



TATEM: Technologies & Techniques for New Maintenance Concepts (Publishable Summary)

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The TATEM project has investigated 'Technologies And Techniques for nEW Maintenance concepts' to increase aircraft Operability by reducing the occurrence of unscheduled maintenance and the time/cost of scheduled maintenance. The project brings together a consortium of 57 contractors from 12 countries across Europe, Israel and Australia. The project is led by GE Aviation (formerly Smiths Aerospace), Cheltenham, UK. The project started in March 2003 and finished at the end of 2008.

The aim of the TATEM project is demonstrate the means to achieving a 20% reduction in airline operating costs within 10 years and a 50% reduction over 20 years. TATEM's success in meeting this aim has been assessed through a cost benefit analysis that has been underpinned by the physical validation of the TATEM concepts on some; 40 sub-system and 6 system level evaluations. It is anticipated that these outputs will add momentum in the move towards a 'health managed aircraft for new enterprise and operational solutions'.

The ambition of the TATEM project reflects the growing demand of both military and commercial customers for improved aircraft Operability and new enterprise models to support more sophisticated outsourcing and purchased service agreements. The emergence of these new enterprise and service models in commercial aerospace has been fuelled by the success of the engine business model and the dynamic growth of the Low Cost Carrier (LCC), which in turn has resulted in further outsourcing of fleet maintenance.

The TATEM project work break down structure comprises the following 9 major work-packages figure 1 These work-packages contribute to a health management programme that has focused on the following 5 themes.

1. Health Monitoring.
2. Integrated data management.
3. Health based maintenance planning
4. Process Orientated Maintenance
5. Mobile Maintenance

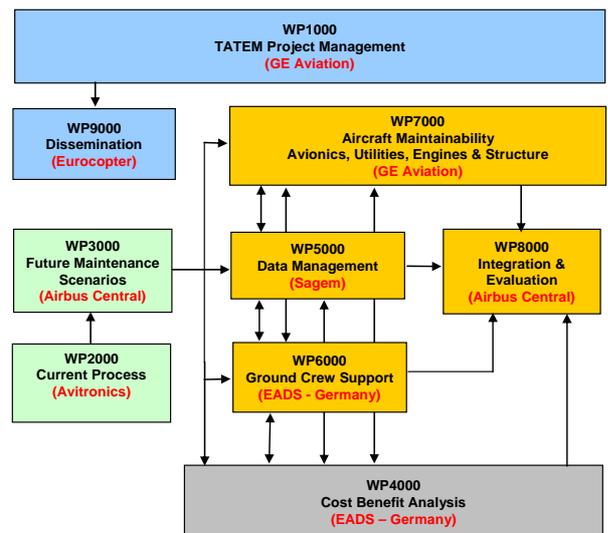


Figure 1 TATEM's project work package structure

The technical work programme is complimented by a cost benefit analysis that provides the means to measure the Operability value of improved diagnostics, prognostics, mobile maintenance and process orientated technical information. The cost

benefit tools are both novel and comprehensive in calculating operability effects but do not currently support logistic or life-cycle effects.

TATEM in the Context of Current and Future Operations

Providing a flexible range of services is a concept familiar to the general aircraft engine businesses and 'value chain'. For example GE Aviation's OnPointsm provides a flexible approach to support servicing that includes 'cradle-to-grave' engine maintenance, materiel and asset management.

The benefits to the customer include; a reduction in working capital costs, improved asset residual value, focus on the core business of flying passengers under guaranteed performance and costs per flight hour. The key benefit to the engine supplier is data on engine health and performance, which subsequently incentivises through-life product and service improvements. This has been achieved for the engine gas path and engine systems through an array of sensors feeding advanced ground based analytical tools that ensure optimal operational performance and safety. This is feasible for the engine because it is a high value system that hitherto has been relatively self-contained on the aircraft.

Decades of collecting and sharing engine health and performance data has resulted in a 'win-win' situation for both customer and engine supplier. The motivation for this behaviour is high because the engine is the largest component of maintenance related cost (MRC) and direct operating costs (DOC). After many years of refinement the approach has yielded robust engineering, financial and commercial risk models that under-pin the service provision. The success of this approach validates the wider use of health management for service based contracting of complex high value aircraft systems.

As a consequence airframe and aircraft equipment suppliers, like GE Aviation Systems, are engaging in similar contracting frameworks with the end customer. A recent example in the military domain was the 'Total Support Services (TSS)' alliance formed between Thales UK, GE Aviation and Selex in 2005. Under this framework the MoD concentrated on achieving its operational objectives, while the TSS provided integrated through-life support services for avionics and electrical systems to the prime contractor on UK MoD rotary and fixed wing aircraft.

Such alliances can be successful if the value chain is successfully embedded with the Customer's business and incentivised to provide full domain knowledge and supply chain skills, to drive down costs and improve equipment availability. This ensures that all of the effort goes

into supporting the aircraft and solving problems before they impact the customer.

Similar service based contracting frameworks in the civil domain include Boeing's 787 GoldCare programme, which appears to be a support service that brings together the capabilities of the service providers (the airframer, participating equipment suppliers, maintenance and repair organisations (MROs)), to provide a single cost-effective support solution. Under this approach the service providers guarantee the availability of spare parts and maintenance for their systems and sub-systems, i.e. avionics, landing gear, high lift etc. In principle the customer is able to select from the range of services on offer to 'best fit' their business model.

Again, the customer benefits by fixing costs on a multi-year per flight hour basis. The service providers benefit from a sustained revenue that minimizes inventory and logistics costs but focuses on keeping parts on the aircraft longer.

Airbus has thus far taken a different approach in developing a collaborative MRO network. The network aims to improve the performance of participating MRO members by the sharing of best practise through techniques such as benchmarking. Airbus collects the maintenance man-hours, materiel spend and time of task information and provides feedback to the members on their relative performance.

A small number of the larger airline operators have also developed similar service-based offerings through their MROs. Perhaps the most sophisticated offering at that this time is Lufthansa Technik's Total Support Services (TTS®), which aims to offer everything from line maintenance, customized maintenance planning, troubleshooting, engineering services, repair and overhaul of aircraft, engines and components, spare-parts pooling, spare engine leasing, painting, cabin modifications, logistics, training, leasing/loans, right through to resale.

This trend is likely to continue if Aerostrategy's forecast of growth for the Maintenance and Repair Organisation (MRO) business increases from \$41bn in 2008 to \$58bn by 2016. Such behaviours demonstrate that both industry and the customer base are keen to embrace more sophisticated contracting regimes for larger and more complex systems. However, there are significant challenges for the value chain to overcome before the complete enterprise approaches the maturity of the engine business model. These challenges are an integral part of the TATEM project and will be explored briefly under the following headings:

- Acquiring relevant knowledge.
- Managing complexity.
- Creating the 'Value Chain'.

Acquiring relevant knowledge

The TATEM project aims to improve Operability by reducing the occurrence of unscheduled maintenance and the time/cost of performing scheduled maintenance. In terms of cost the aircraft systems that have the largest influence on Operability are; engines, landing gear (including tyres & brakes), structure, systems, equipment and furnishings.

Health management systems have a long pedigree on both fixed and rotary wing aircraft. Equipment is monitored for local fault detection with systems and aircraft level fault modelling consolidating these findings with flight deck messages to ensure effective maintenance action. The outputs of these findings are provided to the maintainer in customised reports, processed or raw data form. Real-time airborne communications is possible but these currently experience cost and bandwidth penalties. Broad-band capability is available at or near the gate.

The next generation of health management systems that will emerge from the advances made in TATEM will enhance current capabilities through; integration of flight deck applications (i.e. the electronic flight bag), with wider system coverage, employing process orientated maintenance information management, improved diagnostics and new emerging prognostic capabilities.

The fundamental engineering processes in all health management systems are data collection and abstraction of knowledge. All other processes are dependant on receiving and of course acquiring further relevant and appropriate data to avoid the maxim of ‘garbage-in, garbage-out’. The challenge on modern aircraft is two fold; to identify affordable and robust sensing systems (no one sensor fits all), and to manage the huge amount of data that is generated from the raft of equipment that can be monitored.

This has been addressed in the TATEM project with an extensive selection procedure to identify the sensing and data extraction techniques that would offer the most promise for improving Operability. One of the interesting outputs of this exercise was the success of fusing sensor data with a-prior information (from perhaps the flight deck), to form virtual sensors for the equipment and systems that are not directly monitored. As a result, virtual sensor applications have been developed to monitor the performance and health of the following systems; aircraft fuels pumps, engine oil lubrication and the landing gear.

From this work, it is clear that understanding the interactions (intended or otherwise) of complex systems can be as important as monitoring individual equipment or sub-systems. This is an area of work that requires serious attention if the

full capability of aircraft health management is to be unlocked and deployed. The challenges of complexity are explored further in the following section.

Managing complexity

Providing maintenance and support services involves a complex interaction of people, organisations, technology, policy and economics. This is a classic ‘system of systems’ because these interactions can expose emergent and unexpected properties and behaviours. Emergent properties and behaviours can have an evolving nature that customers and suppliers may struggle to recognize, analyse and understand. The health management approach offers a potential solution to managing some of the technical complexity.

