TITLE: Long-Term Operation and Maintenance of Engine Monitoring Systems - Recommendations Derived from 15 Years of OLMOS Use by the GAF

Long-Term Operation and Maintenance of Engine Monitoring Systems - Recommendations Derived from 15 Years of OLMOS Use by the GAF

Hugo Pfoertner
MTU Aero Engines GmbH
Dept. TPM
P.O. Box 500640
80976 Munich
Germany
E-mail: hugo.pfoertner@muc.mtu.de

Abstract

Some aspects of the operation of a monitoring system over a time of several decades are discussed. It is shown, that the classical system design approach with well-defined definition, development, introduction and operation phases has to be replaced by a network of parallel activities. These activities are driven by the requirements to maintain fleet readiness and safe operation under the constraints of shrinking budgets and personnel reduction. Other factors driving the need for adaptations and enhancements are the obsolescence problems caused by the significantly different time scales for IT system components used in commercial or consumer oriented applications and for military applications.

The most important source for modifications in an engine monitoring system is the engine itself. A well-coordinated approach is necessary to match the introduction of new engine hardware with the required consequential changes in all components of the monitoring system. High quality of the monitoring results produced during operation can only be maintained by well-designed data handling procedures, user interfaces and appropriate documentation and training. There remains a practically unavoidable small percentage of data errors introduced by human data handling. Due to the potentially severe consequences of undetected errors in the life usage data of fracture critical engine components, it is necessary to apply suitable plausibility checks that are derived from statistical models of the life usage process in a fleet of engines.

Overview

It is very likely, that in-service times will exceed 40 years for existing and newly designed military jet or helicopter engines. One prerequisite for an achievable and safe extension of engine usage times is the application of engine fatigue life usage monitoring. The German Air Force decided to introduce fleet-wide on-board engine monitoring for the RB199 engines 15 years ago [BP97]. The application of the OLMOS system has made available comprehensive life usage data for all fracture critical parts to the fleet managers of the Tornado aircraft.

The operation of the OLMOS system has revealed that monitoring systems themselves need a considerable amount of maintenance and adjustment. Monitoring systems have a lot of internal and external interfaces, as shown in *Figure 1* [BPR98]. Both hardware and software cannot be kept unaltered over decades. The supposedly cost-saving use of COTS components causes a continuous need for adaptation with a frequency given by typical life times of operating systems, software development tools, database systems and of course also of computer hardware. The typical mismatch in time scales between commercial IT systems and their military derivatives is illustrated in *Figure 2* (Source: [A100]). Strategies are known how to mitigate both hardware and

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software related obsolescence problems [CT98, NRC01]. Implementing these strategies will require sufficient budgetary support. If this support is not available, equipment and methods have to be used beyond their planned replacement dates, which may cause data quality problems and frustration of personnel. Updates in the IT systems will also affect user interfaces with consequential requirements for documentation and training. Due to personnel reduction, system operators often are assigned their duties as secondary or even tertiary tasks. These changing skills of available personnel have also to be addressed in appropriate adaptations of the user interfaces.

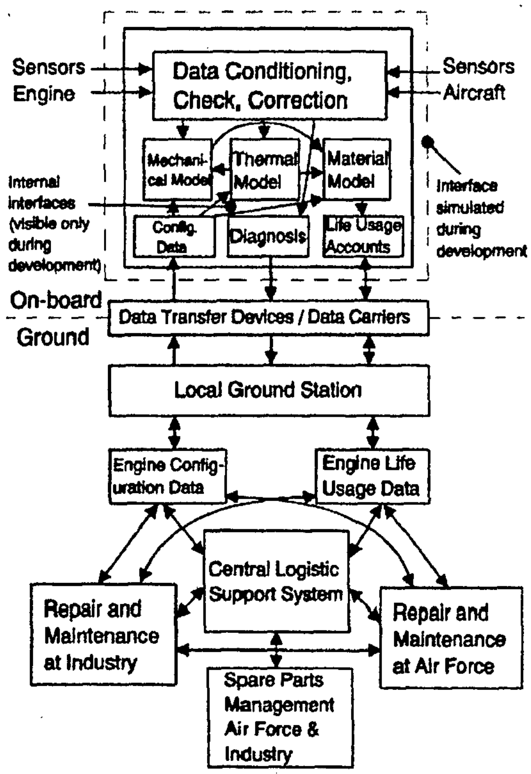

Figure 1*: Interfaces of a Life Usage Monitoring System (from [BPR98])*

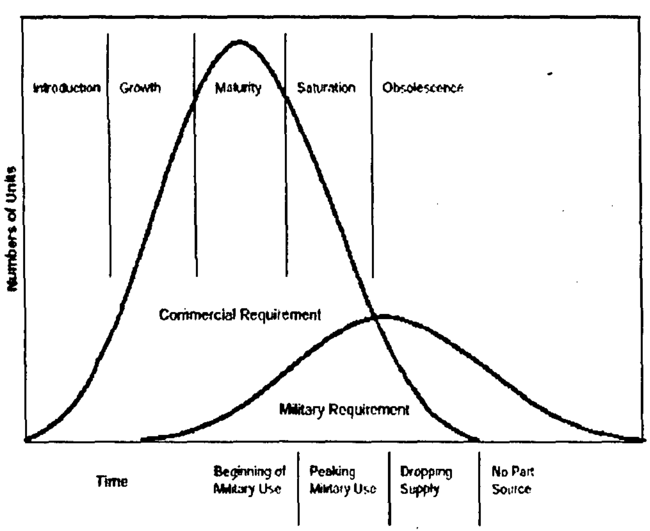

Figure 2: *Commercial and Military Time Scales for IT Equipment (from [Al00])*

Figure 3 shows the hardware components and interfaces of OLMOS. Together with the high complexity of data handling in the connected logistic systems of the air force and of industry the need for well-organized and coordinated procedures in the maintenance of this system is self-evident. A failure to address data management challenges properly would waist many of the system's potential benefits [HM98].

