ICAS 2020 SHANGHAI
International Council of the Aeronautical Sciences
32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

CONDITION BASED MAINTENANCE (CBM) IN THE DIGITAL TRANSFORMATION STREAM

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Abstract

Condition Based Maintenance (CBM) concept aims to perform a maintenance action on a system or on an airframe when it is most pertinent:

- according to aircraft usage, environment and/or health conditions, operational context and constraints
- elaborated due to aircraft data & engineering models

This paper addresses the necessary digital models what are required to allow such Condition Based Maintenance, with characteristics and performances such as:

- Genericity and Adaptability : regardless of the system or the function
- High Level of Accuracy: to allow maintenance credit
- Dysfunctional rather than functional structure
- With learning capability to improve its accuracy and evolve during the life cycle
- Capability to interface with others models
- Scalability from isolated use cases to the full system of interest

This paper questions the critical issue of the certification of CBM systems in order to maximize the maintenance credit, addressing:

- the need to evolve an explicit safety process that will assess the risk linked with usage of CBM instead of the classic way of working, i.e. MSG3 process,
- the justification of the inherent costs related to systems allowing CBM, it is necessary to define the process that will enable it to take full or partial maintenance credit. This is based on the paradigm that maintenance is defined in a way that the safety level is maintained during the whole operational life.

This covers:

1) Definition of risk/safety assessment process linked to CBM functions replacing maintenance inspections as per the maintenance program from MRBR (Maintenance Review Board Review) and Airworthiness Limitation Section (ALS);

2) Definition of Design Assurance Level (DAL level) requirements or equivalent for the ground segment for the implementation of the CBM function in relation to the risk level determined in 1)

Keywords: Condition Based Maintenance, digital model, safety process, maintenance credit, design assurance level

1. Condition Based Maintenance concept

Condition Based Maintenance is intended to perform maintenance on a system or on an airframe when it is needed depending on the current estimated health status of a considered component or depending on the predicted evolution of this health status. Based on that, the purpose is to perform a correction or repair action to avoid a failure before it occurs, but also to perform it when it is the most effective from an economical and operational perspective.

