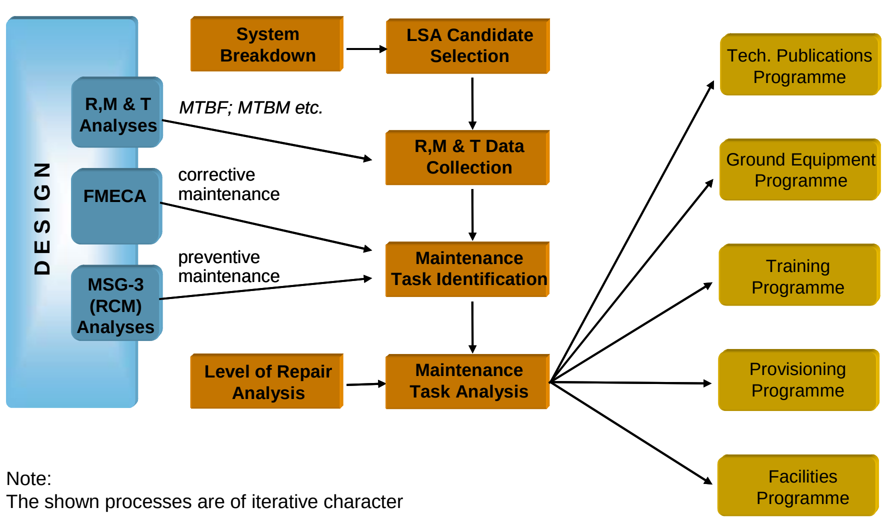


Figure 10: Logistic Support Analysis (LSA) Process.

The basic elements of ILS are:

- **Design influence and integration**, to include logistic-related Reliability, Availability, and Maintainability/Testability (RAM).
  - ➢ The ILS process is concerned with Design influence, mainly in Reliability and Maintainability/Testability characteristics (to reduce Operating and Support costs and simplify equipment operation and maintenance) and design, development, testing, and acquisition of the items of support (to assure satisfactory operation and readiness of the system/item).The degree of effectiveness of ILS in terms of design influence dictates to a large extent the demand placed on support requirements.

- **Elements of support**:
  - ➢ 010-ILS Management / Support Planning.
  - ➢ 020-LSA / SAS (Logistics Support Analysis / Software Support Analysis Hardware and Software) Maintenance Planning.
  - ➢ 030-Material Support, including Packaging, Handling and Storage.
  - ➢ 040-Technical Publications.
  - ➢ 050-Aerospace Ground Equipment.
  - ➢ 060-Personnel Training.
  - ➢ 070-GTAs Ground Training Aids and Training Equipment.
  - ➢ 080-Facilities.
  - ➢ 090-CETS / FSRs Contractor Engineering Technical Support /Field Service Representatives.
  - ➢ 100 Air / Mission Crew Training Aids (Simulators).

4.2 Logistics Support Analysis

Logistic Support Analysis or LSA is an analytical-engineering process. When LSA has been performed, the mission equipment is designed to be supportable at the least LCC. Industry and Customer Program Managers are responsible for assuring that all Weapon Systems designed developed and produced (or procured from Suppliers) are logistically supportable. Therefore, if system design is to be influenced for supportability and logistic support resources are to be identified in the Acquisition process. The objectives of LSA are twofold:

- To influence system design for supportability; and
- To identify the logistic support requirements.

First, impacts on system supportability are identified based on system design characteristics. LSA gives the Program Manager the opportunity to influence system design to accommodate specific logistics requirements.

For example, a system can be designed to be maintained by a high level technician with 5 common hand tools within 2 hours in existing facilities and with common support equipment. The 2nd LSA objective is to identify the ILS Requirements associated with the system design as the mission equipment is developed, operation and maintenance tasks required to support the system are being identified. In addition to the tasks themselves, the data for Spares, Technical Publications, AGE Training (manpower, skill levels), and Facilities etc. are identified that are necessary to carry out those tasks. Thus, LSA is a structured way to get the designer to consider the supportability impacts of his design and also requires the designer to identify and document those Logistics Support requirements needed to support the design.

LSA is a support engineering process. LSA is regulated by 2 military standards: Mil Standard 1388-1A and Mil Standard 1388-2A/2B. The requirements in both Mil Standards are applicable throughout all phases of the System Life Cycle. LSA starts in the conceptual phase of the system acquisition cycle, where various ideas are being tested and demonstrated to prove, whether or not, they meet Air Force needs. LSA considers the support concepts needed to keep the systems operational. In addition, LSA applies to all Defence acquisition programs, which includes aircraft, missiles and equipment, and systems going into space.