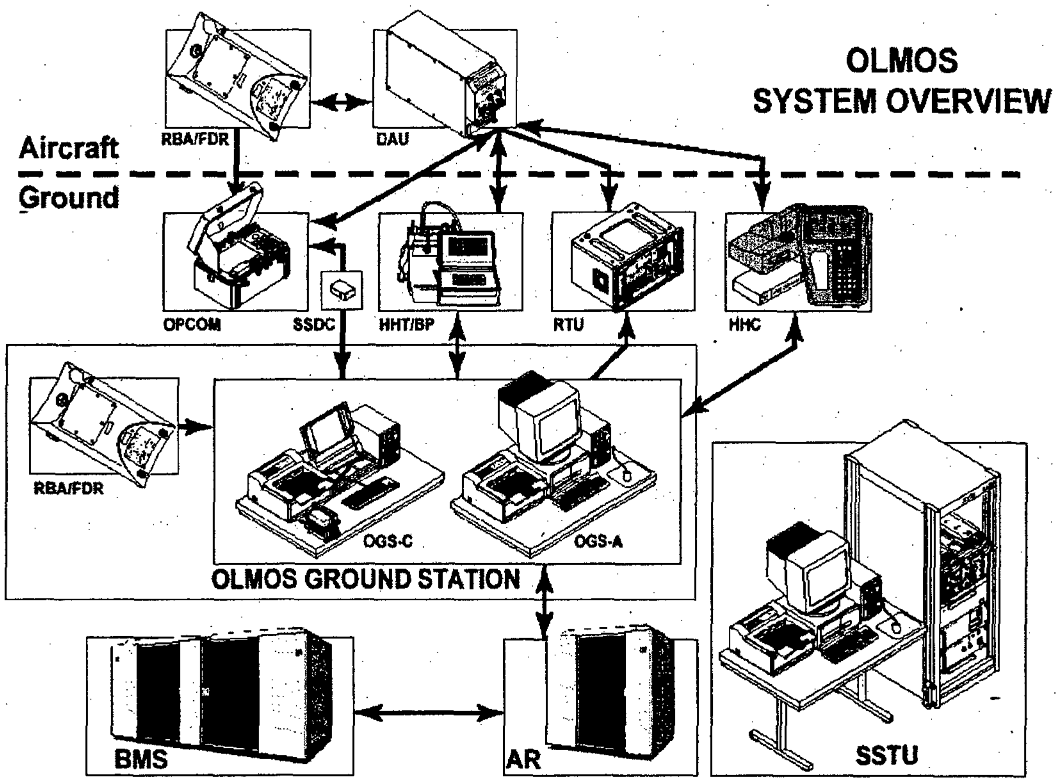

***Figure 3**: OLMOS System Overview (Source EADS Dornier)*

The main source of change requirements is the engine itself. Even after 20 years of operation, the frequency of changes influencing the monitoring algorithms does not approach zero. Typical mid-life upgrades (e.g. improved air seals, new materials for disks or blades, optimised blade profiles) may require substantial modifications or even complete re-programming of parts of the life usage algorithms. There have been various partially still ongoing modifications of the RB199 engine, where the influence on the life usage had to be checked. Not all of them required changes of the previously used algorithms, and sometimes minor changes of some constants may be sufficient to take into account the changes in engine or component behaviour.

Relation between Engine Modifications and Monitoring Algorithms

Whenever a modification of an engine component is planned, developed and introduced, the consequences of this modification on engine life have to be assessed. Quite often, it is not sufficient to check those consequences for the changed component itself. As shown in the following examples, seemingly small modifications may influence adjacent components or even the behavior of the whole engine, thus requiring an adaptation of life usage algorithms.

•After some years of operation it turned out, that a certain vibration mode could occur in one of the compressor blade rows within a narrow speed band. To avoid a limitation of the operating envelope a redesign of the blade was performed. The redesigned blade was heavier than the previous one. This leads to higher centrifugal loads on the disk, which have to be considered in the stress model of the monitoring algorithm. Although the required modification would have been rather simple, there was no means to transfer the blade type information to the onboard system without expensive modifications of the configuration data sets. Fortunately it was found, that the critical areas influenced by the centrifugal loads of the blades would normally not become life limiting, even when the heavier blade type was used. The final decision was to assume the presence of the heavier redesigned blade even in those cases, when the old blade type was retained.

•As a major part of the engine modification for life cycle cost optimization a redesign of the high pressure compressor blades was performed to achieve an increased mass flow and an improved surge margin. The design constraint was that no modifications of the rotor disks were allowed. Besides from minor changes in blade weights, the most important consequence was a shift of the thermodynamic cycle leading to changed boundary conditions for heat transfer to disks. A switch in the gas temperature calculation model that is dependent on the configuration data set treats this. The model for the heat transfer and heat conduction within the rotor itself remains unchanged. Nevertheless, a considerable software adaptation is required to insert the necessary control flow into the monitoring algorithms and to extract the compressor type information from the configuration data.

•A change in the manufacturing method of a disk can lead to a modification of residual stresses with consequences on the stress level and damage calculation. Therefore it is sometimes necessary to introduce different configuration codes dependent on the applied manufacturing methods, even if the geometry of the parts remains identical.

•Modified seal clearances that are introduced together with wear resistant coatings will have an influence on secondary air mass flows. It has to be checked if boundary conditions for the temperature calculation of disks are affected.

