A Certifiable Framework for Health Monitoring and Management

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Abstract: The scope of this paper is to provide an E2E perspective of health monitoring and management (HMM) and structural health mornitoring (SHM) as an integrated system element of an integrated system health monitoring and management (ISHM) system. The paper will address two main topics: (1) The importance of a diagnostics and prognostic requirements specification to develop an innovative health monitoring and management system; (2) The certification of a health monitoring and management system aiming at a maintenance credit as an integral part of the maintenance strategies. The development of a maintenance program which is based on combinations of different types of strategies (preventive, condition-based maintenance (CBM) and corrective maintenance…) for different subsystems or components and structures of complex systems like an aircraft to achieve the most optimized solution in terms of availability, cost and safety / certification is a real challenge. The maintenance strategy must satisfy the technical-risk and cost feasibility of the maintenance program.

Key words: health monitoring and management; enhanced diagnostic, data driven and model based prognostic; ISHM Simulation Framework

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0 Introduction

With growing financial uncertainty, air vehicle operators (both commercial and military) are under tremendous pressure to reduce operational and support costs. It is accepted across the aerospace industry that integrated system health monitoring and management (ISHM) is a potentially valuable strategy for the management of platform integrity. At the same time, ISHM has not yet fully matured as a technology in several key functional areas. Research and development to address this shortfall is occurring across both the automobile and aerospace industries. Although technologies related to built-in test (BIT) and diagnostics have advanced greatly and research into enhanced diagnostics are progressing very fast, prognostics technology for all types of aircraft subsystems are still at a very nascent stage.

Maintenance Strategy, which is generally considered during the design phase of development, greatly influences both the system availability and life cycle cost. Reliability-centered maintenance (RCM) is a systematic methodology used to identify the preventive maintenance tasks that are necessary to realize the inherent reliability of equipment at the lowest possible cost. The conventional practice of developing a scheduled maintenance program by means of RCM consists of identifying those preventive tasks which are both applicable (technically feasible) and effective (worth doing).

Condition-based maintenance (CBM), being a proactive maintenance philosophy, is a core element of health monitoring and management (HMM). RCM decision logic based on existing guidelines[1-3] needs further extension to select CBM candidates along with reactive and preventive candidates in an aircraft.

The novel approach integrates CBM as part of the maintenance strategy. Additionally it also integrates a cost feasibility check through a study

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of ″worth doing″ at the individual task level, ″cost effectiveness″ option of maintenance strategy (combination of tasks for all faults) at the subsystem level and an overall framework with shortlisting of maintenance tasks at different levels: Fault consequence check, technical feasibility check, risk (safety) feasibility check and cost feasibility check.

The validation & verification (V&V) method leading to the qualification and certification of ISHM is a key area of development. Although there has been considerable effort in this direction, the ISHM system is yet to be certified at the aircraft level. Certification agencies (EASA, FAA, SAE, etc.) are yet to establish a comprehensive certification regulation for integrated system health monitoring systems.

Deployment of HMM in an aircraft and the resulting qualification process demands a huge investment. Verification and validation of these HMM technologies are an important step in building confidence, both qualitatively and quantitatively. Practically, the cost of correcting an error after fielding an ISHM system is dramatically greater than that in the testing phase, thus highlighting the need for appropriate verification and validation techniques. Certification considerations must be addressed during the very early stages of technology development in order to successfully meet any significant qualification goals. Appropriate guidelines and strategies should be followed in HMM technology development to ensure successful certification within the desired time frame. Additionally, trade studies in the selection of V&V platforms reduce the eventual cost of V&V processes. This paper focuses on the development of such guidelines for the V&V process while emphasizing the relevance of IS HMM simulation frameworks, and a well devised certification roadmap.

1 Design Elements of Condition-Based Operations

The main elements of condition-based operations are:

(1) On-board health management functions and data transmission.

(2) Evaluation of health management information using prognostic functions to enable predictive decision support.

(3) Decision support including evaluation of different options for dynamic mission and maintenance scheduling.

(4) Performance-based logistics for an optimized resource and supply chain management.

(5) Certification of condition-based decision-making and configuration control to ensure continued airworthiness.

The main technological challenges occur in the development of on-board monitoring functions, regularizations for data security, integration of off-board functions for predictive maintenance and mission management, and the on-demand strategy for supplier and logistic supply chain management. Apart from the technology maturation, all design elements need to be developed under the guidelines of the respective authorities to ensure certifiability for new products and continued airworthiness for upgrades of legacy systems. The field of diagnostics and prognostics is one important contributor for the realization of condition-based operations, as the information from the health management system is one of the main inputs to dynamically optimize maintenance and mission planning.

As for the development of other on-board and off-board functions, diagnostics and prognostics also require the definition of verifiable design requirements. Airbus Defence and Space has developed a virtual framework to support the validation & verification of design requirements for a health management system[4]. The framework described in Ref. [4] has been validated against a certified environment and the requirements and concepts described in this paper are now an integral part of the framework to support the development of diagnostic and prognostic functions. The implementation is performed as shown in Fig. 1, where EHM means enhanced health management.

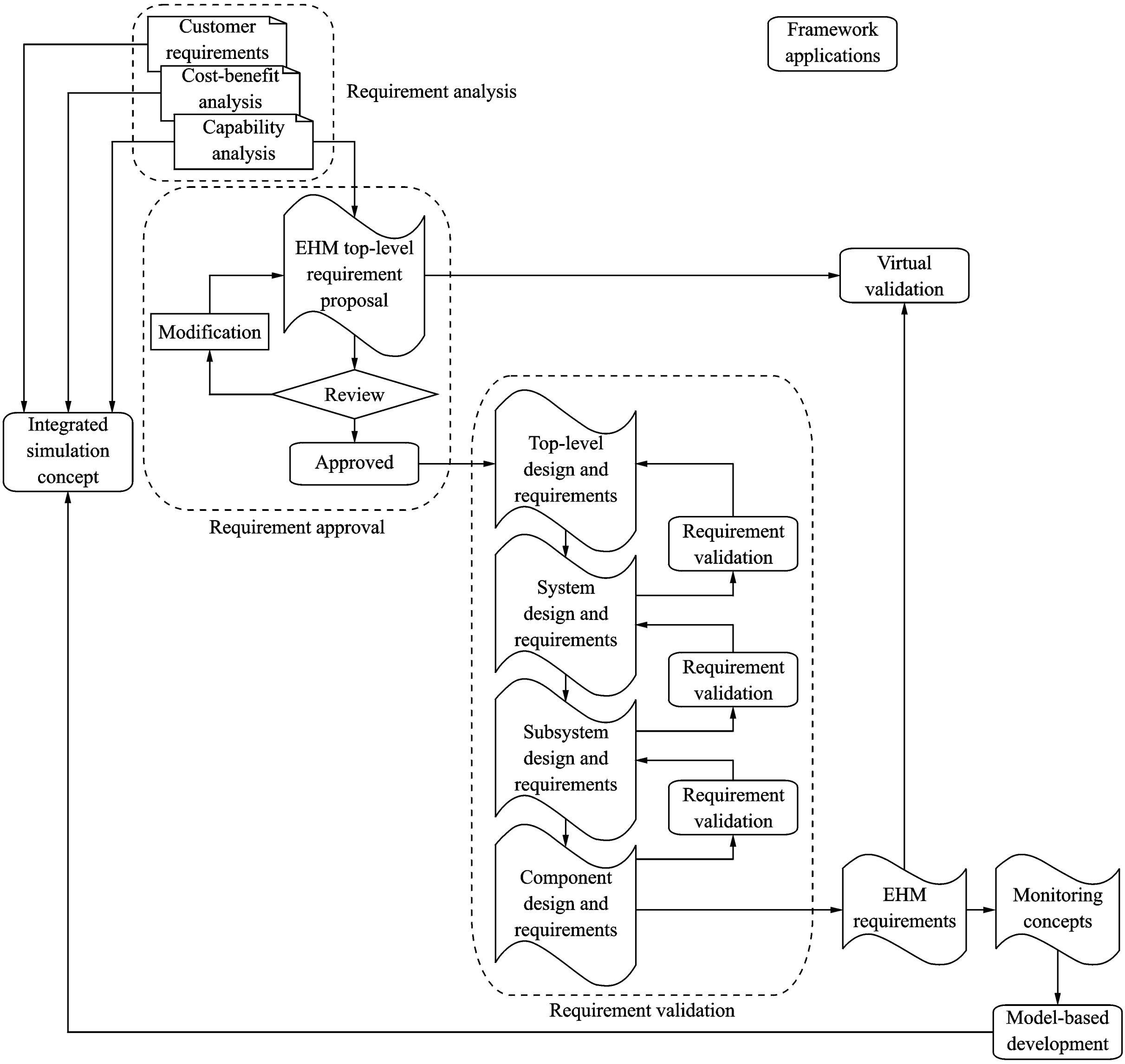


Fig. 1 Development process for diagnostic and prognostic functions

The following chapters will focus on a status review of condition monitoring in general and prognostics and HMM simulation framework as an integral part of condition-based operations. The main requirements for the definition of diagnostic and prognostic functions that can be applied to any design task from this field are presented and discussed.

