A Certifiable Approach towards Integrated Solution for Aircraft Readiness Management

Partha Pratim Adhikari[1], Dr. Dhaval Makhecha[2], and Dipl.-Ing. Matthias Buderath [3]

[1,2]*Airbus Defence & Space, Bangalore, 560 016, India*
partha.adhikari@cassidian.com
dhaval.makhecha@cassidian.com

[3]*Airbus Defence & Space, Manching, 85104, Germany*
matthias.buderath@cassidian.com

ABSTRACT

Aircraft readiness management plays pivotal role for aviation authorities to enhance mission availability, reliability and reduce maintenance cost. This has been the focus area of the industry for many years now. This paper focuses on developing an approach for maximizing the aircraft readiness based on the Aircraft Health Assessment and a novel approach for Maintenance Planning. An integrated solution using results from Prognostic Health Management (PHM) functions has been proposed. The concept is based on the condition based mission planning, operational risk assessment, maintenance planning and supply chain management. Also an insight is provided into the systematic approach to derive maintenance strategy leading towards certification. Although, the solution can be used for both commercial and military aviation, the focus in this paper is on implementation for military platforms. Details on implementation are discussed in brief and the results of this implementation on some hypothetical scenarios are presented. The results outline the effectiveness of the approaches in improving the aircraft readiness.

1. INTRODUCTION

Aircraft Readiness is a related measure of the availability and is a metric predominantly used for military aviation. Readiness includes operational downtime, free time and storage time. Aircraft Readiness covers a broader perspective than just availability of an aircraft, a complete availability of the operational systems with the supporting staff, resources and infrastructure necessary for the operations is a measure of the readiness. Overall readiness of an air vehicle is a joint product of capability assessment of planned missions based on present and future health of the vehicle and efficient maintenance planning considering logistic delay and other constraints related to supply chain. The Aircraft Readiness Management process can be subdivided into Maintenance Planning & Management, Resource Planning & management & Supply Chain.

The effective management of operations of aircraft across fleet, squadron and enterprise levels for an organization highly depends upon the availability of a matured Operation Support System. The Operation Support System, being core off-board ISHM module, generally provides ground support services through Mission Planning and Readiness Management of air vehicle.

Most of the air forces or airlines use disjoint tools for the sub-processes. This may lead to non-feasible mission plans, more maintenance time and introduces delays and operational overheads in identifying the suitable aircraft with the planned configuration. ISHM enables to provide integrated solution of these functions for efficient and cost effective readiness management.

Intelligent maintenance planner has an optimization model for appropriate clustering of maintenance tasks into maintenance events. This model, which synchronizes with resource planning and mission planning, enhances mission availability, fleet maintainability and operational cost saving. Intelligent maintenance planner augments the conventional Reliability Centered Maintenance (RCM) process (Preventive, Reactive, etc) with Condition Based Maintenance (CBM) to generate an optimized maintenance plan.

The novelty of this work includes method to create maintenance database from certifiable RCM decision logic, handling strategic importance of planned missions based on mission types, providing flexibility in selection of optimization modes (availability alone and availability along with cost). This also includes a simplified approach for accommodating resource constraints in order to provide an integrated solution. Simulation results of the solution integrated in ISHM Simulation Framework of Airbus Defence & Space illustrate the convincing performance of the algorithm and help in taking decision on functional architecture of off-board ISHM (Mathias Buderath, Adhikari P. P., 2012).

2. CONCEPT OF INTEGRATED SOLUTION OF READINESS MANAGEMENT

Planning for aircraft readiness generally is done in two phases, namely Long-term, Short-term. However, some operator prefers to implement also “Medium Term” (Muchiri Anthony K., 2002). In order to synchronize aircraft utilization and aircraft maintenance, a close relationship is maintained between air force head quarter and squadron for military operation; the Commercial Planning Department and Maintenance Planning & Support Departments for civil aviation. Long term planning, input for which is driven by Commercial Planning Department (for civil) or Air force Headquarter (for military), consists of the following functions:

- Flying Hours Programs (FHP)
- Aircraft Utilization Scenario
- Maintenance Scenario
- Resource Requirement Scenario

Flying Hours Programs (FHP) by Air force Headquarter determines the number of total yearly flying hours in order to ensure combat readiness and training requirement of Air Force (Philip Y Cho, 2011). Each squadron specifies daily sortie requirements and assigns to each aircraft for complete year and this results to generate Aircraft Utilization Scenario. Preventive maintenance requirements with different frequencies are identified to predict maintenance scenario for each aircraft based on predicted usage for complete year. Then resource requirement for preventive maintenance scenario are identified date-wise for complete year.

Readiness management is a short term planning (1-3 months) of maintenance events and resources required along with associated managements based on health assessment which analyzes results from diagnostics, prognostics, inspections and assesses operational capability of aircraft for planned mission. Mission Planner receives information from Readiness management on readily available aircrafts for operational planning.

Reliability Centered Maintenance (RCM) provides maintenance strategy mapping maintenance type and redesign decision with each fault and PM task details (recommended schedule, Max FH, cycles, calendar date, etc) to Readiness Management. RCM is a well-structured, logical decision process used to identify the policies needed to manage failure modes that could cause the functional failure of any physical item in a given operating scenario.

3. FRAMEWORK TO DERIVE MAINTENANCE STRATEGY

There are at least six key factors required for maintenance to achieve its purpose of optimizing operating performance. These are to reduce operating risk, avoid aircraft failures, provide reliable equipment, achieve least operating costs, eliminate defects in operational aircraft and maximize availability. These purposes are determined by three KPIs: enhancement in mission availability, reliability and