•A redesign of HP turbine nozzle guide vanes was performed to improve their cooling and durability. As a consequence of the redistribution of the airflows a shift of work distribution between turbine stages occurs. This in turn affects the spool speed ratios between HP, IP, and LP spools. Whereas the LP and HP spool speed are measured parameters, the IP spool speed is calculated from a mathematical model. This model has now to be adapted to include the influence of the new guide vane standard.

•The introduction of single crystal turbine blades is considered to be a major cost saving factor due to their superior material properties (e.g. creep life) at high temperatures. Unfortunately those blades tend to have higher weight than their conventional predecessors. As long as both blade types are used in parallel, the blade type has to be transferred to the disk stress computation via a blade type code to take into account the change in centrifugal loads. It even turned out, that blades from different manufacturers systematically used the limits of admissible weight tolerance bands, thus requiring another distinction within the stress computation.

•A change in control system schedules, e.g. a modification of the idle schedule will require an adaptation of criteria for execution flow of monitoring algorithms. To avoid the necessity for a software update, a so-called monitoring control parameter set is used, that contains constants of the algorithms, for which a dependency on external influences is known or suspected. It is then sufficient to introduce an update of the monitoring control parameters that has of course to be synchronized with the introduction of the related changes of other hardware or with changes of handling procedures.

Changes of the monitoring algorithms become also inevitable, if damage mechanisms or critical areas not considered so far turn out to be life limiting. This topic is discussed in [PB01].

Retrofits of improved engine components are nearly never performed in one "big bang" action, maybe excluding emergency fixes caused by flight safety concerns. A more realistic scenario is described in [HC99] with long times of overlapping mixed use of old and new configurations, including both engine hardware and different versions of the monitoring algorithms.

Development History

OLMOS has its roots in the early 1980's, starting from the idea, that most of the data required for monitoring the engines and the aircraft structure were already available in the existing data acquisition box DAU-1B for the tape based crash recorder, that is located in a deployable airfoil (RBA, see *Figure 3*) on top of the rear fuselage.

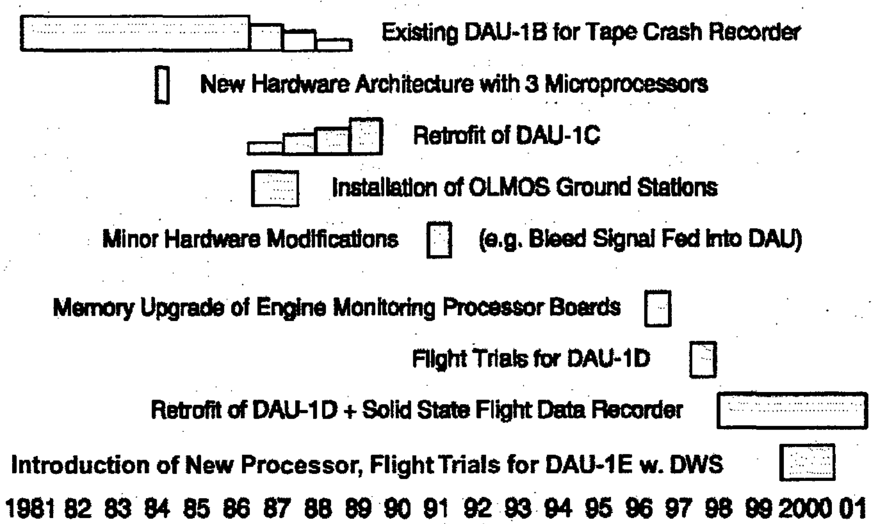

***Figure 4**: Time Scales of OLMOS Hardware Development*

Figure 4 shows the development steps of the hardware configuration starting with the introduction of 3 new processor boards, two of which were dedicated to the engine monitoring functions. There was an incremental approach in both hardware and software development. Major development steps occurred with the introduction of the new engine standard Mk105, that is used to power the ECR Tornado and with the replacement of the obsolete tape based crash recorder by a solid state flight data recorder. The FDR replacement is now in its final phase. On the engine monitoring side, the FDR introduction was used to implement a memory upgrade and a software loading function that will simplify the process of software changes for the engine monitoring algorithms. Currently another upgrade of OLMOS is in its final phase of qualification. By replacing an obsolete data acquisition board by a state of the art microprocessor board it was possible to implement a warning function for aircraft instability (departure warning system). The next upgrade step in the engine monitoring functions will be the inclusion of the life usage algorithms for the so-called life cycle cost optimized engine that includes several improvements, e.g. an HP compressor with increased mass flow.

Figure 5 shows an overview of the development history of the engine life consumption-monitoring program ELCMP. Each change at this complex system requires an inspection and a consideration of numerous existing mutual dependencies, which are partly so serious that actually meaningful extensions or adjustments can either not be introduced at all or only with very long temporal delay. The continued use of LUM algorithms known to be outdated indicated at the end of the time scale in *Figure 5* is caused by the mutual dependence between availability of the software loading function for ELCMP into the onboard DAU and the necessity to have only one version of life consumption data in the data base of the logistic system BMS.