1.1 Condition monitoring

Today's condition monitoring systems for aircraft applications are based on a combination of built-in tests (BIT) and health monitoring systems[5]. Therefore, dedicated instrumentations and data analysis concepts are considered during the system design stage. The BIT shall ensure that all relevant failure modes become evident to the flight operator. Different classes of BITs ("Power-Up BIT" during the component or system start, "Continuous BIT" during continuous operation and "Initiated BIT" during specific operating conditions) are considered and evaluated according to a predefined monitoring concept. The results from the BIT monitors are compared with specified thresholds to decide whether the respective function can be supported as required. Repeatability and reliability of the BIT is ensured by the fixed test procedures and thresholds for unacceptable conditions that have been defined and verified during component and system qualification. The evaluation of BIT information is a mandatory input to continuously verify the airworthiness of the operating system.

In addition to BITs, selected parameters and conditions are subject to a continuous monitoring and assessment of the remaining margin to predefined damage or performance thresholds (condition monitoring function-COM). Examples are the "Usage Monitoring" for structural parts or "engine trend monitoring" for jet engines[6].

The main difference between these two approaches can be seen in the high reliability of the BIT in distinguishing between two conditions (operative or non-operative) and the capability of the COM to continuously quantify changes in the operating conditions before a failure or malfunction occurs. The impact of BIT and COM on maintenance intervals and the useful life consumption is shown in Fig. 2. The BIT would indicate the failure when the predefined threshold is exceeded, causing an operational interruption due to a failure event, while the COM avoids the failure and maximizes the availability by the initiation of a preventive maintenance action. The waste of useful life E can be minimized with the increasing accuracy of the diagnostic and prognostic function. For real world applications, E will always be greater than zero, affecting the useful life consumption of the monitored equipment adversely but avoiding unacceptable degradation levels. Therefore, the design aim for COM functions should be to maximize the component utilization (which is equivalent to minimizing E), while also ensuring a simple and robust monitoring concept with a minimal impact on the system design and operation.

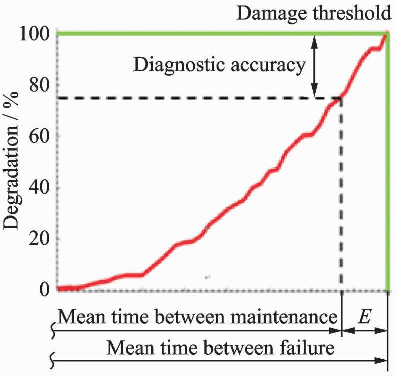


Fig. 2 Condition monitoring concepts and impact on the operating system

1.2 Classification of condition monitoring

In general, condition monitoring techniques can be classified into data-driven and model-based approaches[7-8], shown as Fig. 3.

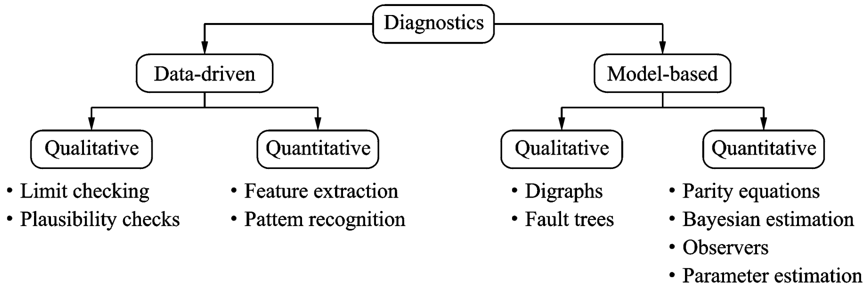


Fig. 3 Classification of diagnostic approaches

The class of qualitative data-driven approaches is robust and easy to implement. Limit checking and plausibility checks are used for numerous industrial applications. These concepts usually require no complex algorithms and the main effort can be seen in the derivation of reasonable thresholds to decide whether the monitored function is satisfying its requirements or not.

The quantitative methods are utilizing extensive datasets with and without failure signatures to identify whether the observed process has a nominal or faulty behavior. The health assessment is performed based on pattern recognition algorithms by analyzing selected features from the collected data[7]. The concept for feature generation is very problem-specific and needs to ensure that the fault signature is evident to the algorithms for pattern recognition. Commonly used classification methods include but are not limited to Bayesian decision theory, neural networks, and support vector machines. Model-based approaches utilize a logical or mathematical description of the monitored process to compare the expected behavior with actual measurements. The results of this comparison are used to derive estimates for the actual health status.

Qualitative models are an abstracted version of the underlying process and are used if no detailed physical modeling is needed or the complexity of the process prohibits the model development[7]. One example is logical graphs, which include information about the cause-effect relationship of failure modes that can be used for fault detection and isolation[9].

Quantitative model-based methods are based on a detailed mathematical model, which represents a virtual redundancy of the monitored process. The models are used to derive a residual, which describes, when a fault occurs, the difference between the nominal and faulty behavior. The residual is then used to isolate and quantify deteriorations or malfunctions of the process. Various examples like parity equations[10], recursive Bayesian estimation[11], or parameter estimations techniques[12] have been discussed.

Following the aforementioned definition for BITs and COM, the BIT can usually be seen in the context of qualitative methods, enabling detection and isolation of a failure that has already occurred. The capability to detect, isolate, and quantify a deviation from the nominal behavior requires a deeper analysis of the monitored process and therefore COM approaches would be expected to come from the field of quantitative methods.

1.3 Development of condition monitoring

The development of the above-mentioned capabilities requires the establishment of design requirements for the V&V of the diagnostic performance. To support this task, the following qualitative requirements have been identified as relevant for the development of diagnostic functions (DF) for all COM-monitored items:

(1) The DF shall indicate the minimum detectable damage size.

(2) The DF shall quantify the remaining margin until the damage size exceeds a maximum allowable limit.

(3) The DF shall enable root cause isolation at component level.

(4) The DF shall provide the confidence level of damage size quantification.

(5) Each DF shall be provided with a value for the critical damage size of the monitored feature.

Once the requirements for DFs have been defined, the particular monitoring concepts and applied algorithms combination is very problem specific, therefore the task needs a case-by-case solution. The following set of quantitative requirements is considered as a generic baseline to verify the diagnostic performance of DFs:

(1) The system shall ensure a diagnostic capability rate (DCR) of more than $X\%$.

(2) The DF shall achieve a probability of detection of more than $X\%$.

(3) The number of COM false alarms shall be less than $X\%$ of all COM failure detections.

(4) All DFs shall ensure an error for damage quantification of less than $X\%$.

(5) All DFs shall ensure an uncertainty for damage quantification of less than $X\%$.

(6) All DFs shall ensure a probability of failure detection of more than $X\%$.

The following definitions are used for these requirements:

(1) The DCR is defined as (FRD = failure rates with diagnosis; FRSYS = system failure rate)

$$\mathrm{DCR} = \frac{\sum \mathrm{FR_D}}{\mathrm{FR_{SYS}}} \cdot 100$$

(2) Probability of detection shall be defined as the probability to detect the minimum detectable damage size.