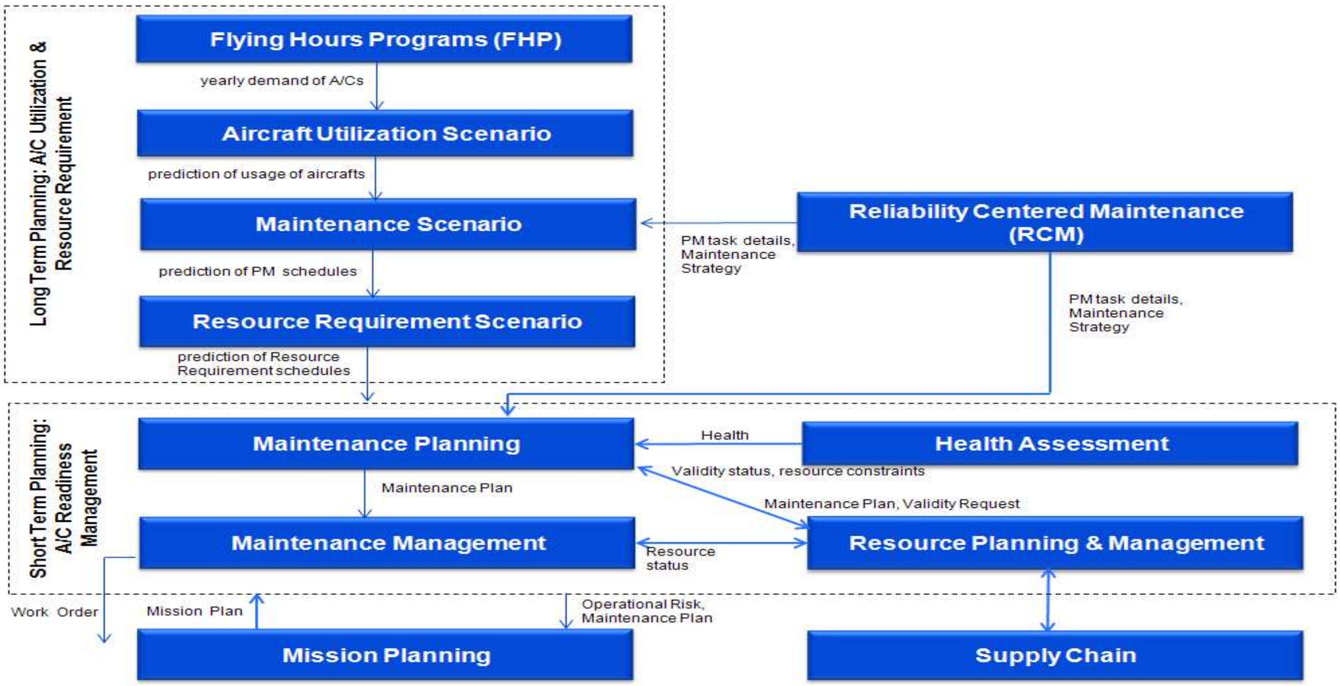

Figure 1. Functional Block Diagram of Aircraft Readiness Management

reduction of maintenance cost. Suitable maintenance strategies are selected during design stage to provide the required values of the KPIs. However, maintenance strategy may get changed based on periodic evaluation of maintenance effectiveness and risk assessment during operation phase.

Maintenance Strategy aims to map all fault modes at individual and LRU levels to different maintenance categories: PM (S-Servicing, L-Lubrication, OC-Scheduled On-condition, HT-Hard Time and FF-Failure Finding Inspection), CBM, Run-to-Fail and other actions consisting of redesign, change in operation or maintenance procedure or restriction in operation. Optimized maintenance strategy is also derived at component/LRU level.

Maintenance credits are acquired when an ISHM system can replace the existing industry standard maintenance for a given component or complete aircraft system and this enhances availability, maintainability and mission capabilities of aircraft. To reach this level, evolution of ISHM development has to pass through effective process for technology maturation, development, verification, validation, qualification and finally certification.

After determination of the potential functionality and benefits of ISHM, technology maturation efforts are initiated. The maturation efforts are often performed through technology development guided by appropriate roadmaps. Efforts are allocated to RCM analysis, design and analysis of algorithm for diagnostics, prognostics, sensor selection and other enablers related to off-board ISHM. This also includes enhancing the performance of ISHM in terms of increased accuracy, reduced weight, improved reliability, advanced communication and efficient data transfer. Technology gaps and risks are identified and efforts are allocated to fill the gaps and to mitigate the risks. During the maturation phase, the potential benefits and credits of ISHM are re-assessed and validation evidence is gathered through component rigs, integrated simulation framework, etc. The Figure 3 details the activities during concept refinement and technology development phases.

RCM analysis is the foundation to establish a framework for candidate selection. The Figure 2 depicts the logic for deciding maintenance strategy for a LRU. The proposed decision logic is based on existing guidelines: SAE JA1011, SAE JA1012, NAVAIR 00-25-403 and ATA MSG-3 with suitable modification. After fault consequence check, maintenance options for each fault type of a LRU are short listed based on technical feasibility only. Cost effectiveness and risk are computed for each selected option of the fault type. Best maintenance option or combinations of options are selected for LRU by solving optimization problem which maximizes availability, ROI of selected option and minimizes risk at the LRU level.