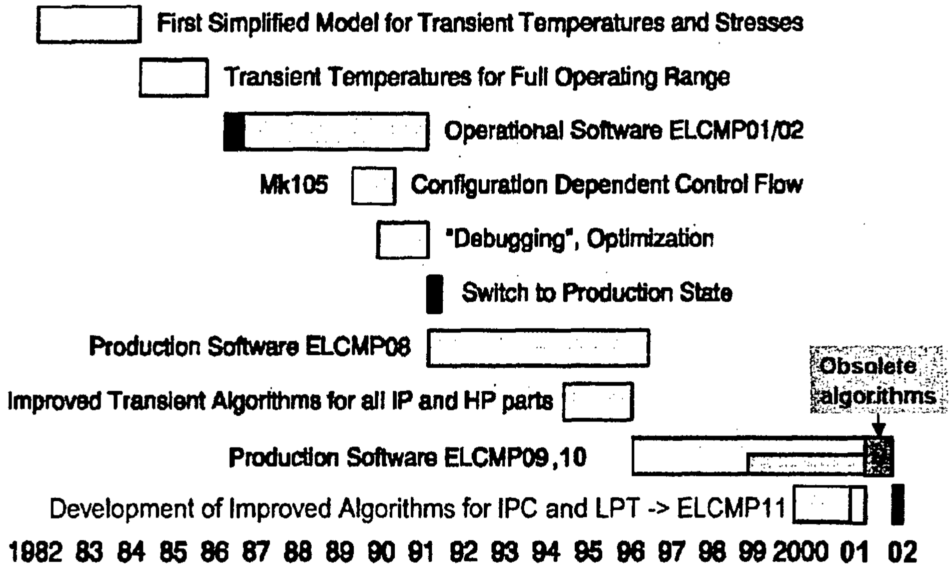

Figure 5: *Time Scales of Algorithm Development for Life Usage Monitoring*

Problem Tracking

A very important tool to maintain a high quality of a monitoring system is a reasonable procedure for problem data gathering and tracking. In the OLMOS system there exists one central query list, where all known problems are collected. Entries come from all parties in the development, management and planning, but the focus is on reports from the end users. This list is the basis for regular system reviews and for the planning of correction and update packages. Currently there are some 150 entries in the list. 70 of these queries have their origin in the introduction phase of major system changes, dealing mainly with requirements that were set aside during the specification phase (low priority, financial constraints), whereas the remaining larger part deals with problems detected during system operation.

The list is maintained at the technical training center of the GAF, which acts as an advisor to the GAF material command. This choice has proven to be rather beneficial, because the air force personnel assigned to the OLMOS system visits training courses before they start to work with the system. When problems show up, that can't be solved by using the documentation or the system's help functions, in many cases the first address to consult is the training center. As the query list contains also recommendations for a solution of known problems, it is sometimes possible to give hints how a problem may be solved manually or be circumvented until it is solved by a system patch or update.

User Training Environment

The environment of the training center is also used during tests of new features to be incorporated into the monitoring system. A very useful feature is the presence of virtual aircraft and engine data in the productive database of the BMS system operated by the material support command. All data records used for training purposes have unique, easily recognizable serial numbers that have no correspondence in the form of existing engine hardware. It is of course necessary to exclude those parts during statistical analyses or during productive database queries by means of suitably defined import filters. By means of this construction it is possible for the OLMOS personnel to practice all occurring handling procedures, including also the data transfers to and from the central logistic system.

To simulate the consequences of flight operations on the onboard data acquisition unit, the DAU can be fed with aircraft and engine data via two different interfaces. It is either possible to use the serial link for the HHT in a special transfer mode to send digital engine data or to stimulate the analog and digital interfaces using a dedicated test rig (SSTU) with the same data the DAU would see in the aircraft. In both cases synthetic or real recorded engine runs can be used as input. This function has proved to be extremely valuable to verify the correct operation of the onboard components of OLMOS.

Plausibility Checks for Life Usage Data

Another area of improvement is the elimination of manual handling of life usage data. Human interaction always produces some low, but nearly unavoidable percentage of errors in the data. Besides from trying to eliminate the need for non-automatic processing steps (e.g. by a better integration of the data processing systems of the air force and of industry), methods have been developed to detect and correct inconsistencies in the logistic data by using suitable checks.

The life consumption data accumulated in the onboard systems are transferred via the processing chain indicated in *Figure 1* and finally collected in the BMS database at the GAF central computer facilities. Every month the life usage data of all monitored parts are extracted from this database and are sent to industry for statistical analysis. The results of the statistical assessment are summarized in a monthly status report. Currently a system for plausibility checks of those data is being introduced. The basis for the plausibility checks is a statistical analysis [PB01], which is based on simulation runs using recorded engine data together with the accumulated life usage data available in the logistic system BMS of the German air force. The planned application of those checks will allow an early detection of errors and thus avoid potential risks of hidden data errors on flight safety.