(3) Uncertainty of damage quantification shall be defined as the $X\%$ probability of correct damage assessment.

(4) Probability of failure detection shall be defined as the probability of detecting an exceedance of the maximum allowable damage size.

The capability to quantify incipient failures is seen as a prerequisite for prognostics，as the output from the DF will be used to predict the future state of the degradation.

1.4 Prognostics

The task of prognostics is to determine the point in time from which the specified requirements of a function cannot be satisfied anymore. The criterion of failure can be defined as an unacceptable deviation from any operating condition or the loss of functionality. The different concepts for the implementation of prognostics can be divided into data-driven，model-based and hybrid approaches[13-15]，as shown in Fig. 4.

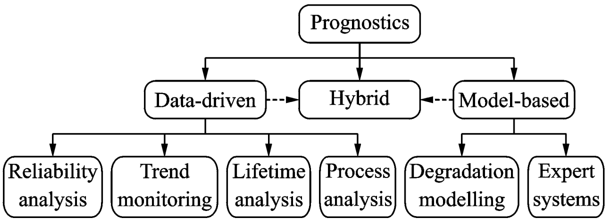


Fig. 4 Classification of prognostic approaches

The reliability analysis is based on a statistical evaluation of collected failure modes and correlation with recorded operating conditions to derive an estimate of the useful life for a given usage profile. No information about the real status will be used. Conservative assumptions can minimize the risk of failure but the useful life consumption is overestimated and a mismatch between the real and theoretical usage profile raises the risk for a failure during operation. The Weibull analysis is one of the most popular methods for reliability analysis. A qualitative overview about the fields of application for data-driven，model-based and hybrid concepts in general is depicted in Fig. 5.

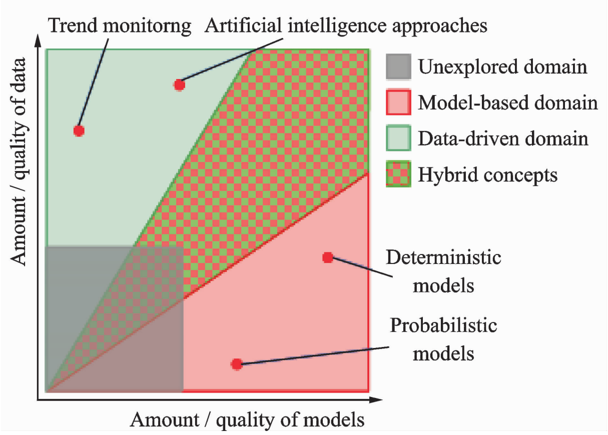


Fig. 5 Areas of application for prognostic concepts

All mentioned prognostic approaches can be classified into two main categories：

(1) Lifetime calculation

(2) Failure prognosis

Only approaches that enable the prediction of the path for a CI under consideration of future operating conditions are accounted for in the category of failure prognosis. This includes trend monitoring，selected data-driven process analysis concepts，as well as model-based approaches，which use damage propagation models or suitable expert systems.

Exact determination of the CI and related uncertainties for damage quantification through appropriate DFs are a prerequisite for failure prognosis. The period for which the prognosis can satisfy certain accuracy and precision requirements is called the prognostic horizon and indicates the potential for predictive measures like spare parts ordering or maintenance scheduling.

Every failure prognosis accumulates and integrates all uncertainties for damage quantification，prediction of damage trends and impact of future operating conditions：Prognostics deals therefore with uncertainty. In the last step of the DF，before the prognosis is started，uncertainties come from the imperfect data acquisition and representation of the underlying process of damage quantification as well as uncertain knowledge of future inputs. Since these sources of uncertainty cannot be avoided, the full prognostic task deals with variables like remaining useful life and end of life, which are random in nature. For these reasons, every prognostic algorithm must account for these inherent uncertainties. Moreover, every conceived algorithm contributes to increasing the uncertainty of the overall framework: In fact, the conceived algorithm only has a partial knowledge of the state of the system at the time in which a prediction is initialized, of the future input statistics, and of the description of the underlying process; above all, it does not know exactly which model the system will follow during the time interval of prediction.

2 Main Objective of Simulation Framework

Airbus DS has developed a comprehensive integrated HMM simulation framework which contributes in the following areas:

(1) Integrated demonstration of proof of enablers (PoE).

(2) Training and maturity of PHM functions.

(3) Maturation of ISHM requirements (KPIs).

(4) V&V of ISHM functions.

This HMM simulation framework is used primarily for demonstrating Proof of Enablers (PoE) and System Integration Laboratory (SIL) testing, including S/W and H/W in the loop, which is the goal of concept refinement and technology development. For the end-to-end demonstration of HMM, the simulation framework hosts a simulation of the aircraft system with fault injection provision, an on-board health assessment function, off-board analytics related to prognostics, operational risk assessment, database management, fleet planning, maintenance/logistics planning, etc. at enterprise level. For SHM, Airbus Defence and Space is addressing the virtualization of structural components to be monitored by SHM (structural component simulation stress, strain …) and facing the challenge of modeling the sensing system (Lamb wave simulation) and the insertion of failure modes.

During the early stages of HMM development for new aircraft platforms, there is an insufficient amount of in-service or test flight data (both nominal and fault behavior, as well as run-to-fail data) available. The physics-based simulation of aircraft systems and fault progression models plays an important role for modeling enhanced diagnostics and prognostics modules/functions. Simulation models and PHM functions undergo continuous evolution of maturity with data (rig data, test flight, in-service flight data) available through progress in the development life cycle. The simulation framework has the mechanism to accommodate additional correction factors related to modeling imperfection.

User objectives and metrics related to HMM can be refined through exhaustive Monte-Carlo simulation of off-nominal scenarios, which is not a viable solution with real flight tests. Simulation framework supports functional analysis related to the selection of candidate subsystems, faults, sensors and performance matrices of enhanced diagnostics and prognostics. This will enrich performance requirements of key algorithms mainly related to enhanced diagnostics, prognostics, etc.

With the increase in maturity of the simulation capabilities, it plays different roles on V&V platforms viz. engineering simulator, system-subsystem test setup, integration test setup, etc. Ground-based HMM systems can be deployed in this environment. This framework, with high-fidelity modeling of subsystems and sensor data, provides enough confidence for the installation of on-board ISHM non-critical systems before a controlled introduction to service for further tuning and refinement of the algorithm. Integrated HILS will simulate aircraft dynamics, aircraft subsystem H/W and adverse environmental effects. Also, there is the capability to inject system faults. This facility can expedite the validation process of the ISHM system and reduce the validation time period during the controlled introduction to service. However, this capability demands a huge investment of time and capital. These investments can be greatly reduced in the case of the V&V of the aircraft's ISHM by utilizing the simulation framework.

3 ISHM System Certification Guideline

3.1 Certification basis

Certification agencies (EASA, FAA, SAE, etc.) are yet to establish comprehensive certification regulation for HMM. This section summarizes existing efforts to establish a certification basis which will act as an overall guideline for ISHM system development.

Wheeler et al.[16] contribute to an extensive survey of recent ISHM system programs and mention that vast differences in user objectives with regard to engineering development is the major barrier for successful V&V. The paper identifies in detail the objectives and associated metrics across operational, regulatory and engineering domains for diagnosis and prognosis algorithms and systems.

Dzakowic et al.[17] introduce a methodology for verifying and validating the capabilities of detection, diagnostic and prognostic algorithms through an on-line metrics-based evaluation.

Feather et al.[18] mentions in his publication that state-of-the-practice V&V and certification techniques will not suffice for emerging forms of ISHM systems. However, a number of maturing software engineering assurance technologies show particular promise for addressing these ISHM V&V challenges.

Gorinevsky et al.[19] describe the importance of a NASA-led effort in open system IVHM architecture. Detailed functional decompositions of ISHM systems with respect to criticality, on/off board operation and development cost are presented and certification standards are mapped accordingly. This paper also addresses the current NASA IVHM test bed along with development and deployment steps corresponding to increasing TRL.