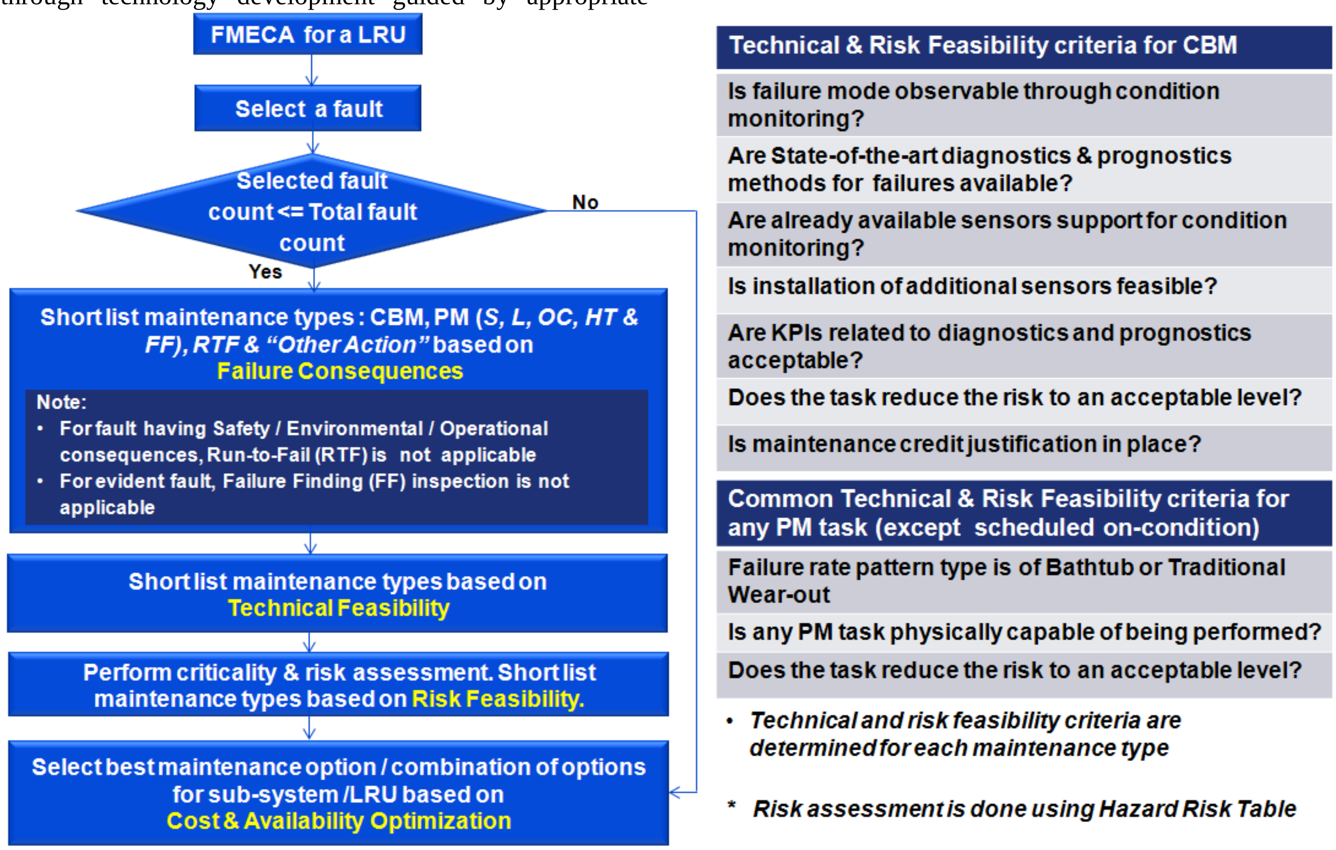

Figure 2. RCM Decision Logic for Maintenance Strategy

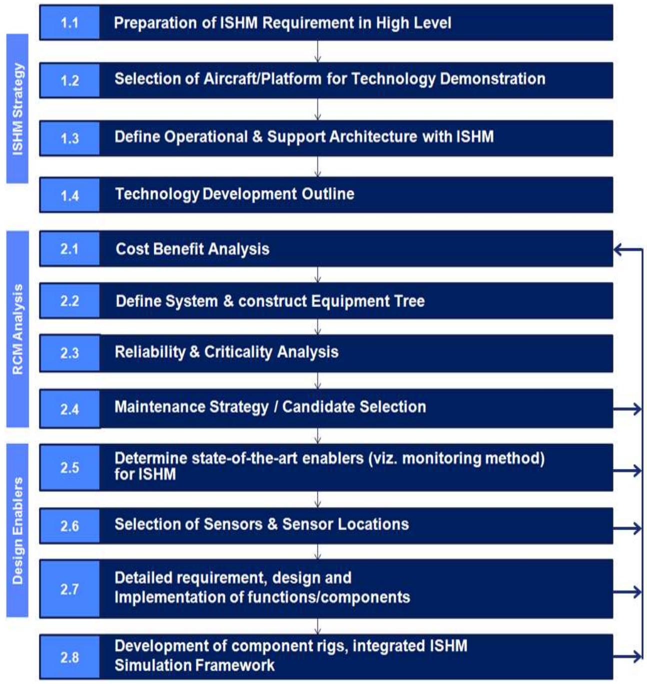

Figure 3. Guideline for technology development & maturation

4. MAINTENANCE PLANNING MECHANIZATION

Operations in commercial airline are more cost sensitive and hence it is no surprise that major focus of the work on maintenance planner has been on airline scheduling. Significant differences in the military and civil flight operations make most of the existing work not directly applicable to military aviation, but can be a good starting point. The basic difference in civil and military aviation is that the civil aviation is highly focused on route selection and assignments with profitability and cost savings being the major goal. On the other hand, the goal for military aviation is a high level of combat readiness with cost being relatively less significant factor. Also, since the fighter squadrons are usually fixed at a given location, readiness does not involve any decisions regarding routes. Hence the objective here is to define a maintenance schedule that will minimize the downtime thereby ensuring most effective utilization of the system with applicable constraints at the lowest possible costs. In other words enhancing the availability leading to combat readiness is achieved through advanced maintenance planning and management.

Maintenance-scheduling is not limited to aviation industry and the benefits are evident in various industries and substantial effort has been put into this over the last few years by various researchers, prominent among them are : power plants (Canto, 2008; Doyle, 2004; Damien et al., 2007); aircrafts and -engines (Almgren et al., 2008; Sarac et al., 2006); production planning (Panagiotidou and Tagaras, 2007). Almgren et al. (2008) presents mathematical models for finding optimal opportunistic maintenance schedules for systems, in which components are assigned maximum replacement intervals. The work is extended for complete aircraft having heterogeneous maintenance types (Run-to-fail, Preventive, Condition Based Maintenance) along with the unique features as mentioned in the introduction.

The following figure summarizes key steps for maintenance planning.

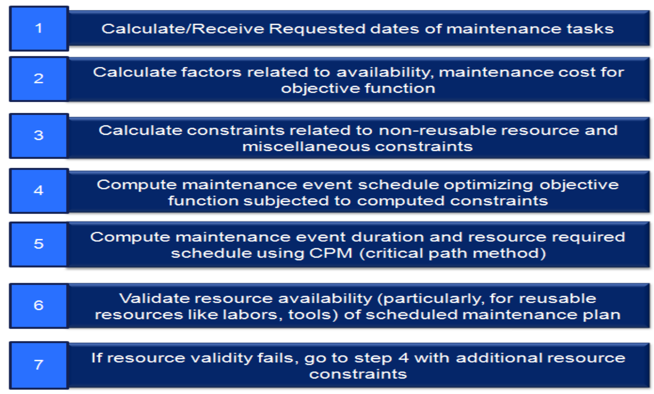

Figure 4. Key Steps for Maintenance Planning

4.1. Mathematical models for optimization

The proposed Maintenance Planner supports the following two modes of optimizations

- Availability Optimization
- Availability & Cost Optimization

Let us consider there are ***'N'*** maintenance tasks and a finite maintenance time horizon (in terms of day/slot) is discretised into ***'T'*** time steps. The optimization problem for all three modes can be represented as following.

$$\textbf{Minimize (X,Z):} \quad \sum_{t=1}^{T}\left(\sum_{i=1}^{i=N} C_{it}X_{it} + D_t Z_t\right) \qquad (1)$$

Subjected to: The constraints related to due dates of maintenance, associated thresholds, minimum gap between two consecutive maintenances, exclusivity of tasks and resource availability, etc are mentioned bellow.