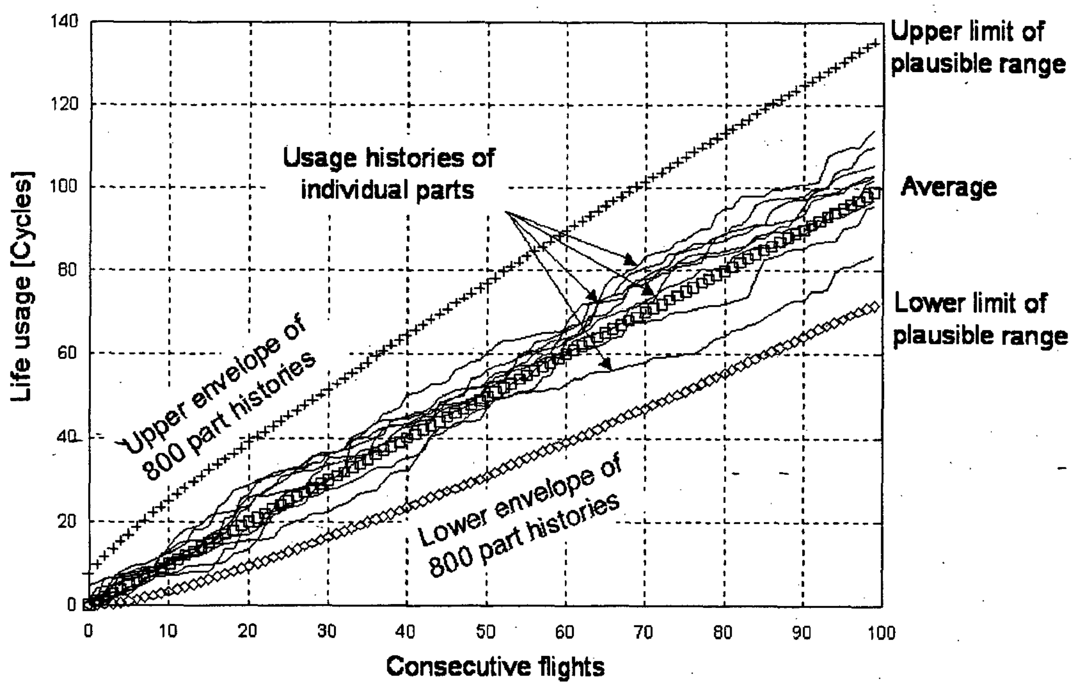

***Figure 6**: Scatter in accumulated life usage*

Figure 6 illustrates the basic idea of the plausibility check. The relation between numbers of flights and accumulated life usage is acceptable, when the relation falls into the envelope of the simulation results. The results of the simulation are tables of upper and lower limit values as a function of the number of engine runs. There is one table per critical area, thus leading to more than 40 such tables for the whole engine. To convert those tables into the more usual dependence

on accumulated flight time, an average flight time per flight is used, that is either a value for the whole fleet or a specific value determined for a certain aircraft variant or for an air base with known mission types significantly different from the fleet average.
The data handling of many tables with several thousands of entries has been considered as impractical and therefore an alternative representation of the limit curves was required. By analysis and numerical experimentation a set of formulas was found, by which all occurring limit curves could be represented with very good accuracy. The idea is to use a weighted mean of two straight lines together with an expansion function that is used to widen the curve for lower times. The following formulas are used:

- 2 straight lines:
  $$g_1(t) = s_1 \cdot t + d_1$$
  $$g_2(t) = s_2 \cdot t + d_2$$

- Weighting function:
  $$u(t) = \frac{1}{2} \cdot \left[\frac{1 - e^{\frac{t-a}{w}}}{1 + e^{\frac{t-a}{w}}} + 1 \right]$$
  For $t \to -\infty$ u(t) approaches 1, for $t \to \infty$ u(t) approaches 0. $u(a) = 1/2$, w is the width of a transition zone.

- Expansion function:
  $$wd(t) = d \cdot \left(\frac{t}{b} \right)^{c-1} \cdot \exp\left(-\left(\frac{t}{b} \right)^c \right)$$

The final dependence is determined by a weighted combination of the two linear relations by means of the "sigmoid" function u plus an expansion with the 2-parametric Weibull density function wd.

$$z(t) = u(t) \cdot g_1(t) + (1 - u(t)) \cdot g_2(t) + wd(t).$$

These formulas can be used to represent both the lower and the upper limit curves, of course with different sets of coefficients. The coefficients $d_1, s_1, d_2, s_2, a, w, d, b, c$ are determined by means of a non-linear least squares fit of z(t) to the individual lower and upper limit curve tables. *Figure 7* shows an example of the construction of the combined upper limit curve, plotted versus the number of flights. The topmost line is g_1, whereas the lowest line is g_2. The coefficient s_2 is the slope of the limit curve for a large number of flights, because $u(t), wd(t) \to 0$ for large t. This makes s_2 equivalent to a long-term β-factor, i.e. it gives an asymptotic life consumption for large number of accumulated flights.