The FAA's advisory circular (AC), AC 29-2C MG-15[20], provides guidance in achieving airworthiness approval for rotorcraft health and usage monitoring system (HUMS) installations. It also outlines the process of credit validation, and Instructions for continued airworthiness (ICA) for the full range of HUMS applications.

Larder et al.[21] converted the text of AC 29-2C MG-15 into a flow chart. His intention was to define the generic end-to-end certification process for HUMS CBM credit. Further, he sought to identify the relationships and interactions between different elements of the certification process that are contained in the three separate sections of the AC (installation, credit validation, and Instructions for Continued Airworthiness). This paper also mentions that HUMS have achieved very few credits, and that the material in the AC is largely untested. However, HUMS in-service experience shows that the potential for future credits does exist.

ADS-79E HDBK[22] describes the US Army's condition-based maintenance (CBM) system and defines the overall guidance necessary to achieve CBM goals for Army aircraft systems and Unmanned Aircraft Systems (UAS).

Menon et al.[23] published a paper which summarizes the work of a Vertical Lift Consortium Industry Team to provide detailed guidance for V&V of CBM maintenance credits.

Existing ARPs (viz. ARP 5783, ARP 4761, etc.) published by SAE already supports some aspects of guidance in different stages of ISHM development.

SAE formed an Integrated Vehicle Health Management (IVHM) Steering Group to explore the needs for standardization to support IVHM technology for the following objectives:

(1) The development of a single definition and taxonomy of HMM to be used by the aerospace and HMM communities.

(2) The identification of how and where IVHM could be implemented.

(3) The development of a roadmap for

IVHM standards.

(4) The identification of future IVHM technological and regulatory needs.

Fig. 6 summarizes existing ARPs and standards in the different stages of ISHM process flow.

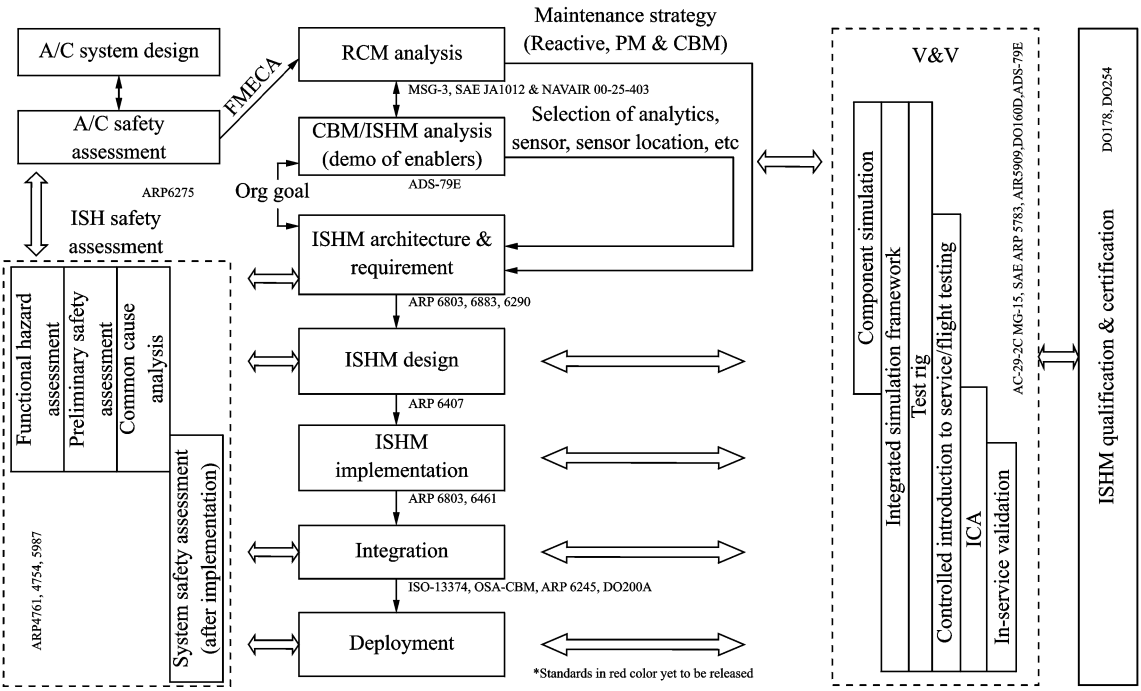


Fig. 6 HMM process flow mapping with ARPs and standards

3.2 Guideline for life cycles

HMM development process steps are mapped onto the ARP 4754A aircraft/system development life cycle, which serves as the baseline. The HMM development process steps can be mapped to the V-model of the ARP 4754A process with the exception of "Concept & Technology Development", "Controlled Introduction to Service", "Instructions for Continued Airworthiness (ICA)", and "In-Service Validation" processes steps, which are outside of the V-model, as shown in Fig. 7. It is assumed that after the transfer from R&T the HMM development will be part of an aircraft system development. This concludes that the HMM development is part of an overall aircraft and system development process. Detailed guidelines for all processes will be available in the respective standards as mentioned in Fig. 6.

3.3 HMM simulation framework

The goal of the ISMM system is the preparation of an intelligent maintenance plan, intelligence mission plan and automatic logistics function for enhancing availability, maintainability and mission capabilities. These functions are achieved through condition-based maintenance (CBM). The Simulation Framework, which is built around OSA-CBM and OSA-EAI architecture, simulates all ISHM functional layers through different subsystem models

Prognostic health management (PHM) is the core of HMM technology. Like in any other domain, challenges in the introduction of PHM systems in the aerospace domain are twofold. On one hand, there are individual challenges in developing sensor technology, state detection and health assessment methodologies and models for determining the future lifespan of a (possibly deteriorated) component. On the other hand, there are integration challenges when turning heterogeneous data from disparate and distributed sources into consolidated information and dependable decision support at aircraft and fleet level. It has therefore been recognized in the community that standardized and open data management solutions

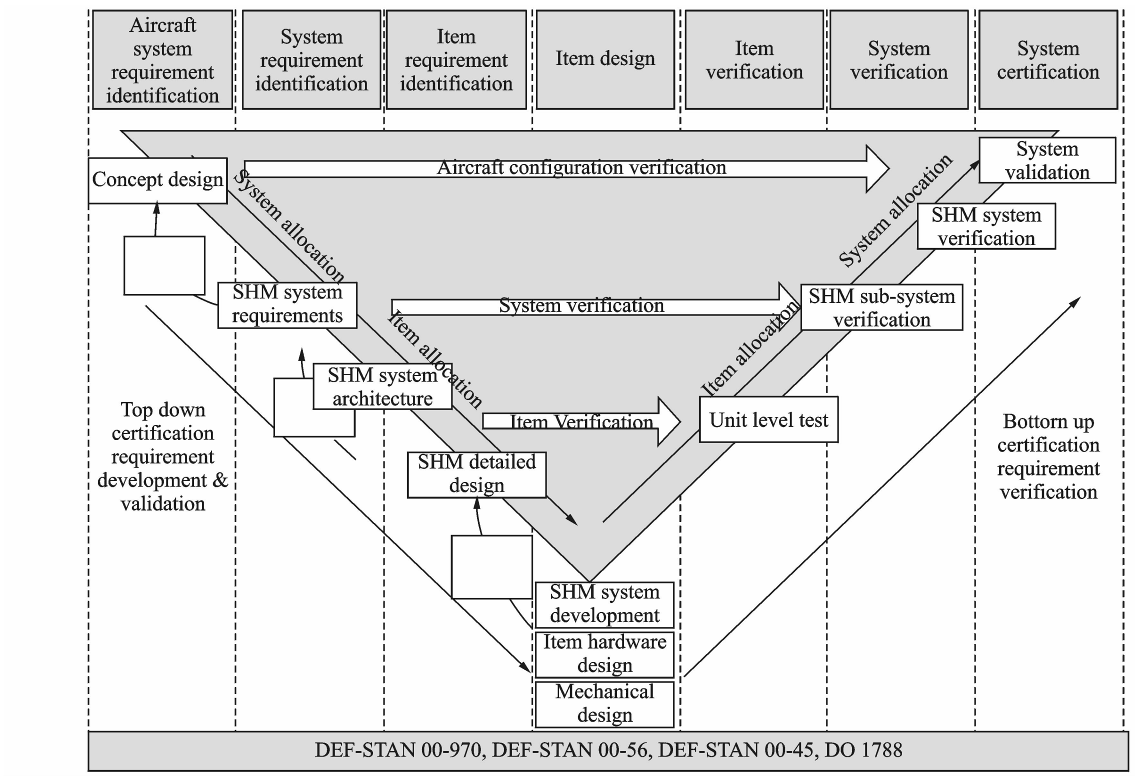


Fig. 7 Mapping of HMM development process steps to aircraft development process

are crucial to the success of PHM. Such a standard should introduce a commonly accepted framework for data representation, data communication and data storage.