The TATEM health management solution has adopted an open system architecture to integrate data from various sources into a modular, scalable information infrastructure. The architecture is shown in the following figure and is derived from the Open System Architecture for Condition Based Monitoring (OSA-CBM) implementation of the ISO 13374 standard. The basic feature of this architecture is that data is transformed into information and then knowledge in a hierarchal process starting from the sensor (DA) upwards.

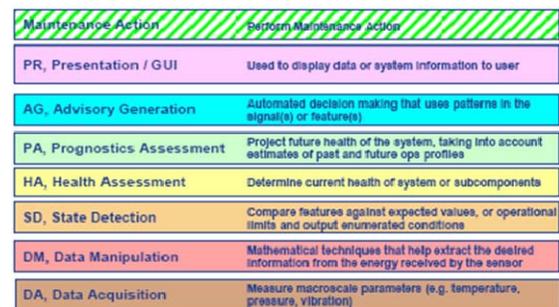


Figure 2 Overview of the OSA-CBM layers

The TATEM experience has shown that an open software architectural approach is a practical solution for providing the necessary tools to transform data in to a maintenance/support action. This has been a major theme throughout the project and without the success of this approach the technical improvements achieved in diagnostics, prognostics, mobile maintenance and process orientated technical information would be difficult to implement due to the need for collaborative working and interoperability of toolsets. It is therefore expected that open standards and protocols for other support functions will be desirable to gain market penetration and customer acceptance.

Maintainers expect to see standardised equipment presenting and collecting data and information through a common interface on all

aircraft types. Effort is required on the part of the value chain to develop standard approaches to realise this aim. For example, mobile and process oriented maintenance is being used by maintainers but the benefits of this technology will only be fully realised when the mobile devices are adapted to the maintenance tasks and integrated into the airline information system.

Managing the complexity in the interactions of people, organisations, technology, policy and economics remains one of the biggest challenges in deploying a future health managed enterprise. It is likely that a future health managed enterprise that supports the next generation of health managed aircraft will require a phased introduction at entry into-service. This will be necessary to validate the accuracy and reliability of the new performance and health models. The length of this introductory period will depend on the coverage and complexity of the system and the size and ramp-up rate of the fleet and the type of services provided.

Creating the 'Value Chain'

The 'value chain' comprises the activities and business that design, procure, produce, market, distribute, and service a product or service. The aim of providing services is to create the greatest possible value for the customer and optimise sustainable profits for the rest of the value/ chain. The benefit to customers and suppliers from service provisions includes the following opportunities:

- To concentrate scarce resources (people/equipment/capital) on what you do best - the core business.
- To secure existing revenue streams and form mutually beneficial teaming arrangements with customers and suppliers.
- To reduce costs by sharing resources with customers, suppliers and competitors.
- To penetrate or capture new revenue streams.

One of the main commercial issues facing the wider use of health management systems is the question of 'who benefits and who pays?' The aircraft engine business has successfully addressed this issue and benefits are accrued by both the customer and the wider value chain. The opportunity to repeat this success across the enterprise are good if the knowledge and lessons learnt in providing engine services are successfully applied.

Ensuring the value chain is understood and is fair and equitable is essential to ensure the new financial and commercial frameworks deliver the expected improvements and behaviours. Understanding the value chain will also result in

the identification and elimination of waste and duplication. Inevitably this will reduce the size of the value chain and reinforce the position of the 'value adder', i.e. greater profit to those offering products and service of value. The key to success is the acquisition, exploitation and management of data.

Arguably the main opportunity for deploying a health managed enterprise across the value chain is the single aisle replacement aircraft that are scheduled to enter service around 2020. The driving force for this opportunity is the forecast of very large fleet sizes, the importance of Operability to the customer and sufficient lead-time to allow current technology to evolve and gain customer acceptance.

Before then there are a number of business jet and small helicopter platforms that will take advantage of incremental improvements in health monitoring and management to improve the customer experience. These platforms are important steps in proofing the technical, cultural, commercial and infrastructure capabilities required for new operational and enterprise solutions.

In terms of the 'journey towards a health managed enterprise' the industry is probably at the mid-point in achieving the required capability. From a technical perspective the road ahead will require far greater attention on integration of the aircraft/aircraft support technologies, technical services and information infrastructure.

This must be the focus for further efforts for the simple reason that the data generated at and around the aircraft is the basis for all further analysis. Only good quality technical data will enable aircraft health management to provide new operational and enterprise solutions. It is difficult to predict the future and what direction aircraft health management will take. However, the following targets are reasonable indicators of a capability approaching that required for a health managed enterprise:

- Right first-time diagnostics to reduce trouble shooting and no fault found (NFF).
- System level Bite functions for complex systems and Sub-system and system level prognostics.
- More complex system interactions particularly with the move to a more electric aircraft.
- Open, scalable, flexible and robust information architecture(s).
- Vehicle wide health monitoring and management.
- Process orientated maintenance information.
- Real-time fault monitoring and management across broad-band to support web-based applications.

- Enterprise models to support flexible short term loan/ leasing of aircraft and support assets.
- Capability contracting of commercial transport aircraft.

Emerging Operational Needs

As TATEM addresses new maintenance concepts, it was essential for the partners to identify and capture the operational needs of operators and MROs. Consequently, the first task on the project was to capture these needs and orientate the later research accordingly. The main supporting concepts were thereby confirmed and a set of top-level requirements were developed, as well as a list of candidate techniques and technologies.

Two major questions arose at the start of TATEM; what are the operators and MROs operational needs and how can Health Management address effectively these needs. A corollary question was also raised at start of TATEM; does the civil aviation community have a common understanding of Health Management?

As for understanding the operational needs, TATEM partners used the first months of the project for collating and analysing the operational information available. This was done through surveys, interviews, search of specialized documentation. In addition, the project took direct benefit of the expertise offered by the partners both in technology and maintenance domains. A big part of this analysis consisted in sharing a vision of current maintenance practices, from which the project identified current strengths and weaknesses.

Current maintenance strengths & weaknesses

This analysis was conducted according to the following segmentation of maintenance:

- Aircraft intrinsic reliability & maintainability
- Maintenance execution
- Maintenance management

From an operator's perspective it is vital that the aircraft is reliable enough and easily maintainable with the minimum impacts on operations. The aircraft weaknesses were identified as per aircraft components, with regard to their impacts on direct and indirect maintenance costs.

Evidence of the aircraft inefficiencies are given through the analysis of the operational interruptions that are actually caused by aircraft technical problems. Unsurprisingly the aircraft components that are the biggest contributors to operational interruptions and maintenance costs are the engines, the air conditioning and bleed air systems, the landing gear system, the hydraulic system and the cabin commercial items.

- The engines, as a major assembly, are primarily a piece of rotating machinery operating in a hostile environment made of vibrations and overheat.
- Air conditioning and bleed air systems contain a great deal of pipes and connections. Therefore, it is not entirely unexpected that the identified sub-systems and their components cause problems and drive up costs, moreover when ageing.
- The landing gear system remains exposed to the environment for long periods of time and is required to take all loads during taxing, take-off and landing of the aircraft. Related components are particularly prone to corrosion, physical damage and leakage.
- The hydraulic system also has a great deal of plumbing and highly sensitive components that may be prone to leakage and handling damages. Sensors are placed in vulnerable parts of the airframe and the system requires a lot of human intervention for check or replenishment. As a consequence faults associated with low oil and pressure levels, whether spurious or real, are likely to occur.
- Cabin commercial items are not required for the aircraft airworthiness; however their service readiness is required from a commercial perspective. As examples, IFE (In-Flight Entertainment) and smart seats cause more and more in-service problems. They require specific maintenance skills and their maintenance can't be performed in an integrated way with regard to the other aircraft systems.

Aircraft major weaknesses result from design, component ageing and to a lesser extent from human intervention and high frequency poor maintenance actions.

Strengths were identified in aircraft modern design methodology, like the MSG3 logic (Maintenance Steering Group) that can effectively address problems associated with aircraft ageing, such as corrosion prevention and check, together with better methods for predicting and detecting potential failures resulting from fatigue, vibration and environmental degradation. MSG3 overcomes more and more potential problems related to aircraft design and usage.

Strengths were also identified in technical training and human factors education, together with the introduction of properly planned and implemented reliability programmes. The introduction of new technology both on and off aircraft was also very beneficial. One can notice the improvement of the on-board diagnostics system, ground-based maintenance aids that combine aircraft data with historical data, electronic documentation and associated tools.

Maintenance execution and management weaknesses

It has to be noticed that these two components of maintenance are inextricably linked since those responsible for executing maintenance rely heavily on management, for ensuring they are able to carry out their tasks efficiently and safely.