LSA applies to these systems within the Definition Design and Development, Production and Operation and Support.

LSA also applies to modification programs on existing systems. Mil Standard 1388-1A describes the 15 LSA tasks, its goal is to present a single uniform approach to causing support requirements to be integrated with system requirements and design Mil Standard 1388 1A , as it is called, is a tasking document which is comprised of scientific and engineering tasks which, when performed in a logical and iterative nature, comprise the LSA process. The data generated as a result of performing LSA tasks is called LSA documentation.

5.0 INTEGRATED MONITORING AND RECORDING SYSTEM

The general aim of monitoring a system is the prediction of the remaining useful life and the determination of maintenance action according to economic constrains. Since especially military aircraft are exposed to a wide range of usage, the condition state is one of the substantially limiting factors for the in-service life time. Generally there are different levels of effort imaginable to realise a Usage Monitoring. Low effort on Usage Monitoring results in low costs but a high loss of remaining useful life. In this case high scatter factors have to be applied. The benefit of high effort is the maximum exploitation of the remaining useful life but at the same time the costs for usage monitoring system are higher.

Increasing investments for developing and producing a new WS have promoted the tendency to determine more accurately the system or component usage and allowing nowadays to implement a more flexible maintenance policy or to enable the customization of maintenance programmes based on accurate condition monitoring capabilities. The presence and effectiveness of Condition-Based Maintenance (CBM) systems is growing rapidly under market demand for minimum Life Cycle Costs, ever increasing data processing and storage capability, and widespread implementation of network technology. Life Cycle Costs can be reduced and aircraft fleet availability can be improved through implementation of health monitoring technologies, optimal maintenance practices and continuous design improvement.

The Eurofighter Typhoon aircraft consist of an Integrated Monitoring and Recording System IIMRS) software fitted to each Eurofighter (see **Figure 11**). The IMRS forms an integral part of the Avionics suite on Eurofighter. Its main functions are:

- Structural Health Monitoring facility.
- Mission data loading facility.
- Video voice recording facility.

- Mission data recording facility.
- Crash recording facility.
- Maintenance data loading facility.
- Limited configuration checking facility.
- Maintenance data recording facility.
- Special study recording facility.
- Warnings handling facility.
- IBIT handling facility.
- Recording of consumables information facility.
- Erasure of secure data facility.

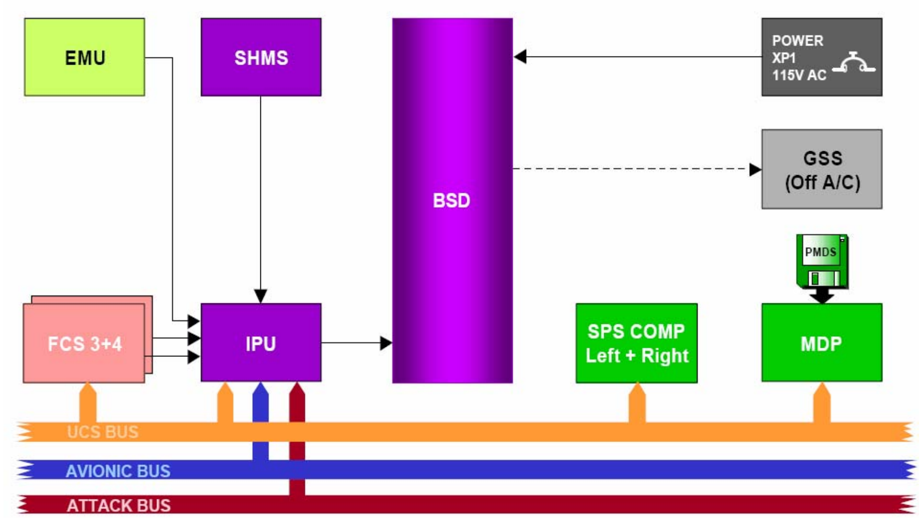


Figure 11: SHM and integral part of the Integrated Monitoring and Recording System Eurofighter.

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*60*25 mm). The PMDS is used to transfer SHM, engine and maintenance data to and from the aircraft.

As a consequence of rapidly growing network capabilities also the on ground segment is being a part of the aircraft’s integrity certification process, concepts and initiatives have emerged that are intended to handle the data flow on ground as well as the follow on logistic processes. Derived from the strong health monitoring initiative around the Eurofighter Typhoon aircraft, analysis and synergy has to be established based on information being generated from the following tools, systems and actions:

- 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).
- Aircraft integrated systems (AIS).