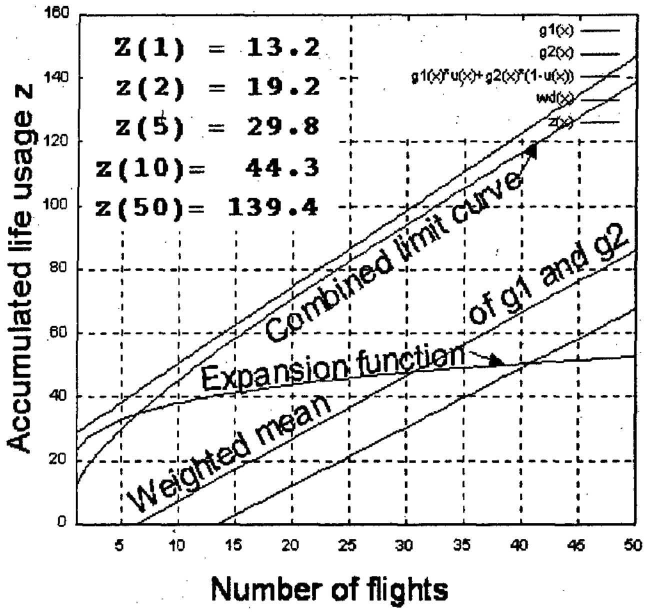

Figure 7: *Construction of upper limit curve for small number of flights*

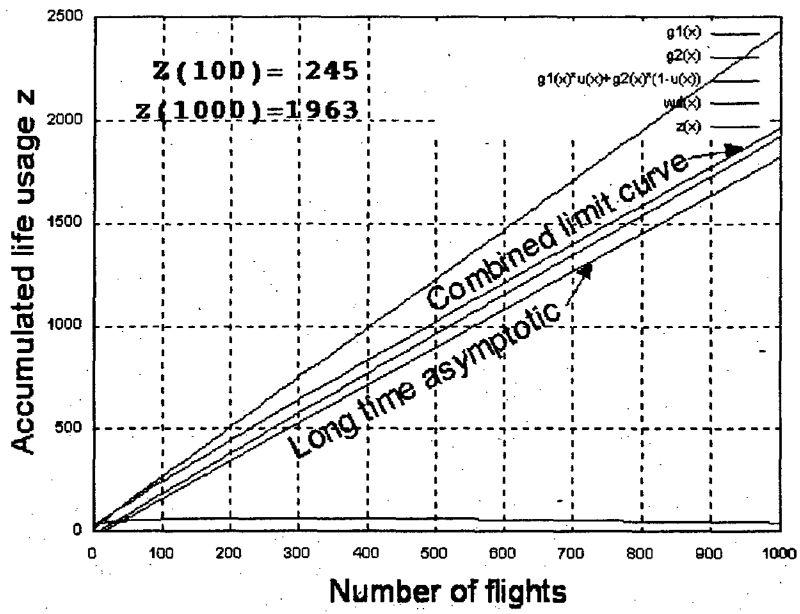

Figure 8: *Construction of limit curve continued*

The example in *Figure 8* shows the same (upper) limit curve as in *Figure 7*, but for a larger numbers of flights. The influence of g1 has diminishes at 1000 flights, but there is still some offset caused by the expansion function shown as near horizontal curve near the flight number axis. The numerical cycle values z(t) shown in both figures give a good impression, how the plausible range may vary for short and long time cycle accumulation. Whereas a life consumption of 44.3 cycles is plausible for 10 accumulated flights, a corresponding life consumption of 443 cycles for 100 accumulated flights has a nearly vanishing probability, at least if the assumption of random mission assignment is not severely violated.

The limit curves derived from the simulations were used in a first step to check all Group-A part data in the BMS database for a plausible relation between accumulated flight time and accumulated cyclic life usage. *Figure 9* shows a comparison of the limit curves predicted by the fleet simulation with accumulated life usage data, for a component that has been monitored by OLMOS from its entry into service. The scatter of the actual data is slightly higher than the predicted scatter. This is caused by the comparatively small number of recorded flights that were available to determine the distribution parameters for the underlying “damage per flight” distribution.

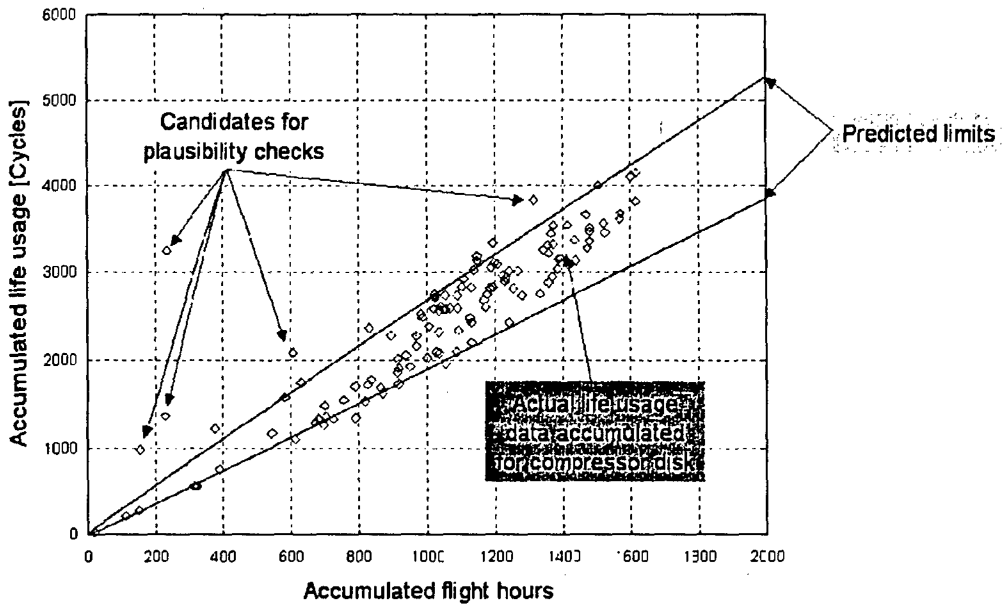

Figure 9: Comparison of simulation results with actual life usage data

A significant difference in data quality was found between parts that were actually used in flying engines and spare parts. Due to the system philosophy, that only parts used in an engine are checked for consistency, the frequency of data errors was higher in the spare parts inventory, than it was for the actively used parts. Especially those parts, where changes of the monitoring algorithms had been performed in the past, showed a higher percentage of inconsistent usage data. This was at least partially caused by incomplete conversions of data after the introduction of new life usage algorithms. Whereas the conversion of LUM data between subsequent versions is designed as an automatic process, the conversion of results from earlier versions usually requires some manual interference.
We found a significant connection between the accessibility of parts and the frequency of implausible data records in the BMS inventory. It was not very surprising, that a correlation existed between the required maintenance level to access a part and the frequency of data inconsistencies. Parts that were only accessible at industry or in the central repair facilities of the air force (e.g. disks of the HP compressor) had fewer data errors than parts that were changed at squadron level (e.g. HP turbine cover plates). For frequently changed or easily accessible parts it may be therefore be worthwhile to increase also the frequency of the plausibility checks.

Correction of implausible life usage data

Figures 10 and *11* illustrate the method to be applied, when the number or accumulated cycles is found outside the plausibility band. It is assumed, that the accumulated flight time could be confirmed to be correct. Whereas the conservative correction in *Figure 10* assumes, that no historical data are available, *Figure 11* reflects the situation currently found in the handling of the data from the OLMOS system, where monthly snapshots of all life usage data are stored and kept within a database maintained at industry. The availability of historical data turns out to be quite beneficial and avoids the necessity for worst-case assumptions for the whole life in case of data errors.