Line, Base and Shop maintenance were analysed, as well as the underpinning functions: Engineering, Planning, Training, Spares and logistics. Weaknesses in maintenance execution and management were assessed through analysis of impacts on both DMC (Direct Maintenance Cost) and IMC (Indirect Maintenance Cost). There are various weaknesses in these domains; the following are examples of what the project could identify:

- Lack of trained and suitably qualified mechanics, technicians and engineers are a big concern, though a large proportion of costs are attributed to classrooms and recurrent training. Unskilled personnel can't be compatible with time pressure in Line Maintenance and use of complex aircraft interfaces, while Base Maintenance requires high skilled personnel and related procedures become more and more complex.
- The MIS (Maintenance Information System) is felt to be a weakness. Effective communication between all components of maintenance management is essential and it directly conditions the efficiency of maintenance execution. One can notice in particular the lack of integration within the MIS. As an example, the combination of a poor MIS with non-appropriate management decisions may lead to unavailability of spares, materials and parts required for maintenance execution.
- Technical documentation remains a major weakness. Updating and using of aircraft maintenance manuals, spare parts catalogues and other documentation, either electronic or hardback, can be complex and time-consuming, and it may occasionally lead to human errors.
- Management is felt to be a weakness in complex situations like work shift. A good example would be the pressure on the night shift for getting the aircraft ready for the early morning slots, which was felt to be unrealistic.
- Specific weaknesses were also identified depending on the aircraft age, type and design, for which maintenance can become quite problematic. Maintenance of old aircraft is heavily manpower intensive and subject to component burning out, thus increasing the requirement for more unscheduled maintenance. Higher servicing frequency is also a big concern for oldest aircraft. In some

occasions the lack of knowledge about current aircraft types can reduce maintenance efficiency, as well as the lack of correct aircraft tooling and support equipment.

Maintenance execution and management strengths

From the survey it was quite apparent that aircraft manufacturers and operators have tackled some of the existing weaknesses, which have turned into strengths.

- Maintenance teams themselves are considered the greatest asset. Good group dynamics, experienced and knowledgeable staff and possesses, flexible and go-ahead attitude, are considered a big strength when undertaking maintenance activities.
- Management and communication become strengths when appropriate, well trained, knowledgeable and effective managers are in place and free-up communication channels at all levels between those personnel directly or indirectly responsible for aircraft maintenance.
- Training becomes a strength when personnel receive adequate and regular technical training, human factor awareness training, for ensuring that maintenance is executed and managed in a cost-efficient and responsible manner.
- Implementation and use of modern technology was found to be very helpful in executing maintenance in a cost effective and efficient way. The installation of modern on-board maintenance systems was considered a primary strength, as well as electronic documentation and on-line systems designed to give quick and easy access to aircraft data and manuals.
- The work environment, maintenance facilities, spares and equipment provisioning, were all considered to be strengths when shown to be conducive and appropriate for the efficient and cost effective execution of all maintenance activities.

Operational needs

Airlines and MROs operational needs were grouped under one major driver, the aircraft Operability. The aircraft Operability federates the following needs:

- Ensure scheduled revenue flights
- Maximize asset utilization
- Reduce all maintenance related costs

'Ensure scheduled' revenue flights is closely linked to avoiding any operational interruption. In TATEM we only consider operational interruptions due to technical issues: failures, damages, in-service problems, etc.

There are various areas where money can be invested for addressing this need:

- A more robust aircraft: the aim is about limiting operational consequences of faults. Fault tolerance can strongly reduce the requirement for unscheduled maintenance to be performed during turn-arounds, thus reducing the risk of ground interruptions. It can also reduce the risk of in-flight interruptions. Thanks to a more fault-tolerant aircraft, maintenance actions can be deferred and planned in opportunistic times.
- Avoid unscheduled maintenance: any requirement for testing, trouble-shooting, immediate action required by the MEL (Minimum Equipment List) and so on, can result in a technical delay. In the survey it was shown that the weaknesses associated with the inability to accurately predict unscheduled maintenance have proved to be extremely problematic for operators. Therefore more anticipation is needed.
- Accurate, fast and cost-effective assessment and rectification of in-service events; more automation and better assistance to the maintenance team are needed. If any task is required it should be simple and rapid enough, executable by one basic skilled technician.
- Lighter and faster aircraft servicing; needs for servicing should be known in advance, and related actions may be planned in opportunistic times with no effect on operations.
- Asset utilization is about reducing downtimes where the aircraft can't be operated due to maintenance actions. This can be achieved through various ways.
- A more robust aircraft, more tolerance to corrosion and fatigue. In particular requirements for structural inspections should be strongly reduced.
- Reduction of Scheduled Maintenance requirement; this maintenance should more rely on the aircraft actual usage and actual fatigue. More use of CBM (Condition-Based Maintenance) and usage monitoring is required. In particular there should not be needed to get access to a particular area of the aircraft if there is no confirmation of potential damages in this area.
- More flexible and opportunistic maintenance planning; operators should be able to plan their maintenance tasks so as to avoid potential disruptions in their operations. They should be able to choose the most convenient and cost-effective maintenance planning philosophy according to their own policy.
- Accurate, fast and cost-effective maintenance actions; the weight of maintenance tasks should be reduced whenever and wherever possible. The use of modern information technology like wearable devices or process-

oriented technical data is required, especially for complex tasks.

Reduction of maintenance related cost remains a top priority, moreover in the current context where fuel price is dramatically increasing. In a survey of current weaknesses and strengths various fields for improvement were identified. In particular, new concepts will provide operators with advance notice of the aircraft status and service readiness, allowing better management of all maintenance activities. Thus Integrated Health Monitoring and Management should contribute to strongly reduce both DMC and IMC.

TATEM supporting concepts

In terms of operational the project focused on the techniques and technologies that enable the following strong supporting concepts:

- Aircraft Health Monitoring, including:
 - Enhanced Diagnostics; the efficiency of the today's aircraft diagnosis cannot be considered satisfactory. It too often leads to time-consuming trouble-shooting or even to NFF (No Fault Found). In the worst cases corrective maintenance actions may lead to technical delays or even cancellations. The enhanced diagnosis concept should be seen as a concept close to the ideal immediate and error-free diagnosis. It relies on an enhanced On-board Maintenance System (OMS).
 - Prognostics; it is a major component of Health Monitoring and Management. It aims to detect incipient failures, i.e. degradations that are likely to evolve up to the stage of a real failure. Ideally Prognostics would calculate the Remaining Useful Lifetime (RUL) of a component. Prognostics is a strong enabler for reduction of Operational Interruption rates. It will apply at priority on component whose faults may have operational consequences. It is also an enabler to move from fixed interval scheduled maintenance to Condition-Based Maintenance. Aircraft servicing, daily and weekly checks may also be better managed thanks to Prognostics.
- Aircraft Health Management, including aircraft missions risk assessment. It aims to combine the information from Diagnostics and Prognostics with other information (Flight Schedules, Spares availability, Resources availability, Maintenance planning) in order to generate maintenance recommendations together with a mission risk assessment. This is a typical Decision-Support function.
- Mobile Maintenance. This concept means maintenance actions can be performed in

mobile conditions. While performing a maintenance action one technician can get an instant access to the digital technical data that are required in his process and he can interact with the Maintenance Information System (MIS) at the point of his job.. This concept relies on the use of wearable technologies (wearable displays, Head-Up Display, augmented reality, hands-free devices, voice activation, etc.) and maintenance applications have to be adapted for mobile use (re-design of the HMIs, new philosophy for presentation of the information). Mobile Maintenance may significantly reduce the maintenance tasks times and the risk of maintenance errors. Mobile Maintenance enables also Tele-maintenance since it allows a seamless digital process between different players.

- Process-Oriented Maintenance. The access to the right piece of Technical Data is critical in most maintenance situations, however the today's structure and content of technical data cannot be considered optimised with regard to maintenance processes. It may be complex and time-consuming to access to pieces of information that are really needed in one process. Process-oriented maintenance relies on a new technical data structure and content that enables the user to quickly access to the elements of information he needs at the stage of his process, taking into account his progress in the process as well as the associated context. Human Machine Interfaces (HMI) may be re-designed to make them compatible with process-oriented maintenance
- Integrated Data Management System. This concept may be seen as the future of the current MIS. It would enable all maintenance data to be accessed, shared and managed in an integrated way with regard to all maintenance functions using these data. An effective implementation of Health Monitoring and Management calls for such an integrated data management framework simply because optimisation of maintenance actions can only be achieved through an integrated approach of data management.

Health Monitoring and Management is the main focus of TATEM. The underlying concepts are not totally new; some of them are partially implemented. Health Monitoring and Management should provide pertinent answers to most of weaknesses that were identified in current maintenance practices.

Top-level requirements

Techniques and technologies are developed in TATEM according to local objectives defined in

each technical area (structure, engines, avionics, utilities, ground crew support, data management) and based on the perception of potential improvements in each of these areas. However the final achievements depend also on our capability to integrate these areas and show that these techniques and technologies can effectively produce, once integrated, significant benefits at aircraft and fleet level. Therefore some top-level requirements were developed in order to orientate TATEM research. Thirty top-level requirements were defined from which 19 were directly related to Health Monitoring and Management. These requirements provide qualitative and quantitative operational objectives that have to be achieved thanks to the integration of TATEM techniques and technologies in future maintenance. In TATEM a specific application was put in place for ensuring a rigorous follow-up of requirements and the position of the project with regard to these requirements is assessed regularly.