This simulation framework Fig. 8 supports key features, viz. demonstration of the end-to-end value chain of HMM, real-time simulation for the on-board computation, almost real-time for off-board, having features of simulating lifetime (with time acceleration mode), provision for refinement of physical models with data from test rigs, test flights with seeded faults and in-service data.

HMM Simulation Framework simulates the following modules:

(1) Aircraft system model

(2) On-board ISHM system

(3) On-ground ISHM system

(4) Supply chain (enterprise level)

(5) Simulation management

The simulation of the aircraft system model and supply chain (enterprise level) create a simulation environment for HMM system models and simulation management controls the operation of the complete HMM simulation framework.

3.3.1 Aircraft system model

The aircraft system model simulates systems for which we intend to develop HMM capabilities and their sensors. The aircraft system model features high-fidelity modeling of the aircraft aerodynamics model, hydraulics / actuator system model, landing gear, fuel, ECS, and aircraft structure, etc. Each subsystem implements physics-based modeling of dynamic behavior, physics of fault, and computation of states or parameters for deriving sensor data for each subsystem. Sensor data for each subsystem are generated from computed states and parameters after corruption with all possible errors that might occur in real-life scenarios, as well as with noise specific to these sensors. All faults are injected from the simulation control GUI. Any system for which HMM-specific monitoring and prediction capabilities should be validated and verified needs to be modeled with a high level of detail. This should enable the realistic simulation of failures to support the validation of diagnostic and prognostic

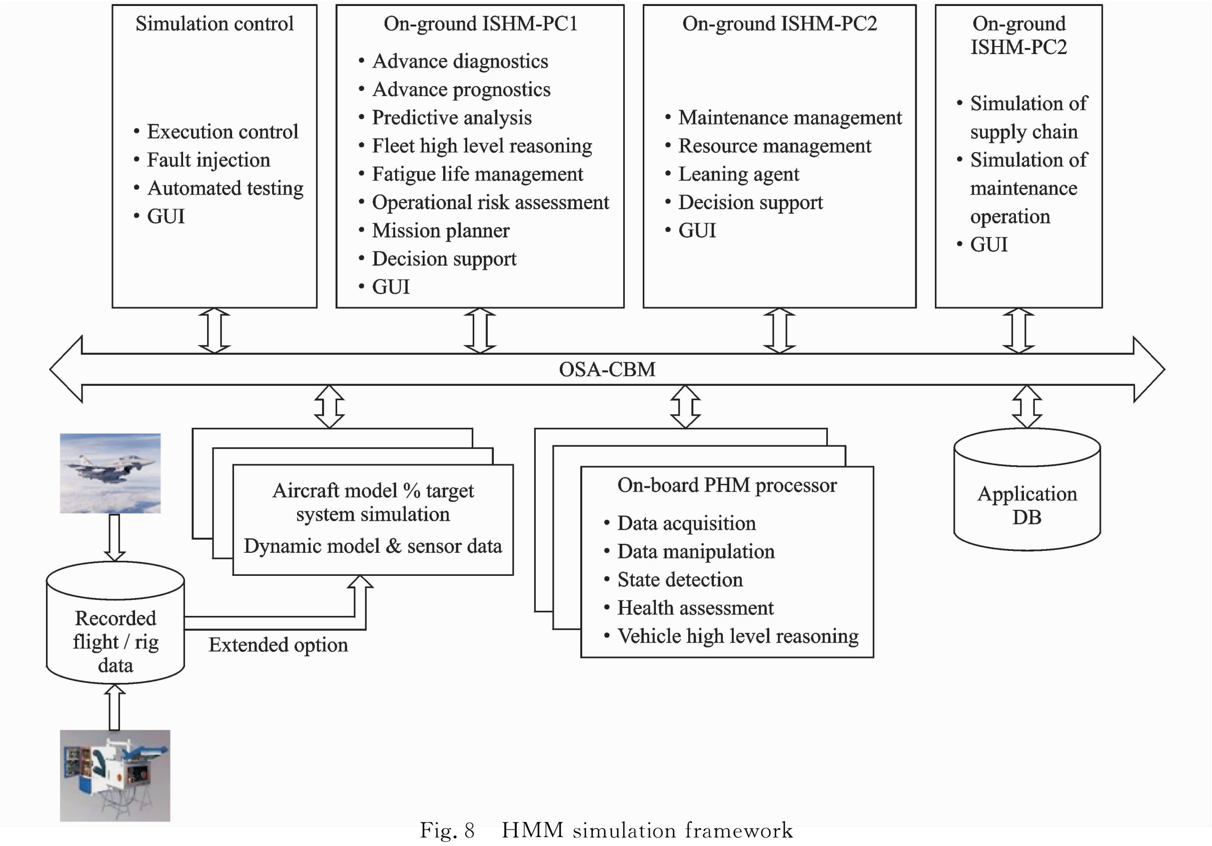


Fig. 8 HMM simulation framework

functions. The respective controller model simulates built-in tests (BIT) and reactive health assessment (RHA) of the subsystem.

3.3.2 On-board ISHM system

On-board ISHM function includes a central ISHM data processor. Sensors push their data to the HMM data processor via an OSA-CBM implementation. The underlying message protocol is optimized for embedded systems. The HMM data processor calculates ISHM information according to the OSA-CBM layer specifications, up to the health assessment layer.

As per OSA-CBM, there are seven functional layers. The central ISHM data processor has the following functions:

(1) First four functions of OSA-CBM

(2) Data acquisition

(3) Data manipulation

(4) State detection

(5) Health assessment

(6) High-level reasoning

(7) BIT function

(8) Storing of on-board health data

Several seeded fault tests under fixed conditions are sufficient to enable the model-based development of diagnostic functions. The development of prognostic functions (to be part of ground-based HMM) also needs to cover the development of suitable failure mode-specific degradation models. Once the degradation models have been developed, it is possible to verify the diagnostic and prognostic functions through Monte-Carlo simulations. These simulations should include stochastic fault insertion for "hard faults" (stochastically occurring failures without impacts on observable system parameters before the specified failure threshold is exceeded) and the usage of degradation models for "soft faults" (stochastically occurring degradations with impacts on observable system parameters before the specified failure threshold is exceeded). This concept is illustrated in Fig. 9.

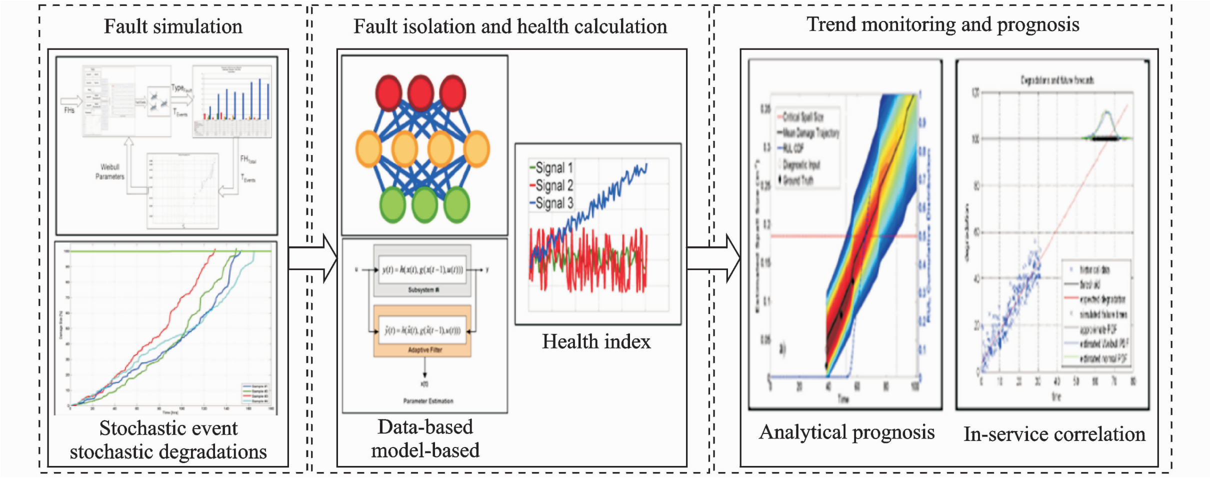


Fig. 9 Fault simulation concept for simulation framework

3.3.3 On-ground HMM

Major functionalities for enhancing availability, maintainability and mission capabilities related to the HMM system are realized by ground-based subsystems. The on-board ISHM system functions only include data acquisition and an equipment health diagnostic function, along with the intermediate processing of data. The ground-based ISHM system has a significant amount of processing related to the following prime functions Camci et al.[24]:

(1) On-ground health management function

The on-ground health management function consists of advanced diagnostic and predictive analysis. Advanced diagnostics validate further on-board diagnostic results with historical data of the same aircraft and a fleet-wide fault database, and refine diagnostic decisions. Advanced prognostics compute RUL & Confidence for the CBM candidate. Predictive analysis (trend analysis) identifies impending failure using a trend analysis of historically collected data, but does not predict when failure will occur.

(2) Maintenance management

Maintenance management functions find one of the following maintenance solutions for a subsystem, depending on the RCM process (Fig. 10):

- Corrective
- Preventive
- CBM

Maintenance management executes the following functions:

① Identify maintenance task corresponding to subsystem/functional failure;

② Compute rank of optimal maintenance task as a function of maintenance effectiveness for the failure mode, maintenance downtime and cost;

③ Execute maintenance (work order generation, Track maintenance action, Receive feedback and close work order) as per approved maintenance plan.

(3) Maintenance planer

The opportunistic maintenance agent determines the opportunistic maintenance time and tasks using the rank of maintenance tasks, mission capability of subsystem/function for future missions, and RUL for future missions. The maintenance planner schedules the intelligent maintenance plan, validates with feedback from resource management and publishes the maintenance plan after getting approval from the decision support system.

(4) Resource/logistic management

This function tracks the availability along with the configuration parameters of LRUs, tools, parts, consumables and personnel, etc. (configurable items). Upon receiving the maintenance plan , the Resource / logistic management

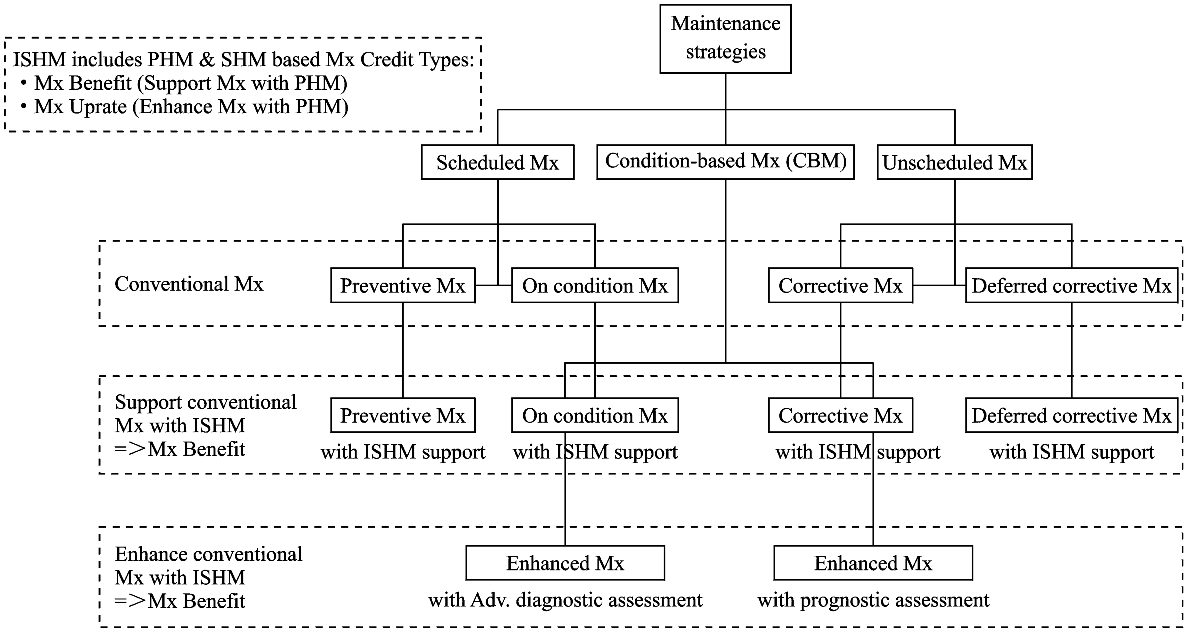


Fig. 10 Maintenance strategies including predictive, CMB

function sends feedback on the validity of the maintenance plan to the Maintenance Planner on the basis of resource availability. Finally, this function generates a plan for resources/inventory and generates order for parts or LRUs to OEMs or suppliers as per the present and projected status of the inventory.

(5) Mission planner

Mission plans and flying programs are entered using a digital map and editing GUI. The Mission Planner instructs users to reschedule the Mission Plan if the performance of the aircraft exceeds the entered and edited mission plan. Flying programs are asked to reschedule if the approved maintenance plan clashes with the mission plan. The applicability of mission segments of a particular aircraft are checked further with respect to the operational capabilities of the aircraft for the segment, computed by Operational Risk Assessment (ORA). If the capability of the flight segment or complete mission is less than the critical threshold, the Mission Planner instructs users to reschedule or cancel the mission for that particular aircraft.

(6) Learning agent

As experience is accumulated, some of the parameters within the model can be learned automatically by analyzing the feedback from the maintainer, OEM industry, mission commander, or resource manager. The parameters to be learned are the opportunistic maintenance threshold, the required maintenance threshold, resource lead time, maintenance effectiveness and different coefficients related to diagnostics and prognostics, etc.

(7) Simulation of enterprise system

This module simulates the supply of specific LRUs or parts from OEMs, service/industry support organizations, wholesale stock point, taking into account an appropriate accumulated delay attributed to the order process by the resource management function, manufacturing (if applicable), shipping process, etc. related to supply chain management.

(8) Presentation layer

Decision support personnel interact through the presentation layer, which consists of the following GUIs distributed across different terminals:

- Health management & monitoring
- Interactive GUI for maintenance management
- Resource management & monitoring

- Maintenance planner
- Mission planner

(9) High-level reasoning / operational risk assessment

High-level reasoning (HLR) is the capability that can estimate an airplane′s (or vehicle′s) functional availability. The purpose of the HLR concept is to estimate the functional availability of a vehicle based on the health assessment results from lower-level systems and subsystems. Both concepts are part of the HLR development and integration into the simulation framework. RUL and confidence is recomputed for each component failure for all future missions and used by HLR. Finally, ORA determines and quantifies the remaining functional/operational availability at the subsystem, vehicle, and mission levels.

4 Key Tools Related to ISHM Design

4.1 Functional failure analysis tool

Fig. 11 shows the concept of functional failure analysis. The first step in HMM capability design is to clearly define how the vehicle and its subsystems function and how they can potentially fail. A clear understanding and representation of the functions to be accomplished provides the framework for recording how a system can fail, the manifestations of the failure, its consequences, and its impact on the vehicle as a whole. The FFA tool plays an important role in the development of the HMM System, CBM candidate selection, refining system performance matrices, and the trade-off study in the design of HMM architecture.