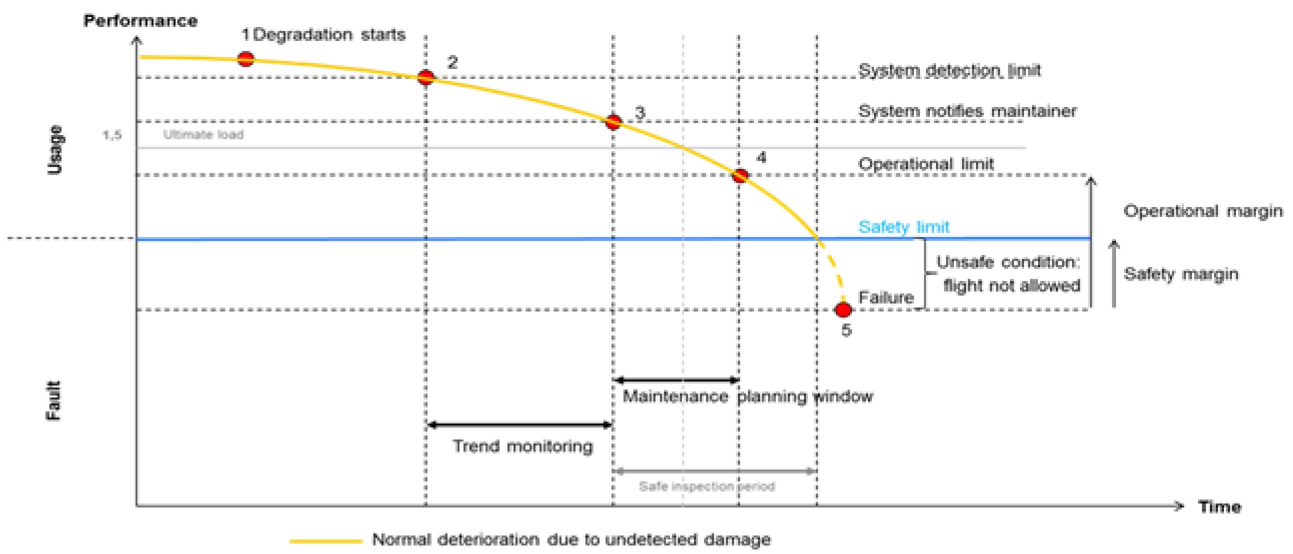

Figure 1 – Condition Based Maintenance principle for systems

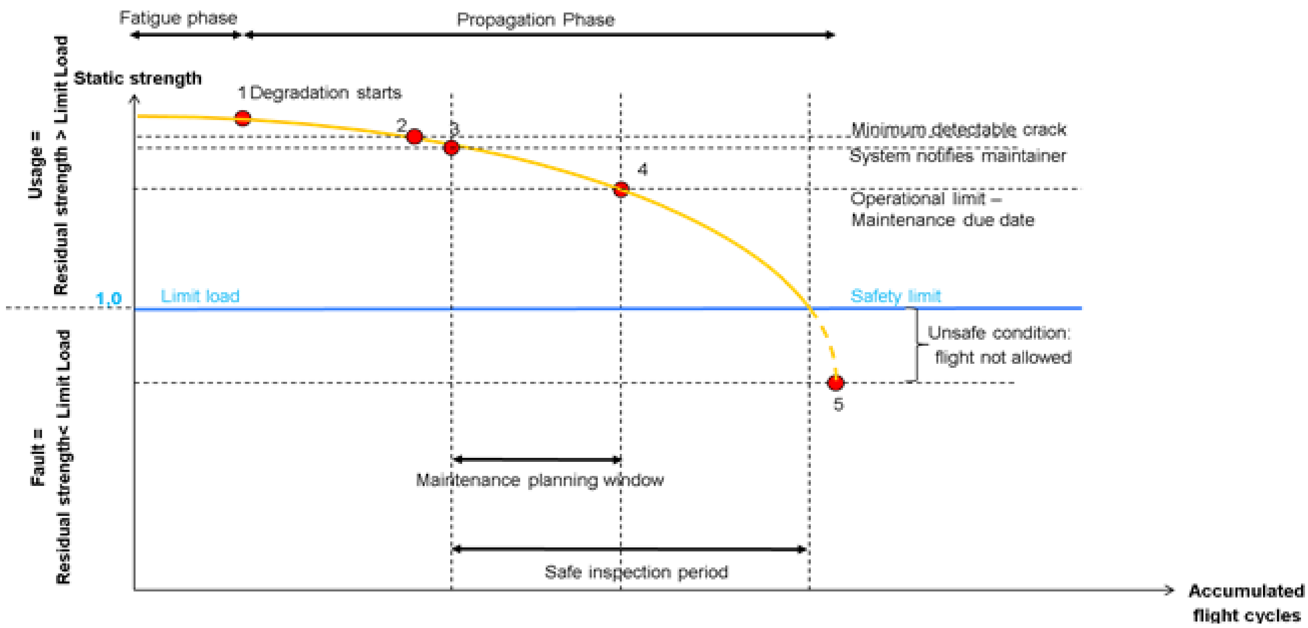

Figure 2 – Condition Based Maintenance principle for airframe

The Condition Based Maintenance concept is often mistaken with the Maintenance on Condition concept [1] for which the maintenance is triggered either by a fault or a decrease in performance beyond acceptable limits or by the outcome of a preventive maintenance task.

The following criteria are generally used to define the pertinence to trigger maintenance:

- Unscheduled maintenance: maintenance shall be triggered before a failure occurs in order to avoid unscheduled maintenance. This is only applicable for evident failures or for hidden failures for which there is a mitigation means to avoid default progression. This is also applicable when the performance degradation is such that even if the related failure is remote, it is worthwhile from an economical or operational perspective to restore the nominal performance level.
- In case of unexpected findings (unpredictable and/or due to external events), CBM shall be used to support findings assessment, root cause isolation and maintenance action definition (including inspection program, differ, mitigation, repair, rectification etc…)
- Scheduled maintenance: the task shall be triggered when the aircraft status requires it and at the next convenient maintenance opportunity. This is considering not only aircraft status but also constraints arising from the operator (program, fleet management) and MRO ones.

Condition Based Maintenance shall contribute to:

- Increase of aircraft / mission availability
- Reduction of unscheduled maintenance
- Remove of preventive maintenance with predictive Maintenance
- Improve maintenance planification
- Lean maintenance support network

CBM concept relies on Prognostic Health Management [PHM] capabilities: they consist of automated hardware and software systems that acquire data, monitor, detect, isolate, quantify and predict component performance and degradation without interrupting daily operations (non-invasive) in contrast to corrective or scheduled maintenance.