The Development of Technology & Technical Solutions

The first objective of was to identify key operational parameters that should be measured to support condition based monitoring concepts for engines, structures, utilities and avionics. The main advantages to the operator of condition based monitoring is the elimination of unscheduled maintenance and the ability to accurately plan scheduled maintenance.

Top level aircraft requirements for the integrated vehicle health management system were defined by the airframe partners in TATEM and these two sources of input were used as the framework for selection of appropriate state of the art sensor technologies, models and algorithms by the equipment partners. Tests were conducted to determine the capabilities of these innovative monitoring methodologies and the sensor data from some of these tests were used to demonstrate integration within the TATEM OSA-CBM integrated vehicle health management system. The avionics work focused on the area of avionics maintainability and health management. The objective was to design and evaluate innovative electronics and software concepts to implement within avionics computers

Avionics

The innovation related activities of this project were pursued on a number of fronts.

- Validation of diagnostic techniques for highly integrated avionics systems taking monitoring from a module by module approach to a total system analysis
- Development of experimental models of prognostic algorithms, to improve the accuracy of avionics degradation monitoring information and detect the state of degradation of circuit boards with a great confidence.
- Evaluation of methods for designing 'disposable' electronic equipment to provide a maintenance-free product.

Diagnostic activities

Activities aimed at evaluating techniques to improve the accuracy of fault detection, monitoring and diagnosis and define maintenance concepts and maintainability requirements for modern highly integrated avionics systems.

The technical approach was to define new roles for avionics maintenance actors and protocols for onboard avionics generation who mix the federate architecture and the new IMA (Integrated Modular Avionics) concept for avionics.

Based on identification of current maintenance processes for avionics limitation and focusing on line maintenance, areas of potential improvements have been identified (on architecture, protocols, data format, new technologies). Those improvements brought progress towards a global effective diagnostic system.

New Maintenance Architecture

A new on-board maintenance architecture has been proposed with new maintenance concepts for avionics maintainability. It is based on a distributed diagnostic approach allowing to get a better localization as close as possible to the defect source. In addition, generic BITE (Built-In Test Equipment) elements were defined, based on a common and efficient core motor for BITE mechanisms, configurable according to the target system.

Different entities of avionics maintenance components were specified. The different functions are the following:

- Generic System BITE (GSB)
- Resource BITE (RB)
- Application BITE (AB)
- Network BITE (NBF)

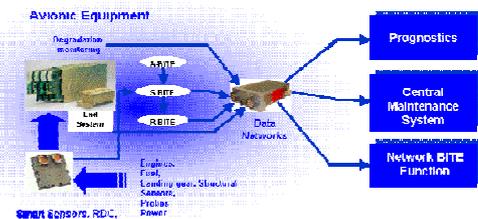


Figure 3 TATEM on-board diagnostic architecture

The contributors to the maintenance exchanges are illustrated below:

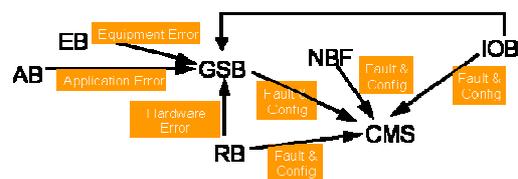


Figure 4 Roles for diagnostic entities.

A deeper study was made on the protocols and data formats envisioned for maintenance exchanges. Whatever the emitter is (A-S-R BITE) and the receiver might be (CMS or GSB), a common protocol has been specified based on SNMP (Simple Network management protocol). The behaviour of the protocol and the associated data contents were detailed.

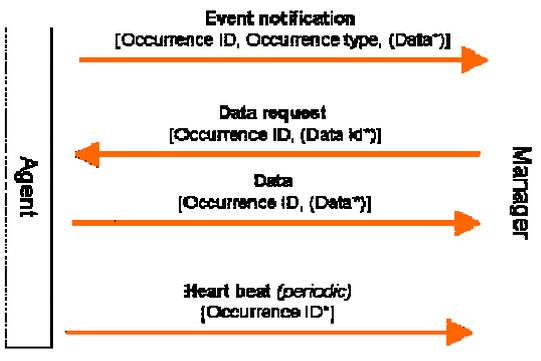


Figure 5 Protocol interactions.

Each of the contributors will be responsible for diagnostic at its level, based on new concepts of Fault Conditions.

Avionics Mock-up

Experimental models of the improved built-in failure detection and isolation mechanisms have been developed at module resource level, at application level and system level and for the aircraft data network.

The avionics diagnostic mock-up has been developed to host the different BITE modules. This platform enables the implementation of the models and the verification of their performance against the specification.

It provides the means and tools to run assessment scenarios. Various test architectures and scenarios have been implemented to enable to evaluate the performances of the new technologies proposed in TATEM concerning the protocols, the different BITE agents definitions (Resource, Application, System and Network) and CMS design and HMI.

The platform HMI allows the compilation of scenarios and activities, for a given aircraft configuration with selected BITE architecture and appropriate failures trigger mechanisms.



Figure 6 Example of HMI.

The HMI provides the means to activate pre defined Aircraft configuration. Once this aircraft configuration selected, one can trigger specific

default on the aircraft, in this case clicking on target inputs or output.

A set of architecture, scenarios were defined to assess the efficiency of faulty devices localization. HMI of the TATEM integration platform provides the means to set up pre-defined Aircraft architecture, then to simulate faulty devices. The assessment analysis has been based on the comparison between TATEM outputs and the diagnostics, which would be obtained on current Airbus Aircraft.

Example of scenario

In this architecture, three different IMA systems are simulated; each including two GSB applications (master/slave) implemented on two IMA CPIOM (Core Process & Input Output Module). Furthermore, three pairs of switches are simulated in order to model a simplified but realistic network. This architecture is described on the following figure:

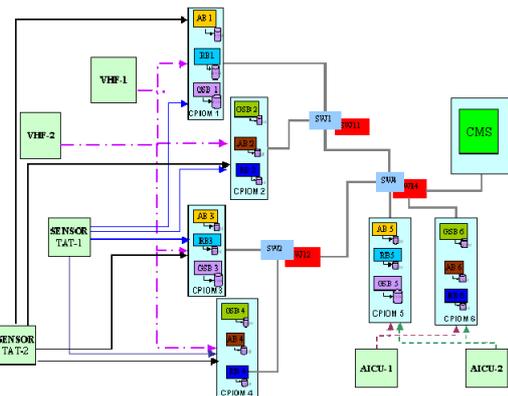


Figure 7 Example of architecture.

Results

Those scenarios were run on the TATEM integration and their results analyzed, in comparison with the results that would have been obtained with existing BITE/CMS technologies.

- TATEM integration platform has proved an efficient simulation tool to validate failure localization performances
- Technical solutions fill the capability gaps identified from flying programs
- Maintainability performances on avionics have been improved

The improved organization at each level of the BITE architecture helps in providing the CMS (Centralized Maintenance System) with more accurate inputs. Correlation/diagnostics is improved at CMS level, hence enabling:

- Reduction of Trouble-Shooting time, i.e. less risk of Operational Interruption

- Reduction of DMC (Direct maintenance Costs); reduction of NFF (No Fault Found)

As a rough estimate, it is believed that the new TATEM Maintenance architecture permits to lower current NFF rates of around 20%-30%.

In the middle term, it is assumed that TATEM results offer a strong basis for building a new BITE architecture. Together with better monitoring, we may expect a significant step thanks to better systems coverage, less spurious, better integration between CMS (centralized maintenance System), technical manuals (e.g. as MEL - Minimum Equipment List), etc. Middle-term projection will consider Diagnostics right first time in 90% cases.

Prognostic activities

Electronic systems are today an integral part of the system, and often critically for the system reliability. Sudden breakdowns can lead in a total loss of the unit, and maybe substantial problems for the rapid maintenance. The existing approach "running or not running" leaves no clearance for prophylaxis, and is thus bound to final events.

The objective is the assessment of the remaining lifetime of operability-driving components and of the foreseeable serviceability of the aircraft, in order to:

- Reduce maintenance costs
- Fewer unscheduled activities
- Reduction in spares inventory
- Have greater flexibility of organizations and processes

Indeed, we expect that Prognostic and Health Management detect the state of degradation of circuit boards and provide an estimation of their lifetime remaining with a great confidence level. This allows a preventing maintenance, with clear improvements in the range of reliability. This results in clear savings of repair costs. Further the knowledge of the "Field conditions" makes the improvements of unit design possible.

The aim was to develop experimental models of prognostic algorithms to improve the accuracy of avionics degradation monitoring information. Prognosis function is fed by degradation monitoring information, gathered by specific monitoring, with residual component lifetime. The complexity is to build up of an accurate "Physics of Failure" Model for a given board.

Description of the modelling phase

The principle of the methodology consists in evaluating the impact of the environment on a Generic Processing Module (GPM). It is important to capture the robustness of the packaging as

each one has a different behaviour in front the same constraint. This is the reason why we aim to build a thermo-mechanical model to be able to calculate the damage ratios associated to each type of environmental solicitation.