Information regarding all this is currently downloaded by different means and protocols and it is a major need to get this organize to get maximum use of the health data.

It is important to understand how and where the data and information are used in the supportability process. The are two main decision support levels which are called “Tactical Level” and “Strategic Level” which require a different detail of information. **Figure 12** details the two levels of decision support and provides a rough indication what type of information is needed.

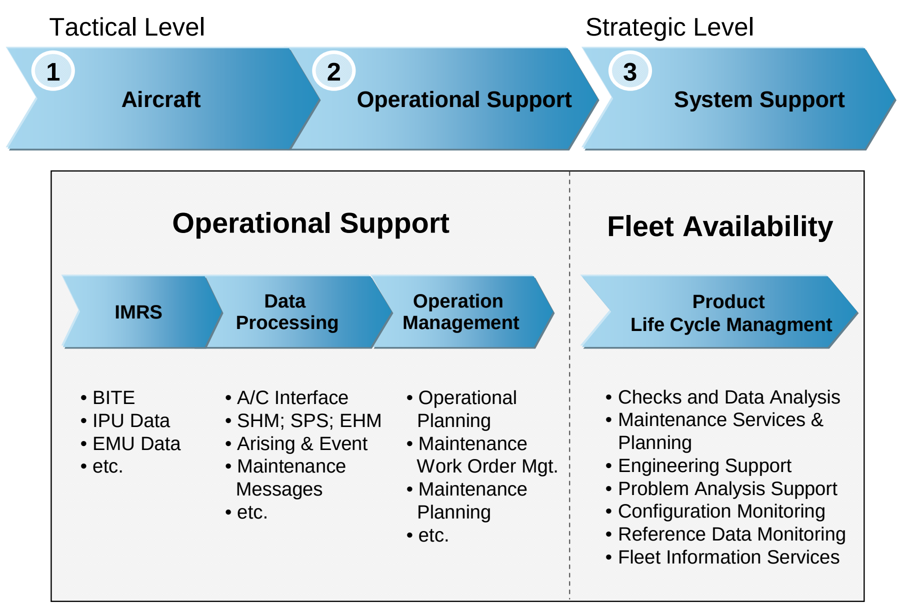


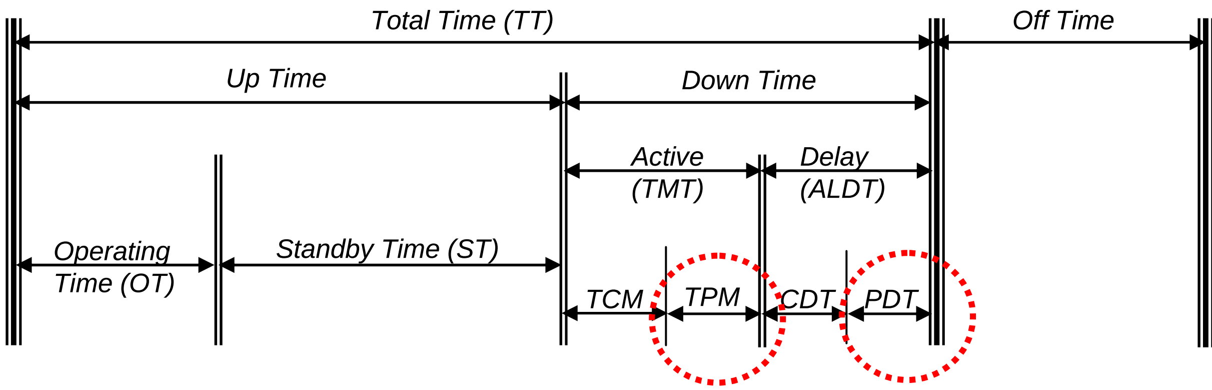
Figure 12: The main Decision Support Levels.

5.1 Tactical Level

The objective at tactical level to support operational planning including trouble shooting, maintenance planning at aircraft level etc. To ensure an efficient operational support 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, the supply and logistic services can be measured by through the operational availability equation where mainly the time of corrective maintenance shall be 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*

5.2 Strategic Level

At the strategic level we have other stakeholders in the process which require a different set of information. The main objectives at strategic level are:

- 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 usage; and
- To optimize operation and support cost and to optimize availability.

At strategic level the optimization of operational availability is related to reduce the total preventive maintenance time and the predicted maintenance delay time.