The main features are as following:

- Data collection and processing: data acquisition from sensors - and possibility their storage - with the associated pre-processing (denoising and additional filterings)
- Health & Usage Assessment: the process of building at a given time an assessment (estimation) of the health level of a component using the collected data. Typically, the detection of specific patterns within data can be considered as signatures indicative of a degradation, and which are typical precursors of failure or damage modes. As outcome, such a process should provide a given set of Health Indicators (HI), built as performance indicators or remaining distance to an anomaly zone (in a data space of reduced dimension)
- Health & Usage Monitoring: continuous or periodic (synchronous or asynchronous) Health & Usage assessment.
- Diagnostic: the process of detection and isolation of faults or failures/damages including two main aspects, which are the fault detection & confirmation, and the root cause identification.
- Prognostic: the process of building a prediction of the future state of a system/component

at a given time t+∆t based on the history of data and environmental conditions (or by equivalence the building of a prediction of the time at which a given future state will be reached). This assumes that the considered system/component fails or faces a loss of performance after a period of observable degradation. From a state-of-the art point of view, it intends to build an estimation of the Remaining Useful Life (RUL) of the considered system/component through a probability density function.

- Health Pattern Detection Monitoring: the monitoring of a specific health condition. It relies on the detection of specific health patterns on top of the Health & Usage monitoring outcomes. Often referenced as an “early detection” monitoring - because linked to the early detection of failure precursors - .
- Maintenance decision: decision to set a specific repair slot in the maintenance planning, and the generation of the associated maintenance task
- Learning: improve models and algorithms through a feedback loop
- Predictive monitoring: encompasses the concepts of “early detection” and prognostic.

Acquired data, digital models, maintenance actions as well as health status of each component of an individual aircraft are stored, updated and enriched in a maintenance digital twin to enable the CBM function.

2. Digital models to support CBM

CBM success depends on the collection of raw data and their accuracy as well as the digital models to support diagnostic and predictive functions (early detections, prognostic, or mixed solutions).

2.1 Definitions

To support the required PHM technical activities (previously described), several digital models need to be considered and developed. The main different ones are addressed here below.

Health (& Usage) Model:

For a given component, it is a model which gives its health level at a given time on a defined “scale”. From a state-of-the-art point of view, it intends to represent a given acquired point (data vector) in a reduced space measuring the functional performance (thus considering as known/defined the areas of normality, anomaly - incl. functional loss -, and degradation).

Such a model takes a set of data as inputs (mainly referenced as raw features), and typically provides as output a set of key performance indicators, also named Health Indicators. More formally, it is a function which transforms an input data vector into an output vector with a reduced dimension, in a way that it is possible to measure the performance (or the degradation level) of a considered function provided by the component. Depending on the targeted usage of this Health Model (Early Detection or Prognostic), the output can be for example a 1D Indicator for a considered function or a 1D Indicator for a couple (function ; degradation mode).

Most of the time, such models are built using the engineering knowledge and the information contained within real data, thus combined - which is called hybridation - on top of which a normalization is applied on the integration platform and to sustain harmonized ways of working and genericity.

More rarely, the usage of a component digital model can be used. In such a case, the health indicator is built as the distance between the output of the component digital model and a subset of the acquired data (the real outputs of the components)

Predictive Models:

Such models intend to anticipate a future loss of function or performance degradation. Typically two main approaches can be followed, without exclusion.

-'Early detection' or 'health pattern detection' models: the purpose is to detect a given health behaviour of a component or equipment in a degradation area (example: degradation level above a threshold over a given period of time). In particular they are relevant when a reliable prognostic model can not be built with a satisfying confidence interval.

-'Prognostic' models: the purpose is to estimate the RUL with the associated confidence interval. From a state of the art point of view, the RUL should be estimated as a Probability Density Function. Such models should consider the future operational scenarii and usage domain, or the distribution probability of them.

Prognostic Model:

They are a subclass within Predictive Models. Using as input a given history of data, such a model intends to provide an estimation of the Remaining Useful Life of a given component. It can be generic if using a Health Indicator - from a Health Model using the computation of an euclidean distance to normality - , or more specific if the strategy is based on trajectory estimation within a multidimensional space. Both will use interpolation / extrapolation methods.