Figure 8 Approach to the calculation of damage ratios

Among all the most damaging external parameters temperature and vibration are the ones to be considered in the project. In particular we are assessing the impact of these parameters on the solder joints which degradation usually leads to most of the internal failures.

Solder Joint Ageing

A large range of source of failure is the solder joint life cycle. Due to extreme temperature alternation and high time gradients it comes again and again to problems, caused by solder joint ageing. This temperature stress reduces the life span of solder joints rapidly.

Cyclic thermal stress conditions in surface mount assemblies' leads to solder fatigue. This results from:

- Bending and stretching of parts
- Considering of inelastic strain energy
- Local stress/strain mismatch (solder / lead)



Figure 9 Example Solder Joint Crack

Description of the modelling phase

A thermo-mechanical model has been elaborated in order to be able to calculate the damage ratio associated to each type of environmental solicitation

- Thermo-mechanical model Mechanical fatigue: Coffin-Manson relation
- Equation resolution: Finite Element Method

For the GPM Board several matrixes have been constituted following the model equations. The results were sorted by dwell times: 10min 30min 60min 120min. The results address the 4 weakest components of the GPM board. These

components are PBGA (Plastic Ball Grid Array) and CLCC (Ceramic Leadless Chip Carrier).

High Accelerated Life Tests: correlation and validation

The first objectives of HALT tests were to have reliable matrixes and to compare the theoretical results with test performed on real boards.

The "Physics of Failure" Model-based approach gave good results to estimate, for a given electronic board, the remaining lifetime of joint solders. The impact of thermal and vibration cycles over those joint solders have been quantified to assess elementary damages associated to each thermal and vibration solicitation.

First comparison of theoretical results with High Accelerated Life Tests (HALT) performed on real boards gave close results

- Accurate lifetime prediction of electronic systems using a Physics of Failure approach, based on thermal cycling, will need further correlation and validation activities
- A smart micro-programmable device has been developed with onboard processing capabilities, capable of computing Real Time Degradation Ratio/Remaining lifetime prediction (thus embedding the "Physics of Failure" Model)

TATEM gives some promising results, but Prognosis for electronic boards is still a very challenging domain. In-service data are required for maturing the Prognostics techniques.

Research is still needed to move forward from degradation indications to quantified results. In any case, doing prognostic on avionic equipment should take into account possible equipment complexity increase as well as increase of equipment price.

For the middle term, it is projected a full implementation of Prognostics techniques on a limited set of aircraft components: NOGO & high cost components at priority.

Disposable Electronics

Disposable electronics are now crucial in many electronic fields which encounter skyrocketing technological changes especially when costs are low: PCs, mobile phones, small and large electrical appliances, automotive computers, etc.. The solutions implemented are all different but two major trends can be established:

- When the whole product is thrown out (small domestic appliances or mobile phones)
- Only sub-assemblies are replaced (large domestic appliances, PCs ...).

At the same time, constraints due to recycling of "DEEE" electronic waste have been reinforced to comply with the environment protection policy.

The continuous increase in MTBF, the growth of complexity of the boards with the use of digital components, the difficulty or unfeasibility to repair some components due to their soldering and global cost management could be some reasons to introduce disposable electronics in aeronautic industry. This concept aims to eliminate the need for maintenance of avionics systems by not repairing defective electronic sub-assemblies. This study represents a first step in the evaluation of the concept and must be continued by a more complete design and economic study. It doesn't aim to orient the reader towards an obvious solution but to give a maximum of tools to understand the concept applicability, its limitations and constraints.

The aim was to evaluate innovative electronics and software concepts to implement within avionics computers to provide "disposable electronics" concepts. The new concepts aim to design new avionics equipment internal architectures enabling the pure replacement (no repair) of small defected hardware sub-assemblies.

Current design of on-board electronics is based on complex boards using more and more integrated components. It leads to expensive boards, difficult troubleshooting (access to components, testability, replacement, etc.), long maintenance cycles (TAT) and complex handling of obsolescence. The problem increases constantly with the fast change of advanced electronic technologies.

The "disposable electronics" concept could efficiently deal with the issues above. The challenge is to meet functional performances whilst dramatically decreasing maintenance costs. The new concept aims at devising new avionics equipment internal architectures enabling the pure replacement (no repairs) of small defective hardware sub-assemblies.

Repair Cycle Analysis

The impact of disposable electronic concept on the shop repair process has been assessed. From a civil aircraft organization point of view, the assessment will be done considering the suppression of shop maintenance Level 3.

From the general scenario type, level 3 tasks will be avoided and the new scenario is the one presented below.

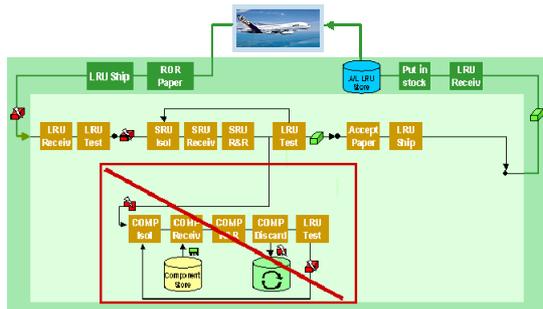


Figure 10 Example of modelling results

With this simplified approach of considering only technical tasks and logistic tasks to evaluate the impact of Disposable Electronic Concept for the next 20 years, we have obtained an interesting benefit in term of DMC reduction (only man hour and material removal have been considered). However, we should keep in mind that the assessment of such maintenance concept cannot be limited to the above study. Many other criteria should be considered to be closer to reality. This conclusion has brought us to think about the different parameters to take into account in our assessment.

Impact of disposable electronics

The key drivers are grouped into several topics:

- Technique and technology issues
- Repair process issues
- Economic issues

New developments in repair activities will be driven by the technical and technological developments expected in the next few years on the electronic market. The complexity of the repair task and the cost of test means will be largely impacted by the frequent use of complex components, COTS sub-assemblies and increasingly complex assembly processes on boards. No significant impact is currently expected on starting recycling activities. Finding the origin of the failure is a real necessity, which means either maintaining the expertise step or improving test capability at level 2. This analysis is used in the economic section in order to quantify the benefits or losses of the disposable electronics concept.

Economical analysis

The financial aspect and mainly the cost aspect have not been tackled completely for confidentiality reasons. Some ways of comparison have been established, when possible.

BOC	Item	Current cost	Disposable concept
1.1	Test		
1.2	Reception		
1.3	Reception		
1.4	Reception		
1.5	Reception		
1.6	Reception		
1.7	Reception		
1.8	Reception		
1.9	Reception		
2.0	Reception		
2.1	Reception		
2.2	Reception		
2.3	Reception		
2.4	Reception		
2.5	Reception		
2.6	Reception		
1.3.1	Planning		
1.3.1.1	Planning		
1.3.1.2	Planning		
1.3.1.3	Planning		
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1.3.1.5	Planning		
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1.3.1.98	Planning		
1.3.1.99	Planning		
1.3.1.100	Planning		

Figure 11 Example of cost analysis

Results

At first, this concept could seem very simple to address but in fact, it reveals high complexity. Basically, not having full capability at a disposable sub-assembly:

- to test, localize at shop and production level
- to repair, to investigate,
- to simulate, to validate
- to get product definition and documentation
- to modify design...

This concept has a major impact on both A/L and OEM repair activities and process. TATEM conclusion is that Disposable concept is not economically interesting with current designs of products. However, considering that the problematic increases constantly with the fast change of advanced electronic technologies (complex boards using more and more integrated components, COTS ..), the disposable solution could arise in future designs to anticipate and to handle repair activities problems (difficult troubleshooting linked to components accessibility, testability, replacement, etc.), long maintenance cycles (TAT) and complex handling of obsolescence.

It is important to notice that A/L and MRO have decreased their level 3 activities at the same time that the equipment complexity grows. Thus, level 3 disposable concepts will be more an OEM problematic.

Several axes are identified for future works on disposable electronic concept:

A first axis will be to find out new designs to make a disposable electronics solution cost effective. The expected results are to define design rules /specifications compliant with disposable concept.

A second axis could be to consider the disposable electronic from OEM perspective versus A/L perspective:

- Economic approach,

- Associated maintenance policy in case of disposable electronics (IP, stocks...).

In any case, specifications and directives will need to be revised to take into account the disposable electronic concept as well as maintenance processes (impact on documentation, training, root cause analysis...).

Selective Passivation

The objectives were to evaluate technical solutions and architectures for selective passivation concept and to identify its potential benefits:

- to increase the availability of avionics computers when part of it is at fault (ie. to enable an avionics computer to continue some part of its functionality even when a hardware or software failure occurs)
- and deferring the need for avionics maintenance.

The aim is that the faulty part is isolated and that the healthy part of the computer can still be used to run some level of function.

The activities permitted to establish a state of the art of the selective passivation implementation, to build a methodology and associated assessment criteria (safety, OR, maintenance costs).

More than 10 potential solutions and architectures have been studied, through the use of electronics simulation tools. The study has been conducted at equipment level (LRU) and brought the conclusion that selective passivation interest increases when:

- The fault detection coverage rises,
- The module size rises,
- The failure rate weight of the I/O rises comparing with those of the common parts.