The optimization of operational availability and the reduction operation and support cost is 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 aircraft and fleet availability management is the capability:

- To link the results of the in service data analysis with system knowledge.
- To perform a cross functional system health assessment.
- To perform health assessment at aircraft and fleet level.
- To distribute the right information to right person in the supportability process.

For Eurofighter Typhoon EADS Military Air System has developed a life cycle management platform which offers the following main functionalities (see **Figure 13**):

- 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, which:
  - ➢ Provide remaining life based on aircraft usage at aircraft, system and sub-system level;
  - ➢ Provide inputs for predictive maintenance planning based on A/C usage, trend and prognostic;
  - ➢ Provide verification for system modifications and upgrades;
  - ➢ Provide verification of corrective maintenance; and
  - ➢ Maintenance Free Operating Time.

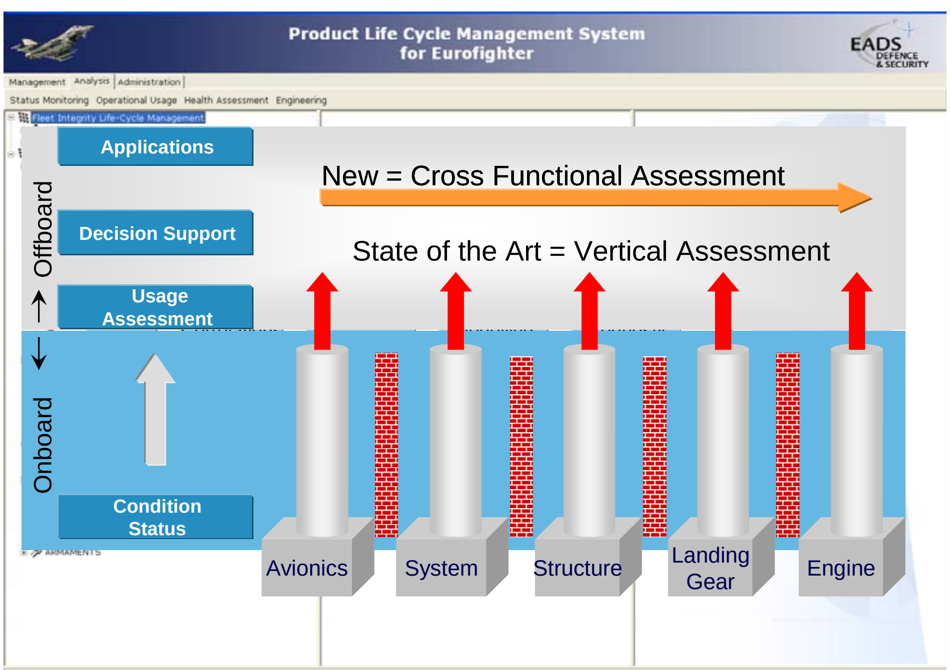


Figure 13: Product Life Cycle Management SW for Eurofighter Typhoon.

6.0 SUMMARY AND CONCLUSION

Maintenance and availability management of aircraft is a complex process that has consolidated over the past decades significantly. This complexity combined with all the safety and reliability issues related to it have made this process difficult to modify. However this complexity should not prevent from continuously questioning the different steps performed with respect to advanced technology being provided.

The variety of activities mentioned in this paper with regard to designing, monitoring and managing availability or deterioration in general of aircraft show that availability management combined with life cycle cost optimization is a major concern.

Despite of significant activity going along with aircraft and fleet availability management the process is unfortunately not complete, mainly due to the fact that the interface between monitoring systems, the subsequent management of aircraft life limitations and repair limits is still missing. A broader thinking in terms of life-cycle cost has become highly important.

Technology and software tools exist for implementing a larger vision for Health Management. Advanced diagnostic and prognostic strategies that incorporate data/knowledge fusion, artificial intelligence techniques and probabilistic will greatly improve Health Monitoring and Health Management capabilities and will maybe influence the RCM process (see also the paper from G. Fresser).

Obtain enhanced availability is an optimization process throughout the whole life cycle. Improve diagnostic and prognostic capabilities link to economic decision support capabilities are key functionalities to introduce new maintenance concepts and strategies combined with integrated data management solutions.

The process of how to maintain the Aircraft is mandatory to understand in order to introduce new technologies because the operator has finally accepted to change existing processes and procedures.

7.0 REFERENCES

[1] European Standard EN 13306, « Terminologie de la maintenance ».

[2] Rokohl, Hans J., << Optimale Strategieplanung: Planung und Kontrolle von Instandhaltungsstrategien in Kraftwerken >>, Köln, 1986.