In addition, a Prognostic Model shall integrate an uncertainty modelling, allowing to propagate uncertainties over the time in order to build the estimated RUL as a probability density function (e.g.: Gaussian process, Bayesian filters …)

Alerting Model:

The model which implements the alerting strategy, combining, for a given topic, the outputs of a health pattern detection model, and the outputs of the Prognostic Model, or both. It intends to raise an alert when a set of programmed health conditions are met. A variety of triggers can be imagined to sustain the strategy: Health Indicator above a threshold, density reached with a given rolling window, slope exceeding a threshold, combination of previous items, RUL under a given limit with a given confidence level ... This model can as well depend on operational/business criteria such as airline dispatch policy, logistic strategy, ...

The strategy may take into account the quality and reliability of underlying models accordingly.

Maintenance Optimization Model:

On top of alerting models, this maintenance optimization model takes as input the cumulated raised alerts, their level of priority, the confidence intervals, some hyperparameters customized at fleet level (e.g. the admitted level of risk), and other parameters associated to different sources of constraints (forecasted maintenance slots, team workload, already planned tasks, spare availability …), and build as output a proposal of optimized maintenance slot. It relies on a solver (optimizer under constraints) using a mathematical background like the well-known 'Markov process' based techniques.

Component Digital Model:

To be understood as a Component Digital twin, such a model intends to have a high level of representativeness of the dynamic behaviour of the real component, as far as safety and maintenance are concerned and the driving parameters are identified and monitored.

Those models were in the past mostly analytical models and defined during the aircraft design phase. Data driven techniques allow us to create data driven models that can be implemented as soon as adequate levels of data are collected. Those data can be acquired during operations or run to failure tests (Run2Failure). Data driven techniques can also allow to improve the analytical models through “hybridation”.

In all cases, their introduction has to be anticipated during development phases and the component architecture and the design adapted accordingly. Model Based System Engineering techniques (MBSE) are well adapted solutions to make the choice of CBM strategy at the earliest design phase in a much more streamlined, formalized and standardized process.

2.2 Key digital model characteristics

This kind of model is a dysfunctional model as compared with the usual functional model used for design, though a functional model may be used to model dysfunctional modes. The key characteristics are as follows:

<u>Health Models:</u>

A Health Indicator (HI) should be provided per degradation mode (~orthogonal basis).

Assuming that the degradation modes will be mainly independant between the system components, it means that at system level, the aggregated HI should be a vector with a dimension equal to the sum of the HI dimensions at equipment level.

Health models should provide only low level HI (i.e. per component or equipment). The granularity of interest (atomicity) is directly linked to the maintenance aspects: the granularity level should be the one in bijection with the components formally identified at maintenance level (parts identified in the aircraft definition, and associated to a given set of procedures, including replacement and repair / refill actions).

An aggregation of HIs should also be considered as having a strong interest, taking into account the organic architecture, in order to build a synthetic view of Health Indicators at system level.

As being the first models in the decision pipeline, they are key in terms of quality, because they will highly impact the quality of the subsequent models. Here a list of uncertainties arising from a variety of sources:

- Modeling uncertainties
    - Unmodeled or badly modeled phenomenon
    - Numerical errors
    - Lack of knowledge or information
- Uncertainties within input data
    - Initial stage (damage) estimation
    - statistical variability in the material
    - statistical manufacturing variability
- Measurement uncertainties
    - Sensors noise

        - Sensors coverage (range / phenomenon)
        - information loss during data preprocessing
        - Approximations and simplifications
    - Operational uncertainties
        - Unforeseen usage scenarios and loads
        - Unforeseen environmental conditions
        - High variability of usage conditions

Such models can be used to support the monitoring of early detections, based on patterns or accumulation in a given area. But to support the objectives of Prognostic, the built HI needs to fulfil additional properties in terms of monotonicity and progressivity all along the degradation phase. To reach this level of performance, more complex studies are needed most of the time, including the usage of specific test sessions called “Run2Failure” tests.

In particular, the quality of such Health Models is key when targeting to allow Prognostic. That is why the usage of “classic” operational sensors is sometimes not enough, specific sensors needing to be added. Indeed, for Prognostic, the main enabler is not to detect a degradation pattern, but is to quantify with accuracy the actual level of degradation. That is why implementing additional sensors measuring the evolution of the considered degradation process is often required to address Prognostic.

<u>Prognostic Models:</u> (a sub part of predictive models)

Such models can be advantageously generic if directly based on Health Indicators. For that, specific properties need to be verified, as described here above.