Utilities (Electrical Power, Actuation and Aerodynamic & Probes)

The activities in utility systems were concentrated in three distinct areas

- Electrical Power Systems
- Actuation Systems
- Aerodynamic Probes

Electrical Power

The electrical power work package has studied three components of an electrical system

Electrical Generator

- Contactor
- Motor

Generators

For TATEM Electrical Generator work techniques based upon monitoring the temperature of the ball bearing and the vibration spectrum of the ball bearing, were investigated, as candidates for health management. An aerospace electrical generator was run over a range of speeds, electrical loads and different bearing health states and waveforms recorded. Off line analysis was used to establish the health of the generator.

As illustrated in the following figures the frequency spectrum of vibration yield additional frequency terms in the presence of degradations. The dominant frequency at 220 Hz is linked to an unbalance of the rotor at the speed of rotation. At 0.95 g it is the main frequency for the good state ball bearing. Things are very different for the others bearings. The main frequencies for those bearings are detected between 3000 and 5000Hz. Those lines at high frequencies are the symptom of the bad health of the ball bearing. Those lines are very small for the good state ball bearing while they are very high for the overhauled bearing. The overhauled bearing seems to be the most damaged one.

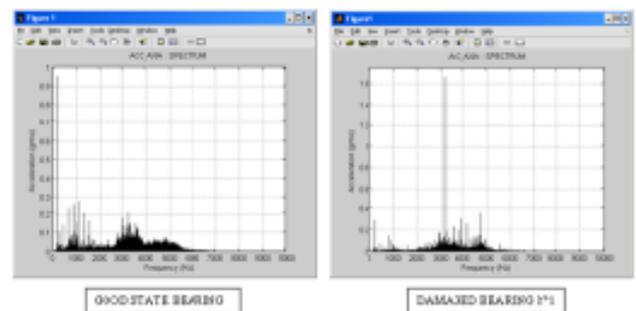


Figure 12 Electrical Generator Ball Bearing Frequency Response

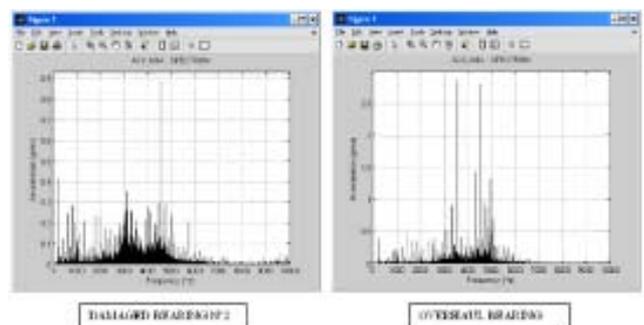


Figure 13 Electrical Generator Ball Bearing Frequency Response

A further low frequency analysis up to 2kHz illustrate other frequency terms related to ball bearing faults, see the following three figures. The presence or absence of these frequency terms can be used as the basis of ball bearing diagnosis for an electrical generator.

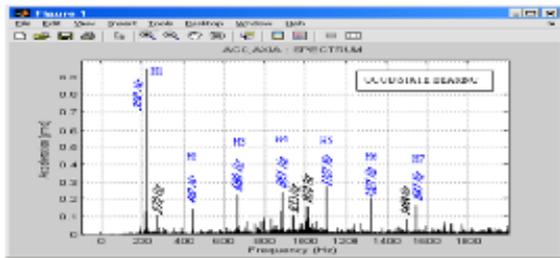


Figure 14 Electrical Generator Healthy Ball Bearing Low Frequency Spectra.

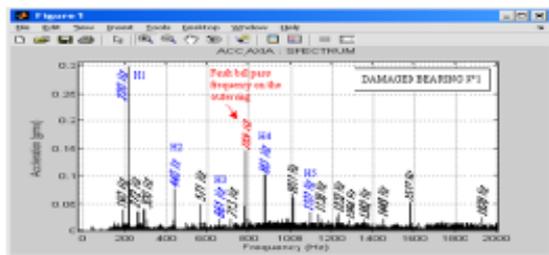


Figure 15 Electrical Generator Damaged Ball Bearing Low Frequency Spectra.

The ball bearing temperature is an alternate measure of the health state. The measured temperature must be corrected for ambient temperature. The following figures illustrate results from two different measures, the first correcting for case temperature, the second correcting additionally for oil & winding temperature.

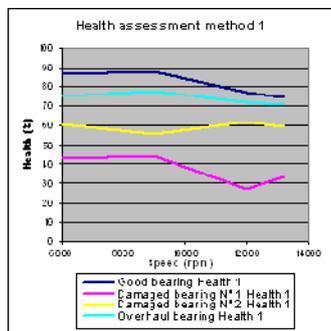
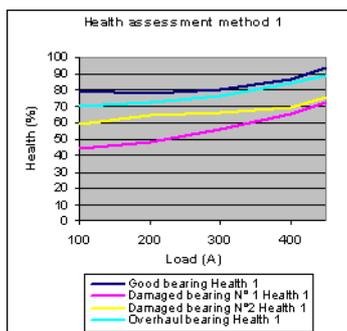


Figure 16 Electrical Generator Health based on bearing temperature-v- speed 3 temperatures measured.

Figure 17 Electrical Generator Health based on



bearing temperature-v- electrical load 3 temperatures measured.

The analysis indicates features that may be used to undertake generator diagnosis.

Aerospace Contactors

Aerospace contactors, have been tested by repeated hot switching with a nominal current of 60A, using a 3 phase 400Hz 115V supply. One phase was loaded with a purely resistive load, a second with an inductive resistive load, to stress the break operation and the third phase a capacitive resistive load to stress the make operation. Each switching operation was recorded and subsequent processing indicated that contact resistance is one measure of contactor health.

Features were extracted from the recorded data. In the figure below the voltage across the contacts is plotted versus the switching cycle. Note the voltage across the contacts increases with switching cycle. Thus the voltage can be used as an indicator of the contactor health.

Actuator Remaining Useful Life

Another package of the work attempted to determine the status of the actuator and it's remaining useful life, with the aim of reducing the maintenance costs associated with actuators. Two actuators, see figure below, were studied an Uplock Actuator, part of landing gear extension and retraction system and GEMA an electromechanical actuator. To maintain reliability additional sensors were not fitted and existing signals used as inputs. The algorithms developed should fit within the Open Systems Architecture for Condition Based Maintenance [A].

A model-based and signal diagnostic approach was proposed for the GEMA actuator. The model based approach is based on a set of different mathematical models, each describing the actuator in a defined failure mode. A hybrid state estimation filter is used to estimate the state and then to derive the actuator health. One signal based approach used the power spectral density, under certain operating conditions, which allowed some fault conditions to be detected. Other signal based approaches were unsuccessful at distinguishing faults or degradations.

For the Uplock actuator a signal-based approach was chosen. The diagnostic concept is solely based on a signal transformation of the measured motor input current. The frequency content of the signal is analysed using a discrete Wavelet transformation. This representation allows automatic detection of the operational phases of the working cycle during release process, the representation further allows detection of discrete

spike events, which are correlated with actuator health. Based on this phase and spike detection a set of features is derived, which allow detection the actuator state. In the necessary pattern recognition step Support Vector Machines are used as binary classifiers. The used features are sensitive to the severity of the emulated fault condition. This is exploited to estimate the actuator health index. The validation of the diagnostic method of the Uplock actuator is underway. The system allows for detection of two different failure modes, a) increased internal friction and b) degraded motor. Both fault conditions can be emulated in the lab. The initial results show a good detection rate for the considered failure states. The quantification of fault severity as input for a health index was demonstrated as well, since the considered faults can be detected at an early stage, it seems possible to realise a prediction of the remaining actuator lifetime. However, to achieve this, validated degradation models, which reflect the timely behaviour of the real-world actuator degradation, are necessary.

The GEMA simulation model is able to reproduce the dynamic behaviour of the actuator. A simulation experiment showed the feasibility of detection of external disturbances caused by wind gusts. This can be used to improve the robustness of the diagnostics system.

This actuation task has identified a series of mechanisms to improve the monitoring, diagnostic, and prognostic capabilities within a Health Management System with focus on actuation systems. The work focused on general diagnostic and prognostic techniques which are validated using two example actuators.

Aerodynamic Probes

The aerodynamic probes task has investigated designs aimed at improving the reliability and maintainability of aerodynamic probes and has focused on the four following areas:

- pneumatic connection
- temperature limitation
- water ingress
- optimized de-icing

A maintenance risk is failing to make the pneumatic connection a probe is removed and replaced. The tests to confirm pneumatic connection are time consuming so a mechanical arrangement device has been designed, such that the electrical connection is impossible unless the pneumatic connection has been made. See the following 3 figures. The loss of the electrical connection can be detected, and since pneumatic connection is a precursor to electrical connection

the probability of a missing pneumatic connection is reduced using this novel connector design.