Where,

C_{it}	Weight factor of each design variable in terms of maintenance cost or over maintenance time/effort related to maintenance task ***'i'*** at day/slot ***'t'***
D_t	Weight factor of each design variable in terms of unavailability and or maintenance site cost related to possible maintenance event starting at day/slot ***'t'***
X_{it}	Sets to ***'1'*** if maintenance task ***'i'*** is requested at day/slot ***'t'***, otherwise it sets to ***'0'***
Z_t	Sets to ***'1'*** if the resultant maintenance event for a/c occurs starts at day/slot ***'t'***, otherwise it sets to ***'0'***

The following table defines objective parameters (**'C_{it}'** & **'D_t'**) in three different modes.

Table 1. Definition of Weight factors

Optimization Mode	C_{it}	D_t
Availability Optimization	w1*(Over maintenance Time) : for each task (***i***) & each day/slot (***t***) within maintenance horizon	w2*(Mission Unavailability) : for probable maintenance event starting at day/slot (***t***) within maintenance horizon
Availability & Cost Optimization	w1*(Individual Maintenance Cost) + w2*(Over maintenance Cost) : for each task (***i***) & each day/slot (***t***) within maintenance horizon	w3*(Cost of Site) + w4*(Mission Unavailability) : for probable maintenance event starting at day/slot (t) within maintenance horizon

Constraints:

If there is no resource constraint, each component is replaced / repaired on or before due date and maintenance schedule falls within opportunistic maintenance threshold and maintenance threshold.

$$\sum_{t=t0}^{tf} X_{it} \geq 1, \quad i \in \{1, 2, \ldots N\} \tag{2}$$

Where, $t0 = \left(t^i_{md} - t^i_{mth} - t^i_{omth}\right)$, $tf = \left(t^i_{md} - t^i_{mth}\right)$ and variables are defined here.

t^i_{md}	Time when maintenance is due for task 'i'; This is calculated based on current and maximum FH, cycles and calendar date for preventive maintenance candidate. This is calculated from RUL from CBM candidate.
t^i_{omth}	Opportunistic maintenance threshold for task 'i'; Opportunistic maintenance threshold is maximum allowable window of maintenance schedule decision.
t^i_{mth}	Maintenance threshold for asset 'i'; Maintenance threshold is threshold time before expiry of RUL; before which maintenance has to be scheduled. This is set to zero for run-to-fail maintenance candidate.

For reactive maintenance of critical item, opportunistic maintenance threshold and maintenance threshold are zeros.

For reactive maintenance of non-critical item, opportunistic maintenance threshold = - Threshold, i.e. Next maintenance event will include this task. For only CBM candidate, maintenance threshold is non zero.

For preventive maintenance (Calendar based), gap between two maintenance dates scheduled should be such that number of days should be less than maximum numbers of days specified ('***Ti***') for the item.

$$\sum_{t=l+1}^{l+Ti} X_{it} \geq 1, \qquad l = 0, \ldots, \ T - Ti \tag{3}$$

If a maintenance event is scheduled, at least one maintenance task will be accomplished.

$$X_{it} < Z_t, \quad i \in \{1, 2, \ldots N\} \& \ t \in \{1, 2, \ldots T\} \tag{4}$$

For exclusives maintenance tasks, two sets can not be included in same maintenance event.

$$\sum_{t \in d} (X_{At} + X_{Bt}) < 1 \tag{5}$$

Where,

$$d_q = \left[\left(t^{i=A}_{mdA} - t^{i=A}_{omth}\right) : t^{i=A}_{mdA}\right] \cap \left[\left(t^{i=B}_{mdB} - t^{i=B}_{omth}\right) : t^{i=B}_{mdB}\right]$$

'A' and **'B'** are selected from two exclusive sets of maintenance tasks.

$$d = (d_1 \cup d_2 \cup \ldots \cup \ d_q)$$

Where, **'*d*'** represents the set of days where maintenance tasks **'A'** & **'B'** may get scheduled together in same maintenance event, **'*q*'** is the maximum number of combinations of maintenance instances of **'A'** and **'B'** during complete maintenance horizon.

A/C has to be mandatorily available for selected days. Cost of maintenance event is set to very high on these days (**$d_{1,2,..n}$**).

$$D_{t \in (d1,2,..n)} \cong 10^{+10} \tag{6}$$

Special Constraints related to resource unavailability:

If there is resource constraint for a critical item, due date (**'t_{mdr}'**) of maintenance is postponed to earliest date when resource is available and opportunistic maintenance threshold and maintenance threshold are set to zeros. A/C will be down until maintenance of the critical items.

$$X_{it_{mdr}} = 1, \quad i \in \{1, 2, \ldots Nr\} \tag{7}$$

If there is resource constraint for a non-critical item, due date of maintenance can be shifted to the earliest date when resource is available and opportunistic maintenance threshold is of negative value, i.e. next maintenance event shall include this task.

$$\sum_{t=t0}^{tf} X_{it} \geq 1, \qquad i \in \{1, 2, \ldots\ Nncr\} \tag{8}$$

Where, $t0 = \left(t^{i}_{md} - t^{i}_{mth} - t^{i}_{omth}\right)$, $tf = \left(t^{i}_{md} - t^{i}_{mth}\right)$ and ***'Nncr'*** is number of non-critical tasks with resource constraint.

No maintenance event can be scheduled if common resources like infrastructure are not available in a set of days ($d_{1,2,..n}$).

$$Z_{t\in(d_{1,2,..n})} = 0 \tag{9}$$

'X$_{it}$' & ***'Z$_{t}$'*** are binary variables. Length of maintenance horizon is ***'T'*** and ***'N'*** is the maximum number of maintenance tasks to be scheduled within this horizon.

$$X_{it}, Z_{t} \in \{0,1\},$$
$$i \in \{1, 2, \ldots\ N\} \ \& \ t \in \{1, 2, \ldots\ T\} \tag{10}$$

The optimization problem is solved by Binary Integer programming**.**

Instead of enhancing more number of constraints due to resources, the solution is simplified by recalculating due date of maintenance requests and opportunistic maintenance threshold. Towards this end, Maintenance planner projects allocation of resources based on maintenance requests, task priority, predicted usage considering missions planned, available resources as updated by resource planner. Figure 5 depicts the interactions between maintenance planner and resource planner along with sequence numbers.

4.2. Availability model

Unavailability of mission due to A/C down for maintenance event, which starts at particular day/slot, depends on the following factors:

- Probable coincidence of maintenance schedule with mission schedule
- Type of mission planned and this is driven by strategic importance factor
- Duration of possible maintenance event consisting of maximum number of maintenance tasks

The aircraft down time for probable maintenance event starting at day / slot ***'d'*** considering importance factor of missions affected is:

$$Ua(d) = \sum_{i=1}^{Mt}\sum_{j=1}^{Dd} Fm(i,j) * Cm((i,j) * Dm(i,j) \tag{11}$$

Where,

Fm(i,j)	Mission of mission type ***'i'*** is scheduled or not scheduled at day/slot ***'j'***
Cm(i,j)	Importance factor for mission type ***'i'*** scheduled at day/slot ***'j'***
Dm(i,j)	Duration of mission type ***'i'*** scheduled at day/slot ***'j'***
Mt	Maximum number of mission types
Dd	Maximum number of days/slots required by maintenance event.