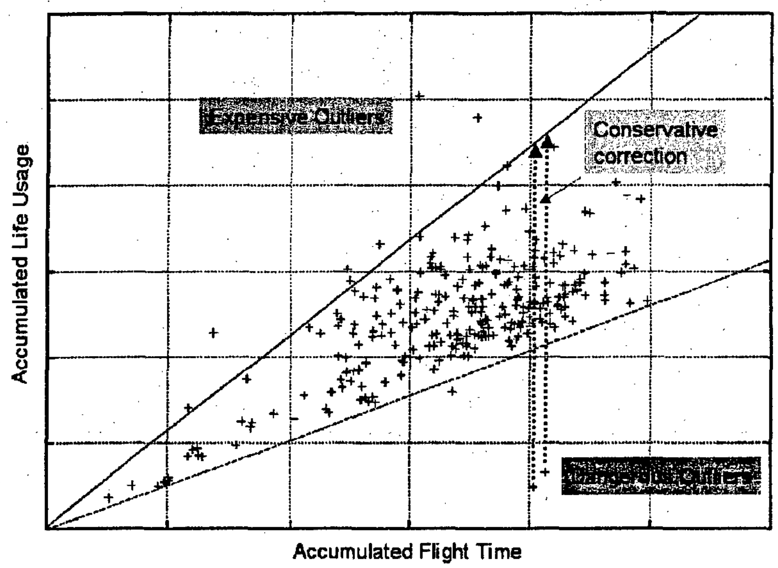

Figure 10*: Conservative Correction of Outliers*

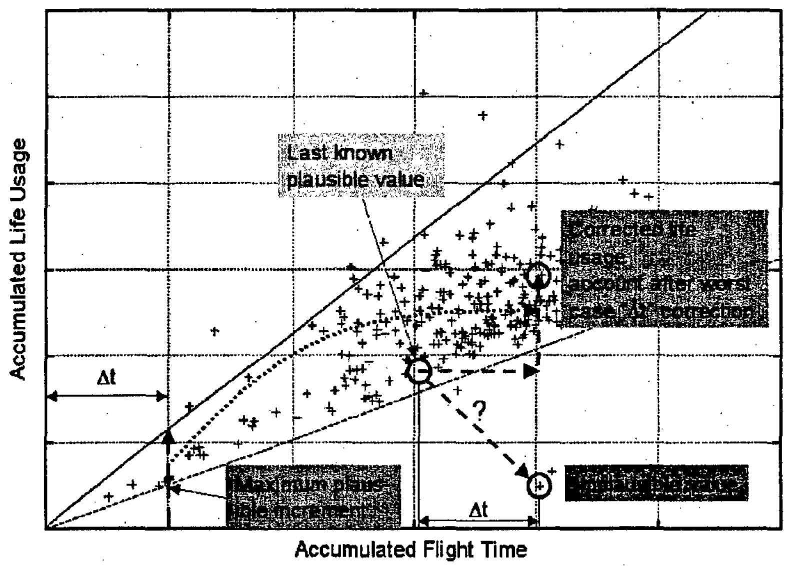

Figure 11*: Correction Using Stored Historical Data*

Influence of Usage Monitoring on Life Cycle Costs

Within the engine monitoring functions the computation of the life consumption of the fracture critical group A components represents the most extensive and also most substantial part regarding its effects on the total costs of the weapon system. The accurate information on the state of life usage in the whole fleet provides an excellent basis for the planning of workload in overhaul facilities, spare parts manufacturing, fleet management and financial requirements. A typical distribution of life usage determined by OLMOS is shown in *Figure 12.*

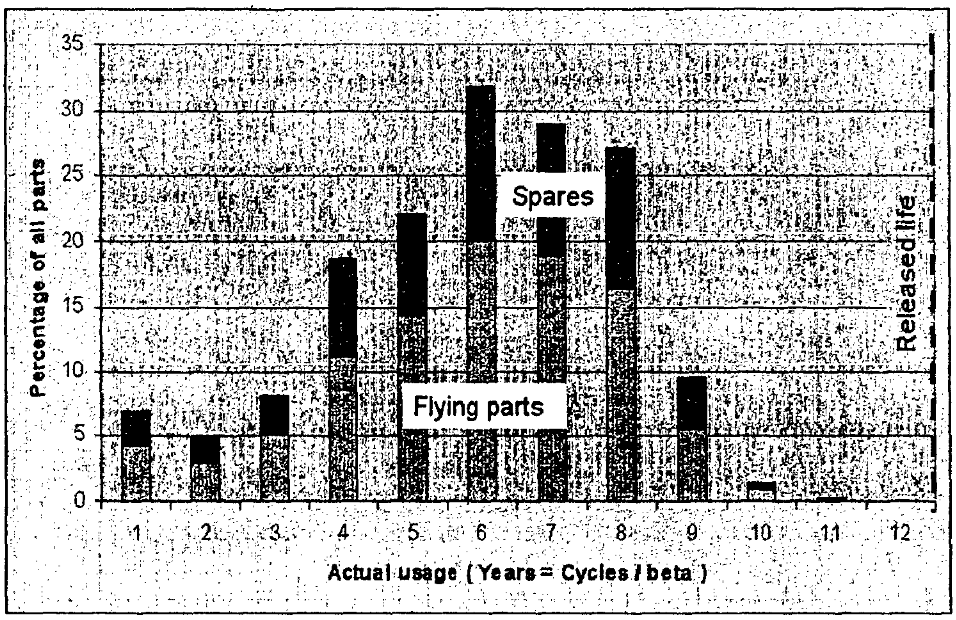

Figure 12: Typical distribution of life consumption at half nominal life

Using such data enables predictions of expected replacement costs as shown in *Figure 13*. Included in this figure is an expected trend of disk replacement costs for the USAF, that is characteristic for aging fleets without application of individual life usage monitoring (Source: [Blo01]). One of the benefits of individual life usage monitoring is the identification of components with low life usage that permits to limit the rising of costs, which would occur if replacement were only based on accumulated flight time. A comprehensive discussion of these benefits is found in [RTOTR28].