Figure 18 View of the mechanical device for Pitot probe



Figure 19 View of the mechanical device and Pitot probe



Figure 20 Operation of the mechanics

On aircraft the pneumatic probes, e.g. Pitot probe, can ingest water during flight. The water collects in small drains located at a lowest point of the pneumatic circuitry. When this drain is full, freezing of the water leads to the loss of the sensed pressure. To avoid this occurrence, the drains are regularly inspected and if necessary emptied. Such regular inspection could be avoided if the presence of water is detected. The concept is to use a small PTC installed at the level of the drain as a level sensor. The electrical power dissipated by the PTC is different when it is in the air or in the water. This allows the detection of the presence of water, as soon as the tip of the sensor is plunged in water.

Aerodynamic probes are heated by means of a coaxial heating wire. Active electronic circuitry can be used to limit the overheating, since overheating degrades reliability. Existing solutions use the electrical resistance of the heater itself as a temperature sensor; but this is difficult to implement, because of limited temperature sensor sensitivity and poor repeatability. This concept

uses a PTC as temperature sensor; which has improved temperature sensitivity, as the primary control for the heating circuitry.

Engines

Operational drivers

The selection of health monitoring topics takes into account engine shop visit causes (Figure 21). The circled causes were considered in TATEM.

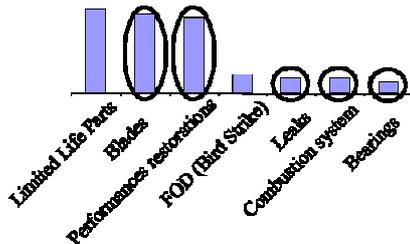


Figure 21 Engine typical shop visit causes distribution

Flight delays and flight cancellations (D&C) causes may also be a driver for topic selection. About 30% of the engine caused D&C result from fluid small leakages, just drips. About 10% of the engine D & C occur during a "No start", i.e. at the most penalizing moment with passengers on board.

Input parameters

Additional technical solutions for health monitoring of engines may take advantage of the existence of electronic engine control systems. Such systems already include a set of sensors and computed control parameters. The availability of such parameters is protected by the MMEL (Master minimum equipment list), which limits the dispatch time with missing information. This would not be the case for additional sensors only devoted to health monitoring.

Specification derivations

A few rules may be derived from the generic specifications:

- Down time to be reduced by engine performance modular diagnosis, which should identify the degraded module
- False alarms or inaccurate diagnosis to be reduced by fusion
- D & C to be reduced by prognosis
- "No fault found" to be reduced by diagnosis accuracy.

Engine health monitoring: Performances modular diagnosis and prognosis

Performances restorations is one of the drivers of the shop visit causes. Traditionally, the engine

efficiency may be followed up by sensing the temperature at the exhaust of the HP turbine. As the efficiency of the engine decreases, the EGT increases. At some temperature level, the turbine is not able to afford the thermal conditions. The engine has to be refurbished. According to the first rule, the efficiency evolution is to be followed up on a modular basis: Compressors, turbines, and combustor. This is made possible by using a performance gas path model taking into account some of the existing control parameters, called performance parameters.

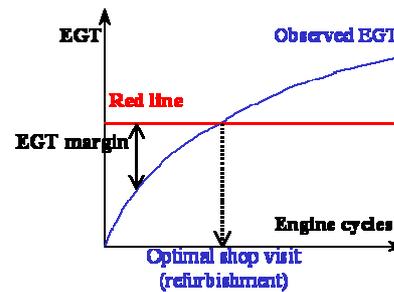


Figure 22: EGT Follow up principle

Tests were performed with real data on existing and improved methods: "physical" methods based upon iterative identification of gas path model, and "non-physical" methods based upon "learning" of model or real cases. "Physical" and "non physical" methods of diagnostic are, now, able to provide good estimation of deterioration of engine components in an important number of cases.

Performance fusion with other events

Some events, such as blade or bearing degradations produce imbalance, which impacts both vibrations and gas path analysis. Development and test of fusion techniques were performed in two ways:

- Fusion between vibration and gas path data issued from real scenarios,
- Fusion between gas path data issued from two different modular diagnosis methods on simulated scenarios.

Investigations of fusion on real scenarios have provided positive results. Algorithms and techniques of fusion are now operative and, coupled to tested diagnostic methods, are able to diagnose new classes of failures.

Beyond performances

Other developments have lead to new perspectives of prognostic and to integration of engine health monitoring on a platform coupling airborne and on-ground segments. These show ability to detect engine systems degradations such as sensor acquisition systems or variable

geometry systems affecting performance parameters.

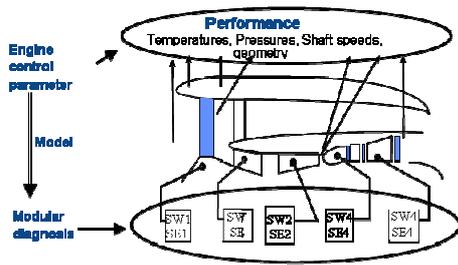


Figure 23: Modular diagnosis principle

Engine systems health monitoring actuation loop

Diagnosis and prognosis techniques for variable geometry control loop degradations have been settled and experienced.

The failures encountered in service have first been considered and modeled.

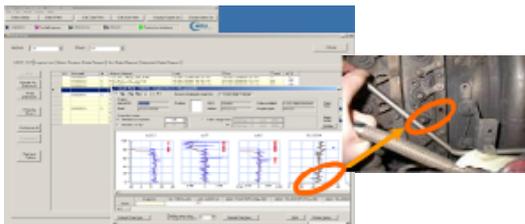


Figure 24: MTU Integrated Health Monitoring graphical user interface.

Diagnosis and prognosis methods were tested on:

- Accelerated bench tests
- Accelerated bench tests input with simulations of the failures.

2D representations of command current to position indication discrete linear transfers functions demonstrate ageing follow up capability

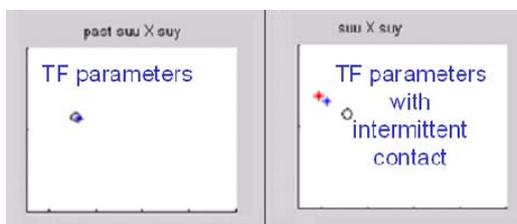


Figure 25: Example of 2D representation of linear discrete transfer function with ageing.

Seal wear count

Rod seal drips are the main cause of hydromechanics' variable geometry actuator removal. Finite element (FE) stress and wear

dynamic modeling based on static analysis with dynamic friction coefficient from rod movement explains degradations encountered in service and assesses simplified "hand calculation" count.

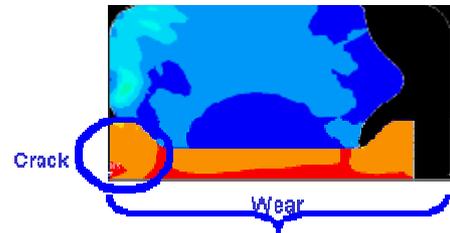


Figure 26: Finite element seal dynamic modelling

It is noticed only 2% deviation between simplified "hand count" and FE wear modeling

Oil quantity track

Present oil quantity track based on oil replacement check is not accurate and reliable enough for abnormal oil consumption early detection. Therefore, an oil quantity model using rotation speed (N2), oil temperature and oil level indications have been developed. Test data were used.

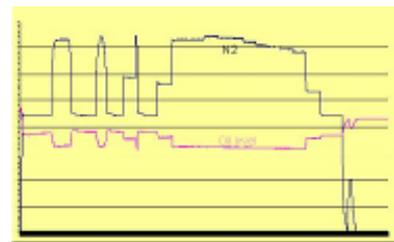


Figure 27: Oil level and N2 evolutions

Main fuel pump

Main fuel pump degradation may cause "no start" or in flight shut down. Therefore, several follow up approaches have been investigated. Finally, a technique, which does not require any additional sensor, has been found. It covers performance degradation due to gears cavitations or bearings degradation.

Start capability

More generally, the "no start" are very penalizing as they occur when the passengers are on board

A start capability diagnosis and prognosis tool was parameterised with a special FMEA (Failure Modes & Effects Analysis) giving probability relations between failures leading to "no start" and effects composed of sets of follow up parameters

ECS-Engine data fusion

Aircraft Engine also provides pressurized air for ECS (Environmental Control System) in order to supply:

- Air conditioning and pressurization systems
- Engine inlet cowl anti-ice systems
- Wing thermal anti-ice systems

Engine performance parameters evolution may be related to local malfunctions. Segregation between engine cause or ECS cause among air leakage alarms turn approximately 17% of the “trend shift related” maintenance actions into scheduled maintenance actions.

ECS malfunctions can be induced by engine behaviours and detected by bleed air status monitoring. High inlet temperature and pressure is a source of ECS/Bleed system component degradation. Bleed air pollution can generate an uncomfortable cabin environment. Saving the time spent on the troubleshooting actions would be profitable, therefore a study was conducted for the design of a system that could provide accurate diagnostics. The relevant parameters for this monitoring were pointed out.