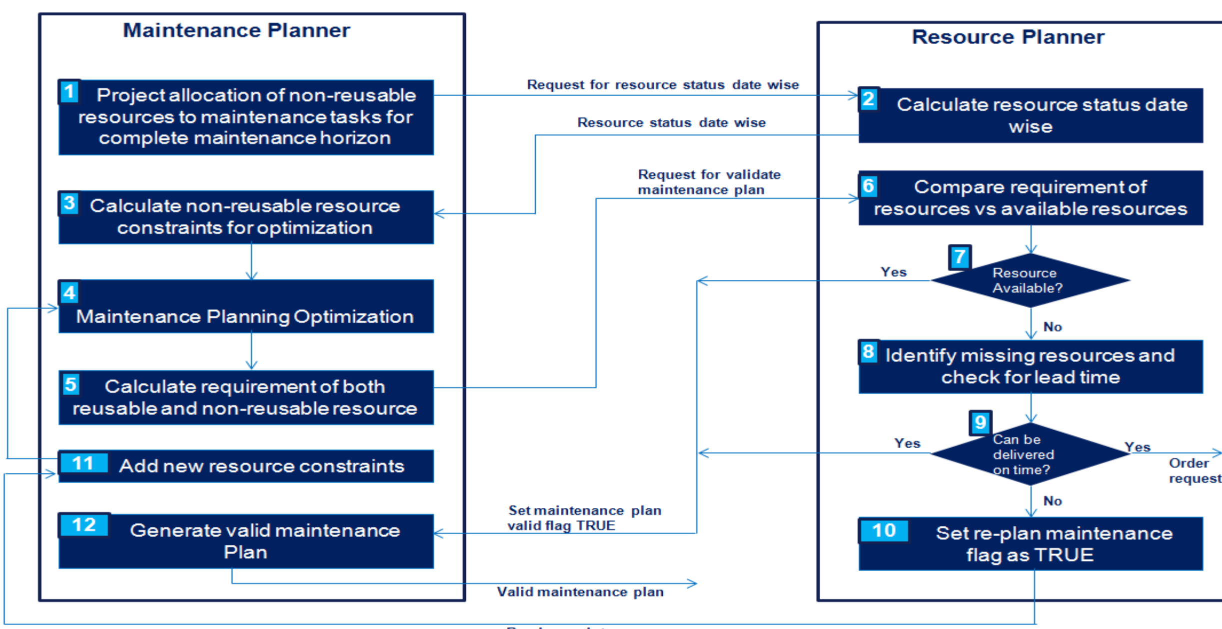

Figure 5. Interaction between Maintenance Planner & Resource Planner

Importance factors for different mission types are configurable. The following table shows an example of gradation of importance of different mission types.

Table 2: Example of Mission Importance Grade

Mission Type (code)	**Importance Grade [Level]**
Fighter Bomber	Very High [5]
Suppression of Enemy Air Defence	High [4]
Maritime Air Operations	Medium [3]
Reconnaissance mission	Low [2]
Surveillance Mission	Very Low [1]
No Mission	No impact [0]

In case of availability & cost optimization mode which may be applicable for civil operation, the aircraft downtime can be converted to cost incurred due to outage of aircraft operation. This contributes common maintenance cost related to maintenance event.

4.3. Model for Aircraft over maintenance

Due to clustering of maintenance tasks for batch maintenance of aircraft, some equipment may undergo maintenance ahead of their scheduled maintenance time. This is referred to as 'over maintenance'. Over maintenance incurs additional cost to operation and support activities.

Over maintenance factor for maintenance task ***'i'*** at day ***'(d-j)'*** can be defined as:

$$Om(i,d-j) = Fo(i) * Hop * j \quad for\ j = 0\ to\ t^{i}_{omth} \qquad (12)$$

Where,

d	Maintenance due date for task ***'i'***
Fo(i)	Over maintenance effort per hour for task ***'i'***
Hop	Average operating hour per day
t^{i}_{omth}	Opportunistic maintenance threshold for maintenance task ***'i'***

In case of availability & cost optimization mode, this over maintenance factor can be converted to over maintenance cost after multiplying with appropriate cost factor and this contribute cost related to each maintenance task.

4.4. Cost Model

In Availability and Cost Optimization mode, objective function for scheduling maintenance events represents total cost to execute maintenance events during complete maintenance horizon and this cost aspects are attributed due to the following factors

- Cost related to each maintenance task
  - The direct maintenance cost
  - Over maintenance cost attributed due to shifting of maintenance task from due date
- Common maintenance cost related to a maintenance event
  - Cost of site/infrastructure
  - Representative cost of unavailability of mission due to A/C down for maintenance