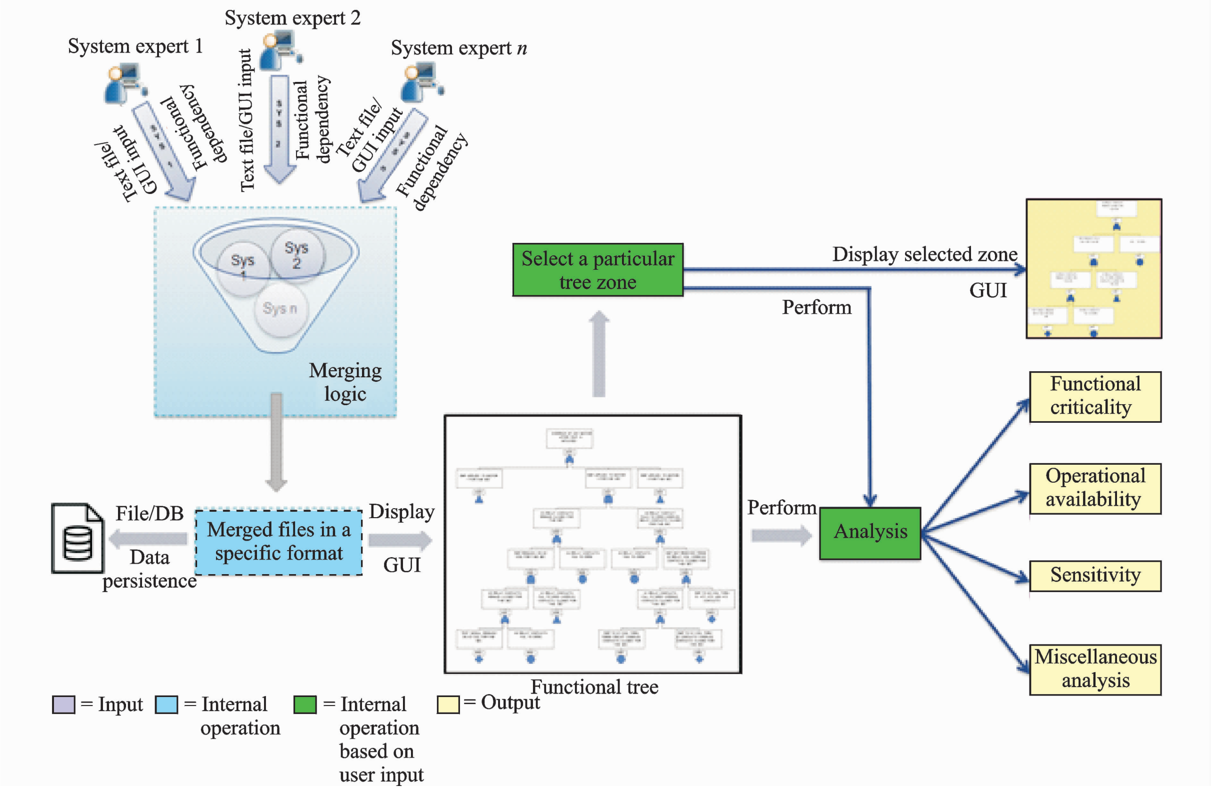
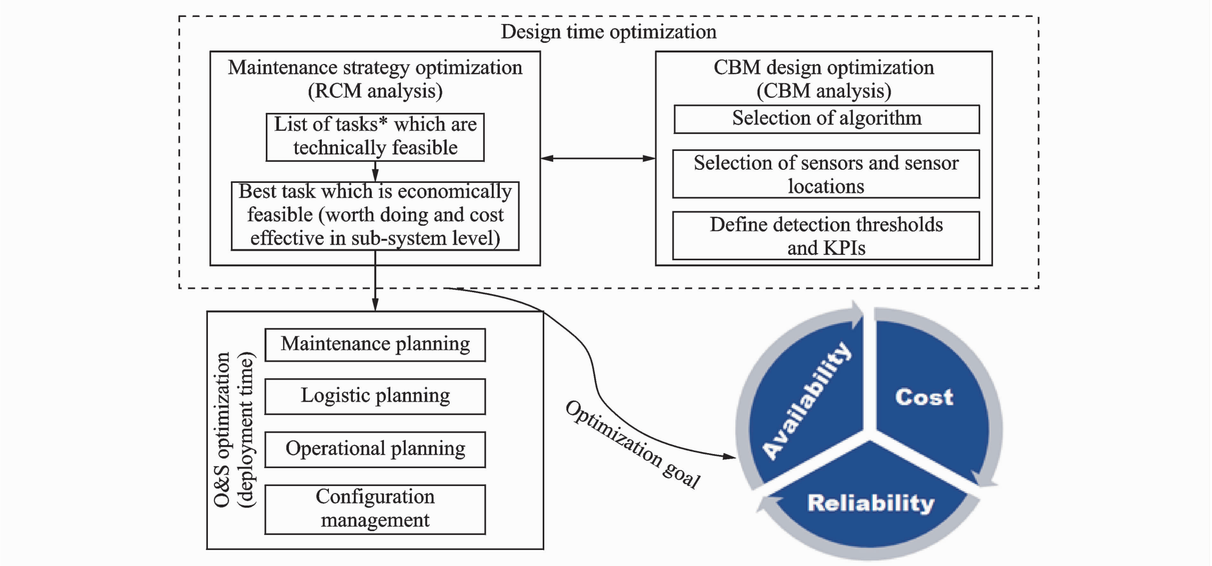


Fig. 11 Concept of functional failure analysis

4.2 Maintenance strategy tool

Maintenance strategy[25] aims to map all fault modes at individual and LRU levels to different maintenance categories. RCM analysis is the foundation to establish a framework for candidate selection. The decision logic is based on existing guidelines: SAE JA1011, SAE JA1012, NAVAIR 00-25-403, and ATA MSG-3 with suitable modification. After the fault consequence check, the maintenance options for each fault type of an LRU are shortlisted based on technical feasibility only. Cost-effectiveness and risk are computed for each selected option of the fault type. The best maintenance option or combinations of options are selected for the LRU by solving optimization problem in a manner which maximizes availability and the ROI of the selected option, and minimizes risk at the LRU level, as shown in Fig. 12.



*Tasks mean maintenance types (PMs, CBM and RTF) or other actions like re-design, etc

Fig. 12 Different categories of optimization for ISHM

5 Role of HMM Framework in Certification

Fig. 13 depicts the V&V road map of HMM with an increasing technology readiness level. On the basis of an earlier discussion, the V&V process towards the airworthiness certification of HMM will be spread over the following phases:

- Concept refinement & technology development
- Development
- Controlled introduction to service
- Instruction for continuous airworthiness

From the V&V roadmap[4], it is very much evident that different facilities are needed for the V&V, certification & qualification of ISHM technologies. The ISHM simulation framework plays multiple roles as a single platform.

6 Lessons Learned

Key findings from the development of the Airbus DS HMM program and Simulation Framework as a validation platform are summarized here.

(1) Enhanced diagnostics (to compute the health index of degrading subsystem components), enhanced fault isolation (to isolate incipient faults), health aggregation at higher levels (subsystem, system, operation) and prognostics (to compute the remaining useful life) are key enablers for PHM functions.

(2) During the early stages of the HMM life cycle, in the absence of in-service/test flight data, the physics-based model plays an important role. The physics-based model undergoes continuous maturity with the help of in-service data.

(3) Once put into service, the PHM functions have to be continually validated to detect potential discrepancies between the initial design/implementation and real-life behavior[17].