Specific (i.e. non generic) prognostic models should be typically considered when different speeds of degradation are observed, in particular in a situation where a reconfiguration occurred at system level (eg: a pump provides a higher flow if the associated one failed), and being thus capable to take into account the hardened operating conditions as a consequence of the reconfiguration.

Besides, key characteristics are required in terms of performance, to be adjusted by the considered topic. Typically, the first time a RUL estimation is computed within a given confidence interval (the prognostic horizon), and the capability to converge - keeping the targeted precision - all along the degradation phase are key performance indicators.

An aggregation should also be performed at system level. To support that, a resilience model should be defined for every system function, describing the redundancies and the different re-configuration modes.

In addition, it is important to keep a strong attention on the scaling factor. Indeed it would be a non sense to target prognostic capability everywhere. In some cases, reliability improvements or other means can be the appropriate solution. It is necessary to step further, compared to the standards of “early detection” methods, to build a HI “ideally” linearly correlated with the actual physical degradation level for a considered degradation mode. Considering also that, most of the time, hybrid Health Models are the best ones, the prognostic key enablers are the following ones:

- A deep physical understanding of the degradation process to build a physical model capable to link the data with the actual degradation level

- A data collection coming from experiences (called Run2Failure data), and obtained through dedicated test sessions on specific test benches (that is, having an appropriate level of representativeness regarding the environmental & operational conditions)
- A relevant data acquisition and data flow (with associated impacts if transmitted to ground)
- An appropriate computational power (airborn, or on ground)

Alerting Models:

They have the responsibility to raise alerts, using the different enablers (HIs, RUL, …), and considering the quality of these enablers (confidence intervals, V&V results - Run2Failure data, confusion matrix computed on existing data … -)

In particular they aim at building a robustified approach in order to avoid spurious detections and optimize the management of intermittent faults.

Moreover, such models should consider some customizations requested at airlines / MROs levels, in particular the tolerance of risk defined per maintenance topic.

3. Risk/safety assessment process linked to CBM functions

CBM target is to initiate a maintenance action only when a default or a potential failure is detected, when the default is becoming measurable and thus can be confirmed positively while it is not impacting safety and related corrective costs are reasonable.

To make progress on CBM and justify the inherent costs related to systems allowing it, it is necessary to define the process that may allow to maximize maintenance credit extracted from the CBM concept.

One of the most critical challenges is to determine what level of quality of the CBM process/model should be demonstrated to ensure the level of safety of the aircraft is maintained during the whole operational life.

However today, there is a clear reluctance from Airworthiness Authorities to provide an effective maintenance credit based on CBM systems and associated digital models.

3.1 From preventive maintenance to CBM maintenance credit

Main issue is linked to the absence of an explicit safety process that will assess the risk linked with usage of CBM instead of classic preventive maintenance (MSG3 process, ALS, …)

In general, the preventive maintenance process has an inherently important safety margin, at least a factor of 2 based on the possible worst case. This is leading to an important number of inspections to verify that there is no damage, even minor ones not requiring any maintenance action. It can also lead to the replacement of a part (Hard Time maintenance) irrespective from its real health status

If this process make sense for an Inspection / Check Based program (to verify that no default is detectable) with a finding rate normally close to zero, the process is questionable for a Condition Based Maintenance concept which aims at triggering the task only when needed and thus will have a finding rate close to 100%, but not decreasing safety level.

On top, for inspection tasks there is correlation between the minimum detectable size of a damage and the inspection type (general visual inspection, detailed inspection etc..) and that by essence an inspection triggered when the damage is close to the minimum detectable size is less effective than a task triggered when the damage is big enough to be more easily detected, while not impacting safety of course

The next major question is, if the proper parameter is monitored with prediction from very accurate/refined models using effective usage of the aircraft enabling to detect the said defect or failure, what is the confidence of such detection capability versus the MSG3 / ALS estimated probable occurrence.

In an ideal case, both should concur to define the same point of occurrence without inherent margins set in MSG3 / ALS analysis and for the effective usage of the aircraft.

There are still the margins set by the design requirements as this point is not defining the point of failure but the point where the default becomes measurable.

The first level of effective safety barrier could be to trigger a maintenance task at a predefined condition called "CBM limit" (i.e. not to exceed threshold expressed in time or other relevant usage parameter) if a maintenance task is not triggered before this condition is reached. The CBM limit needs to be defined in order to ensure the defect is detected by HM in all cases before the default is beyond operational margin.