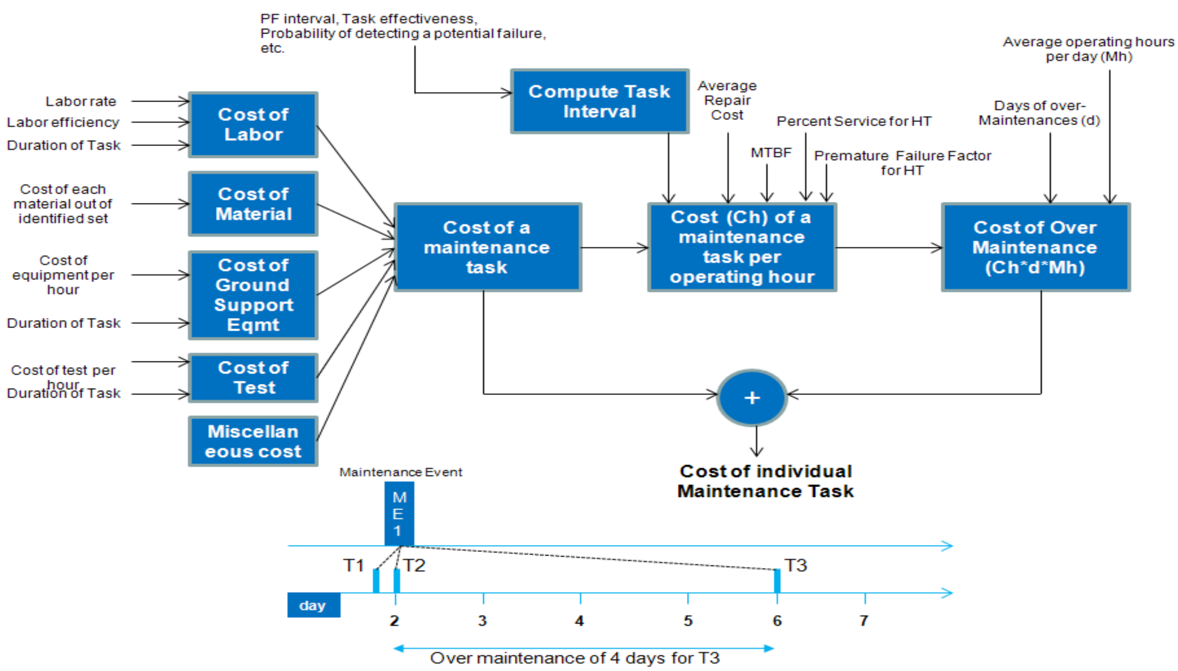

Figure 6. Cost of Individual Maintenance Task

Objective of maintenance optimisation is to reduce maintenance cost and to enhance availability. First type of cost is directly related with maintenance cost and second type of cost is mainly related with availability.

The direct maintenance cost related to each individual maintenance task has the following cost components:

- Material
- Labour
- Test
- Ground support equipment

Corresponding cost equations are given in detail in Table 3.1 of NAVAIR 00-25-403.

Common maintenance cost related to a maintenance event is attributed by the following factors

- Cost of site/infrastructure
- Representative cost of unavailability of mission due to A/C down for maintenance

Cost of site/infrastructure depends upon demand and availability. Even if there is no real cost related to site/infrastructure, representative cost figure based on site availability brings intelligence in optimization.

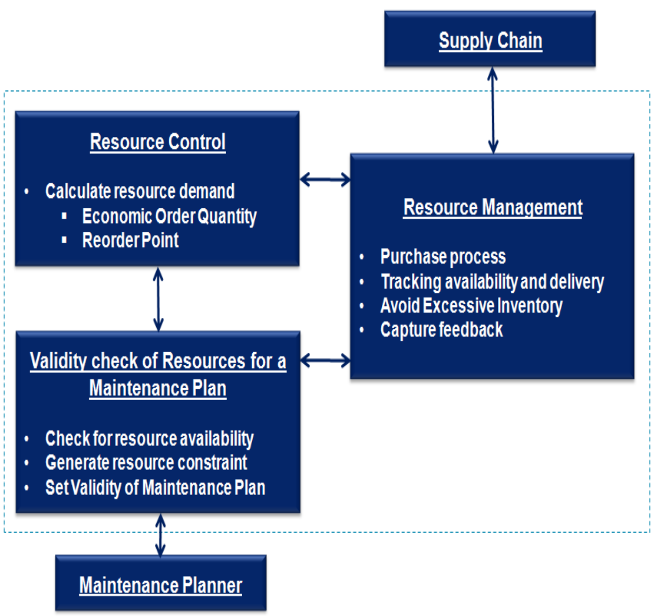

Figure 7. Resource Planner Block Diagram

5. RESOURCE PLANNING

Mission effectiveness is highly dependent on efficient maintenance which in turn is dependent upon reliable and prompt logistical support. Regardless of the cost it is important to have the item readily available to support the efforts of the mechanics in a timely manner.

Resource control function (Figure 7) calculates resource demand based on long term maintenance scenario, historical data. Validity check module generates resource constraints and validates maintenance plan based on request from maintenance planner. Resource Management function manages purchase process, tracks availability and delivery, avoiding excess inventory and captures feedback to refine continuously important thresholds like lead times, etc.

6. CONDITION BASED MISSION PLANNING

The condition based Mission Planner developed has an additional feature of providing warning to user for re-planning in addition to the conventional features like entry of mission plan through digital map, replay of mission with aircraft model in loop, creation of database for mission plan & flying program. Re-planning intelligence of Mission Planner is driven by performance evaluation (level 1&2), mission and segment capability computed by ORA and approved maintenance planned.

Initially the performance parameters of aircraft related to estimated trajectory as per mission plan are computed. If estimated performance exceeds the specified performance limits of aircraft, user is instructed in term of warning to re-schedule the mission plan. Mission Planner warns the user to reschedule the mission plan if approved maintenance plan conflicts with mission plan. Applicability of mission segments of a particular aircraft is checked with respect to operational capabilities of the aircraft for the segment, computed by ORA. It checks whether operational capability for that segment is less than mission critical threshold. If operational capability does not support the particular mission segment for an aircraft, it instructs in term of warning to re-plan the particular segment of the Mission.

7. RESULTS & DISCUSSION

For simplicity, it is assumed that electrical and hydraulic system represents complete aircraft and a representative use case is defined to validate maintenance strategy and planning algorithm. Failure Mode Effect and Criticality Analysis (FMECA) are carried out for selected components which are run through the candidate selection logic to define maintenance type for each fault.

Figure 8 represents different units of maintenance scheduling. A maintenance task is considered as lowest unit of maintenance to be scheduled. Task steps (TS) will be considered in the description of each maintenance task. Maintenance events are scheduled by clustering a number of maintenance tasks using optimization. Maintenance Plan for an A/C is scheduling of all maintenance event during complete A/C maintenance horizon. Final Maintenance Plan is derived after merging individual maintenance plan for a fleet of A/Cs.

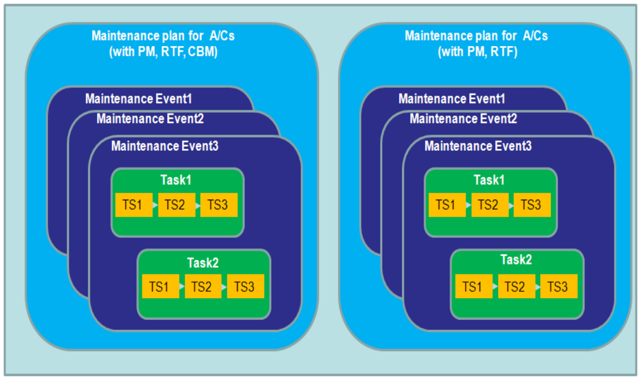

Figure 8. Definition of different unit of maintenance planning for a use case

A scenario is defined with maintenance tasks with asset ids within 100-116 (which are arbitrary). Database tables (~20) are populated with synthetic data related to faults, maintenance task details, resources required, cost details, etc aligning with the use case and mapping with OSA-CBM data structure. Figure 9 depicts the maintenance plan computed by the tool developed. Individual maintenance requests are represented by different red colored symbols whereas the blue line with blue symbols represents beginning of a maintenance event with respective tasks having maintenance event spread across the shaded zone. Maintenance plan is created in Maintenance benefit mode where only PM and RTF maintenance types are considered and the same is created in maintenance credit mode having all possible maintenance types including CBM. The generated maintenance plan for the defined hypothetical scenario leads to the following observations. Availability enhancement is 19% more in maintenance credit mode compared to maintenance benefit mode. This indicates the benefit of CBM compared to PM. Availability enhancement due to optimization is 64% in maintenance credit mode.