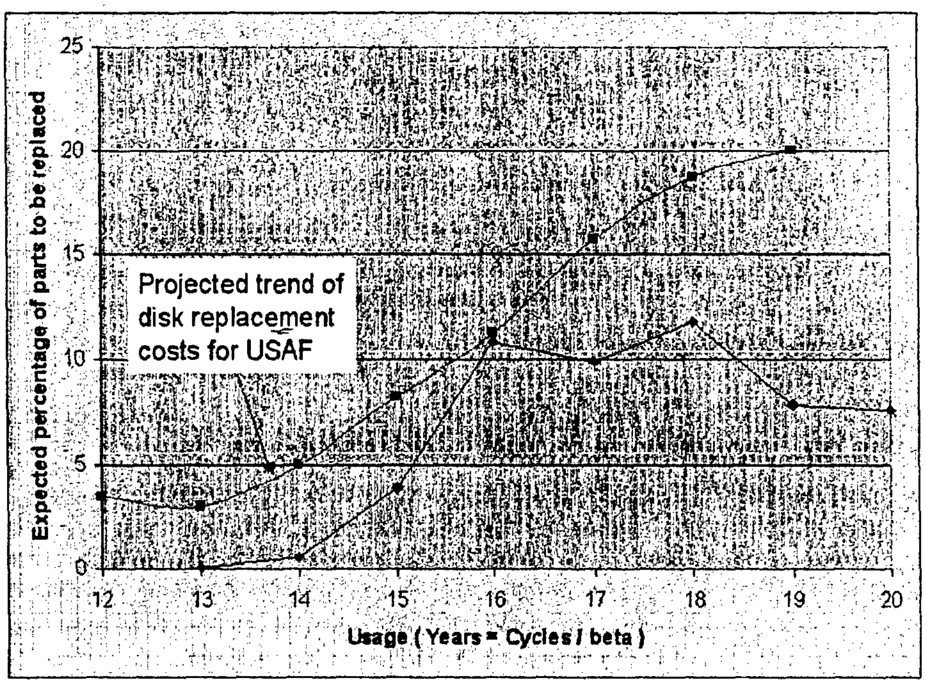

Figure 13: Predicted replacement needs for a compressor disk

On the other hand the maintenance of a sophisticated monitoring system also is a not negligible cost factor. Improvements in engine hardware have to be modeled in updated monitoring algorithms. Some benefits will not become visible until an update of the whole monitoring processing chain has been performed. A reasonable balance has to be found between the additional effort of updating the monitoring system and the cost reductions expected from application of the best available algorithms. Each attempt to reduce the development and investment costs for monitoring should take into account the well-known cost relation shown in the following *Figure 14* (Source: [Al00]).

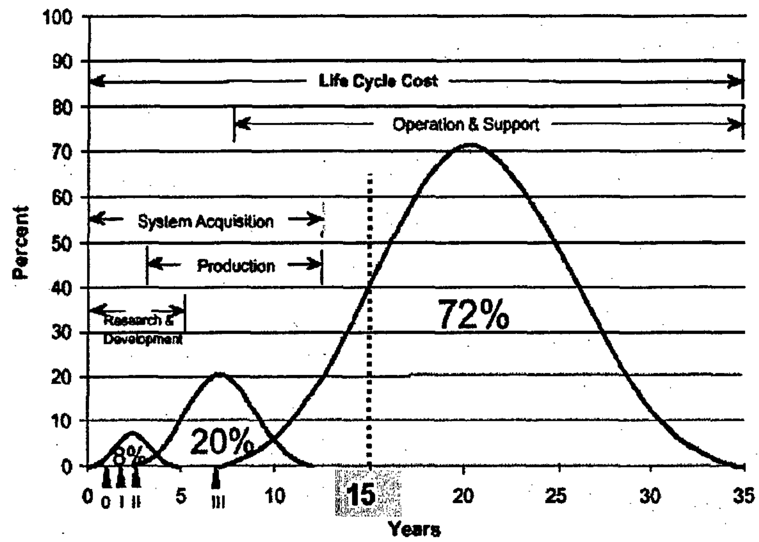

Figure 14: *Typical timescales and cost distribution of military IT systems*

Conclusions

This presentation is based on the experiences that were made in the last one and a half decades during the introduction and the operation of the OLMOS system. These findings can be used on the one hand during a still ongoing improvement and optimization of this system. On the other hand they form a wealth of experience that can and should help to design and implement new monitoring systems as efficiently as possible.

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List of Acronyms

BMS	Logistics system for configuration, material tracking and management
COTS	Commercial Off the Shelf
DAU	Data Acquisition Unit
DWS	Departure Warning System
ELCMP	Engine Life Consumption Monitoring Program
FDR	(Solid State) Flight Data Recorder
GAF	German Air Force
HHC	Hand Held Computer
HHT	Hand Held Terminal
HP	High Pressure
IP	Intermediate Pressure
LP	Low Pressure
LUM	Life Usage Monitoring
OGS	OLMOS Ground Station
OLMOS	Onboard Life (Consumption) Monitoring System
OPCOM	Operator Control and Measurement Computer
RBA	Recorder Beacon Airfoil
SSTU	Signal Stimulation Unit

Paper 3: Discussion

Question from D Shepherd - QinetiQ, UK

Were the data outliers simply identified on the basis of being outside of the predicted range or were you able to go back and positively confirm a problem with the actual data?

Presenter's Reply

The margins used to detect outliers are chosen to be very conservative and we were always able to confirm data handling problems that generated the implausible results. If an engine, or aircraft, is constantly operated in an extreme role, then the assumptions used in the plausibility checks are violated and an outlier may turn out to be a valid result. However, we have never identified such a situation but if it were to occur, an analysis of the results for single flights (raw flight data) or the downloaded data after every flight would be necessary.