It is assumed that the CBM will deploy gradually. Using classical MSG3 / ALS analysis as a starting point will provide a reference and somehow a safeguard. The proposed way of working is also providing a comprehensive way to move from MSG3 / ALS (i.e CBM limit) defined inspection to CBM defined maintenance trigger.

As a result, even if a maintenance task is still performed to check that there is no detectable defect and does not allow taking full credit from CBM, this leads to a significant increase in inspection time and thus dramatically decreases the maintenance burden.

3.2 Safety requirements and design assurance level determination of the CBM function

Currently there is no agreed process nor method to determine the proper Design Assurance Level for CBM systems in accordance with related aircraft safety requirements.

The existing process is defined for onboard systems directly linked to safety of flight and mostly real-time, the DAL is directly linked with this safety assessment.

As a recall, the basic requirement is in CS.xx.1309, ARP4754A and 4761 are defining the detailed processes to achieve that demonstration. DAL requirements are de facto set in the appropriate standards (DO178C) for real time on board systems.

This is in fact not applicable to CBM systems as they are not necessarily directly linked to safety of flight, not real time and maybe being partially or totally on ground.

Thus, it is necessary to set the process and the targets that shall be included in the guidance documentation to derive the appropriate requirements. For the time being, such a process is not defined anywhere and the basic safety process behind is far from being clear.

This is leading to classifying the current CBM system as "advisory" thus not really delivering any effective maintenance credit. In other words, CBM can only be used to trigger early inspection or repair within the MSG3 defined scheduled maintenance program. Some benefits may be found in unscheduled events as CBM may allow to anticipate unplanned failures and thus alleviate the impact on operations through triggering maintenance action before the fault occurs, but analysis shows that the related value is relatively marginal compared with the benefit that may be expected from credits in scheduled maintenance.

So for CBM systems, the safety assessment shall cover the architecture of the CBM function, the aircraft part, the transmission of data and the ground segment.

As the function is not really “real time”, from previous experiences main issues are:

- → Loss of data
- → Data corruption

This is impacting the architecture of the CBM system itself. In first analysis, the architecture shall provide a mitigation mean covering the loss and corruption of data, at least on a short term basis. In a medium term period, engineering judgment will drive to discover the discrepancy between the set of data and the effective state of the aircraft.

The proposed assessment process as defined in §3.1 may offer this mitigation through an independent determination of the Usage Parameters and computation of Useful Time Remaining prior to the next CBM limit.

Another issue is linked to the high volume of data used for CBM functions. This is rendering the assessment of the safety impact of the loss or corruption of individual data very cumbersome.

Thus, it is necessary to identify the data that have a direct impact on safety assessment (e.g. usage parameter) and the capacity to assess the pertinence of the others using global means.
In order to do so, a risk analysis is required if the possible consequence of failing to detect the considered failure is considered greater than “no safety effect”.

3.3 Design assurance level determination of the aircraft part of the CBM function

The main contribution of the aircraft systems is to collect, store and make available the CBM data. The DAL applicable on these systems may vary and are linked to their contribution to flight safety. Thus these data may be issued from systems being DAL A to DAL E. This is independent of the impact of the data to the CBM function itself.

Regarding the on board function collecting the data, storing and broadcasting part of it, there is currently no specific requirement from CBM. To some extent the DAL required is in line with the Aircraft Recording Function (for Flight Recorders) which is at most DAL C.

By analogy and for consistency, computations made on board should be also considered DAL C. This includes Usage Parameters computation, RUL prior to the next CBM Limit. The Life Time Remaining shall be computed in a comprehensive way for the flight crew or the maintenance crew in order they can exercise their engineering judgment to check the computed value without further computation.

The inherent design of CBM drives to consider that the criticality lies with a set of data, not a single one as it may be the case for flight functions.

The set of data is used to feed the model and if some data are missing or are erroneous, the impact is not as important as it would be for flight functions.
The difficulty is to evaluate the consequences of such failures. Thus the CBM function shall be designed to provide a certain robustness against this kind of failure. As such the designer should:

- Provide a mean to identify the missing data;

- Provide a consistent way to mitigate missing or erroneous data e.g. extrapolation and default values. The limits of such mitigation shall be also provided.
- Provide a means to identify out of range erroneous data.
- Identify the possible consequences of in-range erroneous data and possible mitigation if any.