Selection of optimum value of opportunistic maintenance threshold is done based on fact that availability increases with increase of the threshold but cost saving initially increases but starts reducing after some value of the threshold due to over maintenance cost. With this consideration, user may decide opportunistic maintenance threshold as 8 days as per Figure 10 for this specific scenario.

Maintenance Planner ensures A/C to be more available for strategically more important mission. The priorities of missions are assumed as mentioned in the Table 2. A maintenance plan is already scheduled on a particular date, if a strategically more important mission is suddenly scheduled on the same date, maintenance planner will ensure to enhance probability to accomplish the mission and reschedule maintenance date. The Figure 9 (scheduling of maintenance event 3) depicts the same results.

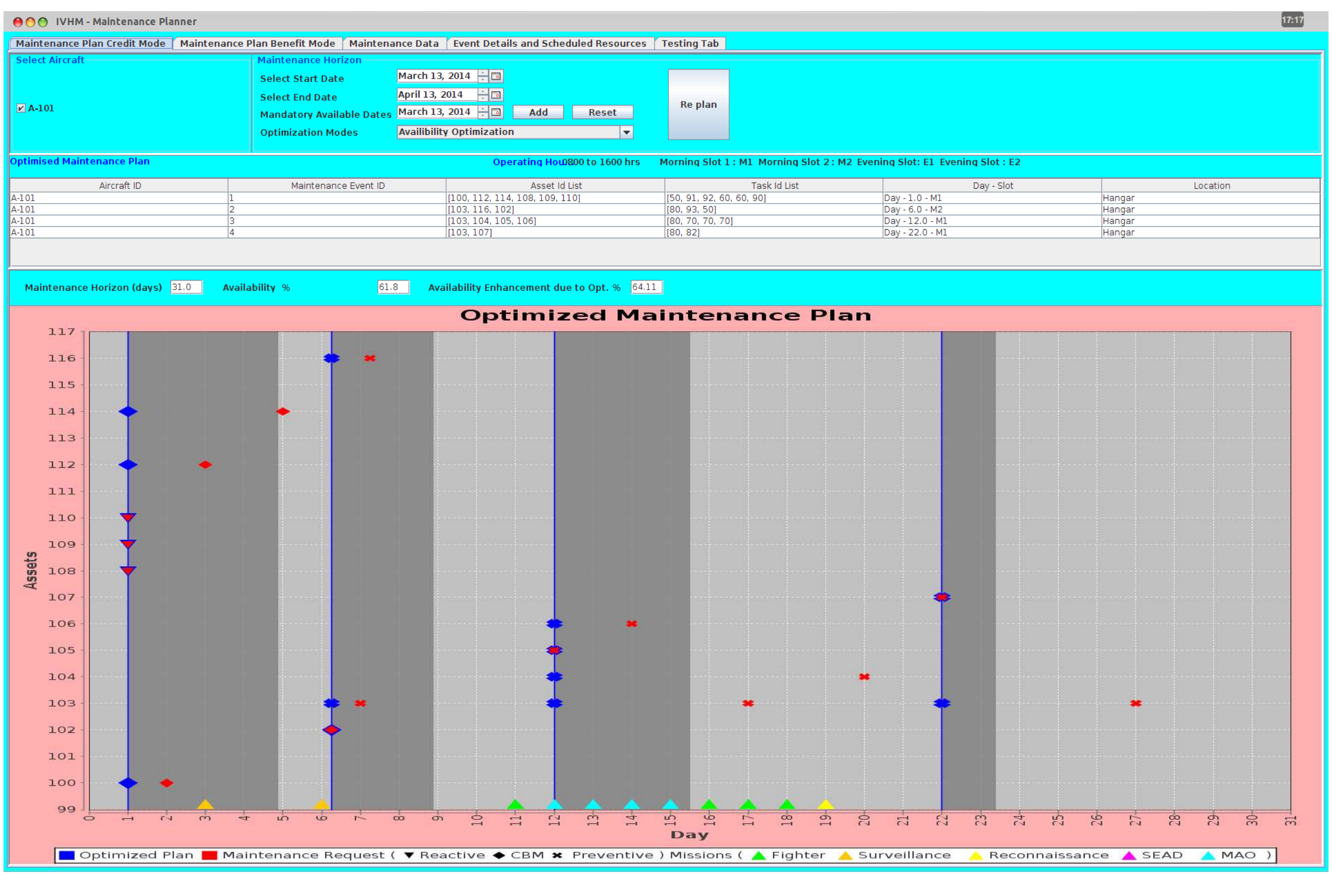

Figure 9. Maintenance Plan: First tab of Maintenance Planner

Maintenance Planer provides feature to input selected dates on which A/C availability is mandatory. Maintenance Planner will also ensure availability of the A/C on the selected dates and shift maintenance to adjacent dates date based on only availability or both availability & cost optimization as per selection of optimization mode.

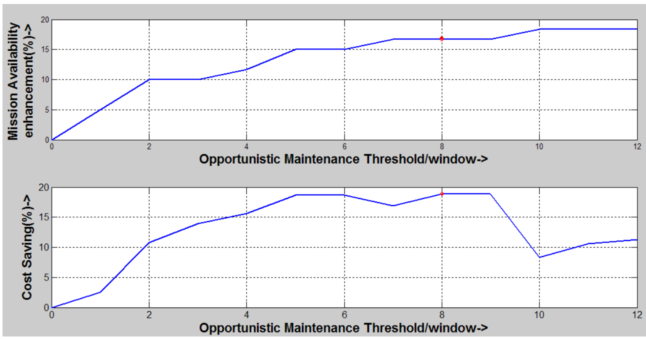

Figure 10. Selection optimum value of opportunistic maintenance threshold

Maintenance planner avoids scheduling the maintenance event on a particular day if logistic resources or required infrastructure is not available on the desired day. Shifting of maintenance date is based on criticality of item, priority, earliest date having appropriate amount of resource types available and optimum value of cost & availability. Relevant resource constraints are also tested and provide satisfactory results.