(4) The initial PHM design/model (technical choices: algorithms, learning database, etc.) is subjected to potential changes in operational (change in the operational cycles, loading of the system) and environmental (e. g. heat, humidi-

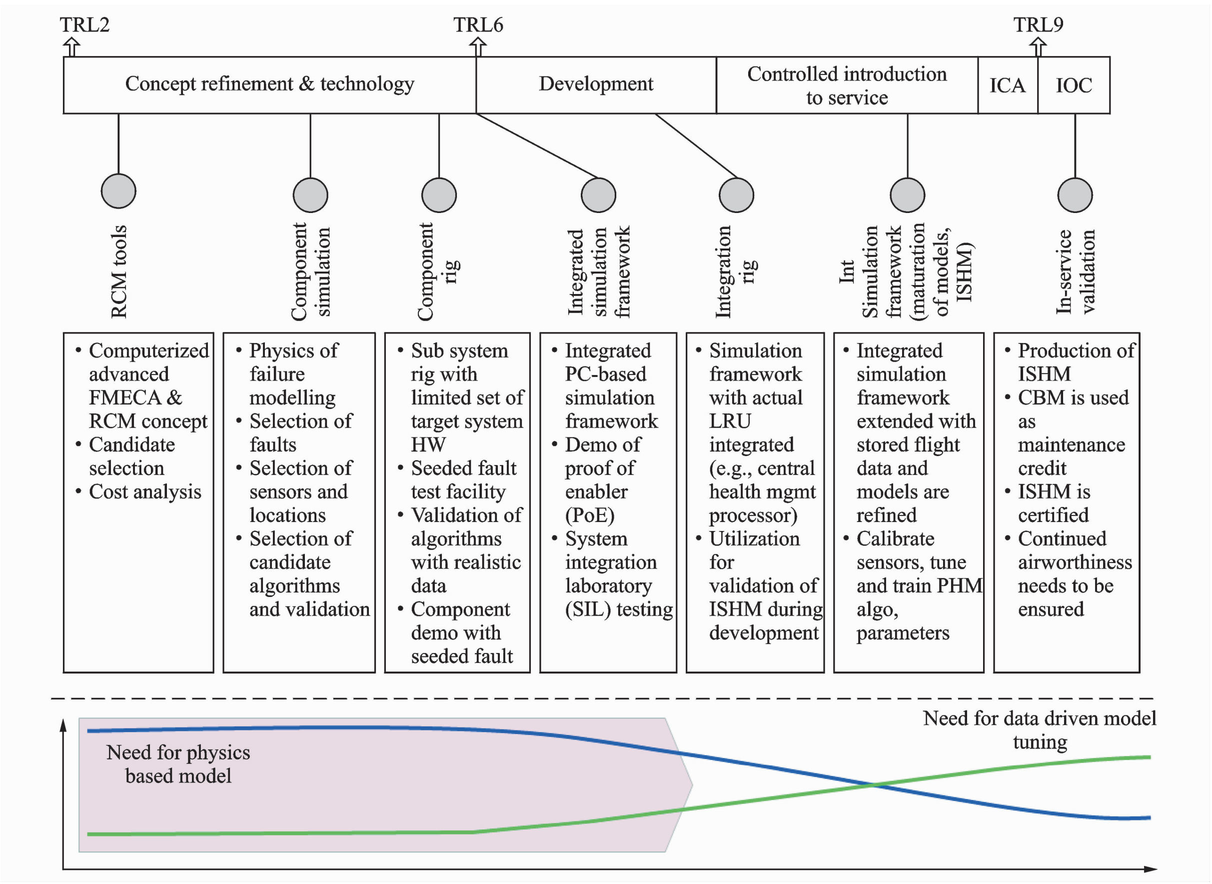


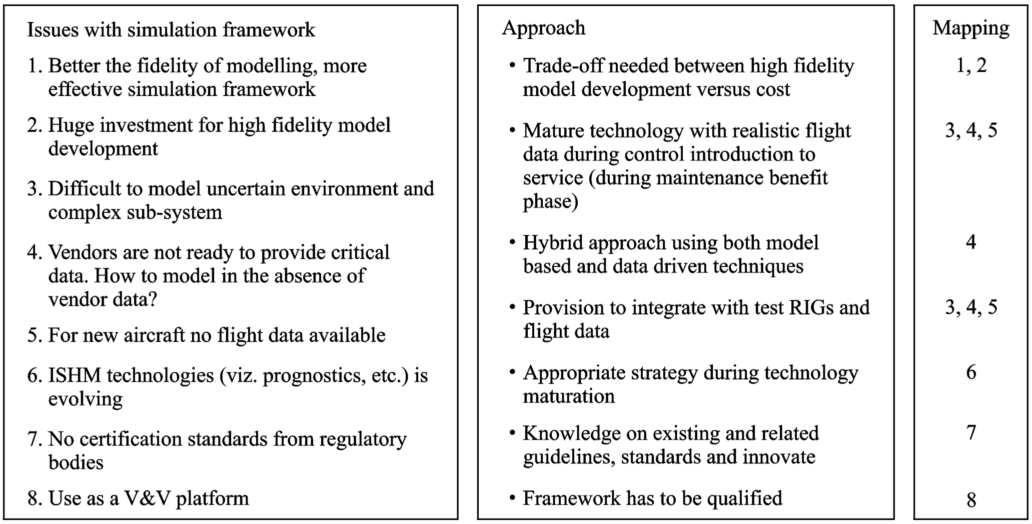
Fig. 13 V&V Roadmap of ISHM and role of simulation framework

ty) conditions[17].

(5) The potential evolution of the maintenance operations may have an impact on the validity of PHM functions[17].

(6) The integration of structural health monitoring is still at a low TRL compared to that of the system because of the complexity of modeling the characteristics of the SHM sensing system, the damage characteristics of composite materials and the required processing, diagnostic and prognostic capabilities.

(7) A few of the important insights related to Simulation and ISHM certification are given in Fig. 14.



Issues with simulation framework

1. Better the fidelity of modelling, more effective simulation framework
2. Huge investment for high fidelity model development
3. Difficult to model uncertain environment and complex sub-system
4. Vendors are not ready to provide critical data. How to model in the absence of vendor data?
5. For new aircraft no flight data available
6. ISHM technologies (viz. prognostics, etc.) is evolving
7. No certification standards from regulatory bodies
8. Use as a V&V platform

Approach	Mapping
• Trade-off needed between high fidelity model development versus cost	1, 2
• Mature technology with realistic flight data during control introduction to service (during maintenance benefit phase)	3, 4, 5
• Hybrid approach using both model based and data driven techniques	4
• Provision to integrate with test RIGs and flight data	3, 4, 5
• Appropriate strategy during technology maturation	6
• Knowledge on existing and related guidelines, standards and innovate	7
• Framework has to be qualified	8

Fig. 14 ISHM simulation framework challenges and approaches

7 Conclusions

In general, it is evident that the nature of challenges in V&V and certification of HMM is different compared to standard stand-alone system. One of the major challenges in the certification of ISHM systems is the unavailability of comprehensive regulatory standards for ISHM. V&V also poses challenges mainly due to the fact that HMM has to handle a large number of off-nominal scenarios, has to ensure performance, safety, and reliability across the entire performance envelope, and has to reliably avoid ″false alarms″. Moreover, V&V has to deal with multidisciplinary aspects of ISHM. The most prominent aspect is the gathering of direct evidence for fault effects related to the V&V of enhanced diagnostics and prognostics. To handle these issues, the key aspects of ISHM V&V mentioned above are summarized here:

(1) V&V maturity starts from the concept refinement and technology development phase.

(2) If a specific subsystem/function of ISHM is classified as Hazardous / Severe-major, then direct evidence must be gathered. (FAA′s advisory circular AC 29-2C MG-15).

(3) If a specific subsystem/function of ISHM is classified as Major or lower, then indirect evidence is sufficient. (FAA′s advisory circular AC 29-2C MG-15).

(4) During ″Controlled Introduction to Service″, CBM maintenance credit is considered as maintenance benefit, i. e. CBM output is compared with maintenance instructions suggested by the conventional RCM process.

(5) After the maturation of the algorithm and certification, CBM obtains maintenance credit.

(6) An appropriate sequence of the V&V process of ISHM function layers is to be considered.

(7) It must be noted that the V&V of ISHM functionalities in the simulation framework does not completely address defects created by the designer. It is evident from Fig. 14 (V&V roadmap with increasing TRL) that subsequent V&V phases (i. e. V&V in the integration RIG, integrated HILS, V&V during controlled introduction to the service and ICA) are suggested in order to achieve maintenance credit.

(8) Since the ISHM simulation framework plays a vital role in the V&V process, the simulation framework has to be qualified[26].

The survey of works backing ISHM system certification, suggested customization, and experiences support SHM development as well. However, a significant challenge is the certification of SHM, which is the probability of detection requirements and means of compliance. Modeling of the structural component behavior, Lamb wave simulation and damage progression model are some of the key challenging areas.

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