3.4 Design assurance level determination of the data transfer for the CBM function

The data can be broadcasted during the flight, in that case it should be CBM high level data, i.e. Usage Parameters. In some cases, these data may trigger the downloading of supplementary data though, given the time frame of CBM, these data may be not broadcasted.

All the necessary data may be downloaded when the aircraft is on ground. This includes the raw data but also all the CBM data computed on board, broadcasted or not.
It is expected that some data are also uploaded into the aircraft to secure the overall process, being the confirmation of the Usage Parameters and Life Time Remaining. Other parameters arising from ground maintenance may also need to be updated e.g. equipment change or software update.

To be consistent with the aircraft part assumed to be DAL C and using DO200A standard it may be assumed that the proper DPAL level (Data Process Assurance Level) to be used for CBM is level 2. This is also consistent with the fact that CBM data are not individually critical.

3.5 Design assurance level determination of the ground part of the CBM Function

To define the Design Assurance Level of a maintenance ground system, there is no standard nor process applicable in Part 21. For continuing airworthiness part, following requirements have a link:

- Part M
    - M.A.305 Aircraft continuing Airworthiness record system
    - M.A.306 Aircraft Technical Log System
    - M.A.714 Record-keeping
- Part 145
    - 145.A.45 Maintenance data
    - 145.A.65 Maintenance procedure and quality system
    - 145.A.55 Maintenance review records

In short, these requirements are only dealing with data archiving and general quality requirements mostly covered by EN 9100.

Nevertheless two documents are dealing with the subject, D0-200 AIED-76, "Standards for Processing Aeronautical Data" already cited and, DO-201 AIED-77, “Industry Requirements for Aeronautical Information".

DO-330-ED-215 “Software Tool Qualification Considerations” covers the software part only and not the whole system.

Another standard is also relevant to ground systems, DO278A-ED109A CNS/ATM Software Approval, but this document should be interpreted as a guide to implement DO-178B/C for CNS/ATM systems.

This document is introducing a new Assurance Level, AL4, while AL3 is directly comparable to DAL C and AL5 to DAL D.

Level AL3: Software whose anomalous behavior as shown by the system safety assessment process, would cause or contribute to a failure of a CNS/ATM system function resulting in a major failure condition for the aircraft.

Level AL4: is not associated with any failure condition category. AL4 requirements are more or less AL3 requirements without real time considerations. As a consequence the Failure of the system is not considered as such, providing the system can be restored within a time frame compatible with aircraft operations. This is allowing, under certain precautions, to use non certified COTS hardware and software.

In order to determine the DAL requirements on the ground system, it is necessary to determine the requirements from ground part architecture. This architecture will drive the DAL requirements in the same way it is done for aircraft systems.

In the absence of a specifically defined standard, we may use DO278A in the meantime.
This has several advantages:

- ✔ Terminology is in line with DO178, verification and validation methods very similar to aircraft parts.
- ✔ From a formal standpoint, a function implemented with AL3/AL4 can manage functions classified as Major without further precautions.
- ✔ The requirements set on CBM by aircraft designers are easily transposable from ground to flight and vice-versa.

If we apply considerations set in the definition of DO278 categories, the ground system overall software shall comply with AL4 while the CBM assessment part should be AL3.

As far as software quality is concerned, this is corresponding to the same level of requirements with additional architecture/validation requirements for AL3 as compared to AL4.

This makes sense for the CBM assessment part as this function is used to control and validate short term, even not real time, decisions and actions.

So additional certification/standardisation activities have to be conducted to ensure appropriate assurance level framework of the ground part of the CBM function.

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5. Copyright Statement

References

All the definitions, basic concepts and methodology are developed as part of the various IVHM working groups of the SAE, namely the ones focusing on Health Monitoring Systems themselves, Aircraft Systems in general, Engines and Powerplant, Landing Gear, and Airframe/Structures.

See:

[1] SAE JA6097: Using a System Reliability Model to Optimize Maintenance Costs A Best Practices Guide

[2] ARP 6883: Guidelines for Writing IVHM Requirements for Aerospace Systems

[3] AIR 6904: Rationale, Considerations and Framework for Data Interoperability for Health Management within the Aerospace Ecosystem

[4] ARP6803: IVHM Concepts, Technology and Implementation Overview.