8. CONCLUSION

An integrated solution of aircraft readiness management based on ISHM has been presented. A logical approach has been proposed to provide framework for maintenance strategy based on certification guideline and optimization model for maintenance planning which efficiently handles important factors, resource constraints and flexible means of selecting optimization mode based on available data. The proposed approach reduces the complexity of the problem, but the solutions found may not always be the optimal solution. If optimization iterations can be done in single stage, that is, schedule of task steps in maintenance events is also part of main optimization model; the solution may be optimal. The results have been shown for one hypothetical scenario; more realistic data along with a Monte Carlo simulation would be more accurate. The present concept can be extended to finite time horizon optimization of maintenance and replacement models for multi-unit system having both deterministic and stochastic parts.

ACKNOWLEDGEMENT

The authors are grateful to ISHM team members (Mr Heiko Mikat, Mr Harsha Gururaja Rao, Mr Madhuraj PH, Mr Kandukuri Surya-Teja) for supporting in implementation, testing, stimulating discussions and helpful suggestions. We are also grateful to reviewers for many of the improvements to the document.

NOMENCLATURE

A/C	Aircraft
BIT	Built-In Test
CBM	Condition Based Maintenance
FF	Failure Finding (inspection)
FH	Flying Hour
FHP	Flying Hours Program
FMECA	Failure Mode, Effects and Criticality Analysis
HRT	Hazard Risk Table
HT	Hard Time (task)
ISHM	Integrated System Health Monitoring
IVHM	Integrated Vehicle Heath Monitoring
KPI	Key Performance Indicator
L	Lubrication
LRU	Line Replaceable Unit
OC	On-Condition (maintenance)
ORA	Operational Risk Assessment
OSA	Open System Architecture
PHM	Prognostic Health Management
PM	Preventive Maintenance
RCM	Reliability Centered Maintenance
ROI	Return on Investment
RUL	Remaining Useful Life
RTF	Run-to-Fail (maintenance)
S	Servicing
SHM	Structural Health Monitoring
TS	Task Step

REFERENCES

Almgren, T., Andréasson, N., Anevski, D., Patriksson, M., Strömberg, A.-B., & Svensson J. (2008). *Optimization of opportunistic replacement activities: A case study in the aircraft industry*. Preprint 2008:45, Dept. of Mathematical Sciences, Chalmers Univ. of Tech. and Univ. of Gothenburg, Göteborg Sweden.

Andréasson, N. (2004). *Optimization of opportunistic replacement activities in deterministic and stochastic multi-component systems*. Licentiate thesis, Dept. of Mathematics, Chalmers Univ. of Tech. and Univ. of Gothenburg, Göteborg, Sweden.

ATA MSG-3 (1993). *Operator/Manufacturer Scheduled Maintenance Development*. Maintenance Steering Group – 3, Task Force Air Transport Association of America.

Canto, S. P. (2008). Application of Benders' decomposition to power plant preventive maintenance scheduling. *European Journal of Operational Research*, Vol. 184, pp. 759–777.

Damien, P., Galenko, A., Popova, E., & Hanson, T. (2007). Bayesian semi parametric analysis for a single item maintenance optimization. *European Journal of Operational Research*, Vol.182, pp. 794–805.

Doyle, E. K. (2004). On the application of stochastic models in nuclear power plant maintenance. *European Journal of Operational Research*, Vol. 154, pp. 673–690.

Fatih Camci, G. Scott Valentine & Kelly Navarra (2006). Methodologies for Integration of PHM Systems with Maintenance Data. *IEEEAC* paper #1191, Version 1.

Matthias Buderath & Adhikari P. P. (2012). Simulation Framework and Certification Guidance for Condition Monitoring and Prognostic Health Management. *European Conference of Prognostics and Health Management Society 2012*.

Mike Sondalini. *How to Change RCM2 to Get Really Useful Maintenance Strategy*. Lifetime Reliability Solution.

Muchiri Anthony K. (2002). *Maintenance Planning optimisation for the Boeing 737 Next Generation*. DELFT Aerospace, Master Thesis.

NAVAIR 00–25–403 (2005). *Guidelines for the Naval Aviation Reliability Centred Maintenance Process*. Director of Commander, Naval Air System Command.

Philip Y Cho (2011). *Optimal Scheduling of Fighter Aircraft Maintenance*. Massachusetts Institute of Technology, June 2011.

Sarac, A., Batta, R., & Rump, C.M. (2006). A branch-and-price approach for operational aircraft maintenance routing. *European Journal of Operational Research*, Vol. 175, pp. 1850–1869.

SAE JA1011 (2009). *Evaluation Criteria for Reliability-Centred Maintenance (RCM) Processes*. issued in 1999, revised in 2009.

SAE JA1012 (2011). *A Guide to the Reliability-Centred Maintenance (RCM) Standard*. Issued in January 2002, revised in 2011.

BIOGRAPHIES

Partha Pratim Adhikari - has more than 15 years of experience in the field of Avionics and Aircraft Systems. Partha has Bachelor's degrees in Physics (H) and B. Tech in Opto-electronics from Calcutta University and a Master's degree in Computer Science from Bengal Engineering and Science University. In his tenure across various aerospace organizations, Partha made significant contributions in the fields of IVHM, Navigation systems, Avionics and Simulation technologies. Partha published several papers in the fields of estimation, signal processing and IVHM in national as well as international conferences and journals. Partha, in his current role at Airbus Defence & Space, Bangalore is working on devising ISHM technologies for aviation systems with focus on complete vehicle health, robust implementation and certification of the developed technologies.

Dhaval Makhecha – Aerospace Engineer with more than 15 years of experience in structural design, composite manufacturing and general systems. Dhaval has a Ph.D. in Aerospace Engineering from Virginia Polytechnic Institute & State University (Virginia Tech). During his carrier he has published several papers in the field of composite design and analysis, fracture mechanics and simulation technology. Currently he is head of Air Vehicle Engineering team at Airbus Defence and Space, Bangalore with focus on ISHM, optimization and systems modeling.

Matthias Buderath - Aeronautical Engineer with more than 25 years of experience in structural design, system engineering and product- and service support. Main expertise and competence is related to system integrity management, service solution architecture and integrated system health monitoring and management, Today he is head of technology development in Airbus Defence and Space, Germany. He is member of international Working Groups covering Through Life Cycle Management, Integrated System Health Management and Structural Health Management. He has published more the 50 papers in the field of Structural Health Management, Integrated Health Monitoring and Management, Structural Integrity Programme Management and Maintenance and Fleet Information Management Systems.