Structures

Landing Gear Shock Absorber

For the landing gear system a test was conducted on a shock absorber and modelling on brake cooling predictions. The landing gear shock absorber testing involved fitting a combined pressure and temperature transducer and a rotary variable differential transducer to a main landing gear. The purpose of selecting these sensors is that they replicate the manual measurements that are currently made, during scheduled maintenance, namely pressure, temperature and shock absorber closure. The sensor results are input to an algorithm which calculates the service state and removes the manual reference to servicing charts or tables to determine the service state of the shock absorber. The key advantages to having a monitored system is that readings can be taken when the landing gear is first extended on approach as well as on the ground which, combined with the stored readings enables the comparison to be made against multiple reading points which is more accurate than doing a comparison against a single point.

The tests were conducted under a wide range of conditions to simulate different aircraft weights, ambient temperatures and fluid volume. An algorithm (Figure 27) has been written which takes the sensor inputs and determines if the shock absorber has the correct nitrogen pressure and fluid volume for the given temperature, pressure and shock absorber closure. The algorithm

assumes, as a starting point, that the shock absorber is correctly serviced which is the case for newly delivered landing gear. An inflation curve is predicted from the temperature (T1) is measured after the landing gear have been deployed on approach. The shock absorber extension (Z1) and pressure (P1) are then measured and checked to see if they fall within the tolerance band of the curve for T1.

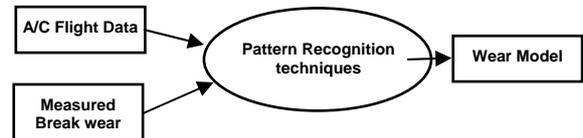


Figure 28: Shock absorber two point check algorithm logic

Regular assessment of the readings would enable the calculation of the rate at which the shock absorber is losing either nitrogen pressure and/or fluid so that a scheduled maintenance task can be planned by the operator.

Research into reducing maintenance costs and turn around time has also focused on the brakes. Models have been written and validated to predict brake wear rates and cooling rates.

Brake wear

Brake wear is currently determined by visual inspection of wear pins after each flight which is costly and an error of only 0.001 inches can mean a brake being replaced ten flights earlier than necessary. The measurable parameters chosen to infer the brake wear are as follows:

“aircraft mass in tonnes (including payload), aircraft landing speed in knots, relative to ground, flap position in degrees, runway rolling resistance coefficient, brake pack temperature in degrees centigrade”.

As the physical principles behind brake wear are not fully understood, the method described below uses pattern recognition techniques to learn a wear model (Figure 29) from pre-existing wear data

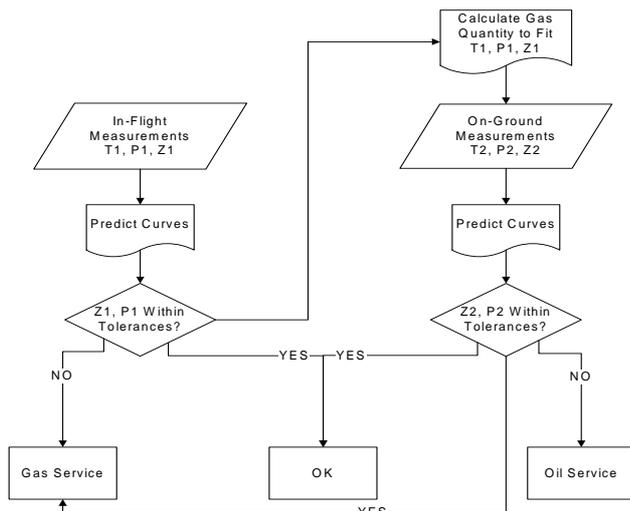


Figure 29 Creation of a wear model from data using pattern recognition techniques

Brake cooling prediction

Brake cooling prediction is a very useful parameter to assist with turn around time and dispatch as it can ensure that an aircraft’s brakes are below the limiting temperature of 300°C for take off, before it reaches the end of the runway. It also enables maintenance crews to know when they will be able to work on the brakes. A Matlab/Simulink model of the aircraft and brake was constructed to simulate the on ground phases. Flight test data was then used to validate the model, the algorithm was tuned using Matlab code and then implemented into the Simulink model.

The level of taxi braking is estimated and updated as the aircraft transitions through the on-ground phases. The cooling time is updated to reflect the amount of taxi braking still to occur and the duration of the taxi-out is estimated using the predicted time of pushback.

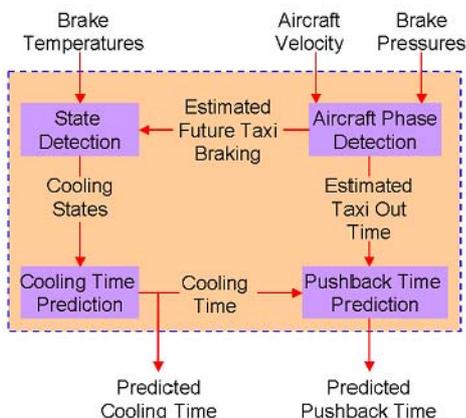


Figure 30 Brake cooling prediction

Airframe Structures

The airframe structures work within TATEM investigated the use of state of the art sensors, fitted to metallic and composite panels, to detect impact damage and crack initiation and propagation. The current state of the art requires NDT inspection by an approved inspector but an inspector may not be available at short notice. This can cause the airline to decide to ground the aircraft for a long time or possibly conduct unnecessary repairs. The vision for a future structural health monitoring system is that it will give a clearance or repair decision giving ground time saving and elimination of unnecessary repairs

The table below describes the airframe structural panels that have been tested and the sensor systems that were fitted. The objective of the work was to determine how effective the current state of the art sensor systems are at detecting typical damage that is experienced by composite and metallic structures. These sensors were selected using a rigorous process that was developed by the partners working in this area of TATEM.

Use Case Description	Sensors Fitted
Impact testing of honeycomb stiffened composite panel (F/A-18 horizontal stabilator)	Phased Array, Acoustic Emission, Acousto Ultrasonic (Acellent), Comparative Vacuum Monitoring
Impact testing of a carbon fibre stringer stiffened sandwich structure with a foam core panel	Phased Array, Acousto Ultrasonic (Acellent), Comparative Vacuum Monitoring
Fatigue testing of an aluminium riveted panel (A340-600 longitudinal joint)	Phased Array, Acoustic Emission, Acousto Ultrasonic (Acellent)

Table Summarising airframe structural panels and sensor systems

Honeycombed Stiffened Composite Panel

The objective of testing the honeycombed stiffened composite panel was to detect debonding and delamination damage for both impact events that lead to damage and the size and location of the damage. With a very dense sensor network (~100mm spacing) the Acellent system was capable of locating impact damage, giving a measure of damage severity.

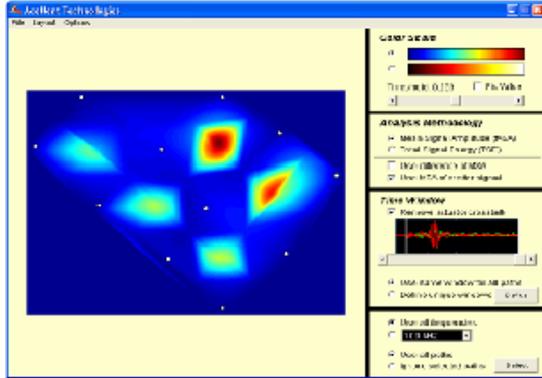


Figure 31: Acellent system screen showing damage

The conclusions were that there was poor correlation between the damage severity data from the Acellent system and damage area (as measured by C-Scan). System calibration data would be required for accurate damage characterisation which would be performed in the Health Assessment layer of the OSA CBM architecture.

Carbon Fibre Reinforced Plastic Structure

The second composite test was designed to address the maintenance issues of detecting impact location and energy and the detection of delamination in skin and stiffener, core damage or debonding location and size. The panel was a generic Carbon Fibre Reinforced Plastic structure “stiffened foam sandwich box”. A series of static tests were conducted to introduce barely visible impact damage and visual impact damage to the panel. The results showed that the acousto ultrasonic provided good results once the damage had reached a certain size but there were shadowing effects for multisided damage sites, see table below:

Measurement	Acellent Damage Location		Real Damage Location	
	x-Axis	y-Axis	x-Axis	y-Axis
SK-2	N/A	N/A	120	500
	Not Detectable			
	No Localisation			
SF-2	350	720	320	780
	Good Detectable			
	Good Localisation			
SF-1	50	200	110	380
	Barley Detectable			
	Good Localisation			
SK-1	200	200	150	100
	Barley Detectable			
	Good Localisation			

Table Comparing acousto ultrasonics output with actual.

The conclusions from the testing were that the phased array sensor system suffered from a significant number of false positives on the skin and there were also false negatives in the sandwich structure. The comparative vacuum

sensors performed well and did not display false negatives or false positive results.

Metallic panel

The purpose of the metallic use case was to simultaneously monitor various cracks of small size which is representative for a very large proportion of metallic aircraft fuselages, wings and any type of riveted repair of ageing aircraft structures. The constraints imposed on this test were that the transducers were only to be placed inside the fuselage and it was recognised that acoustic signals passing a lap can reduce up to a factor of four and the area around a riveted lap allows for a multitude of acoustic wave reflections.

The test panel was subjected to constant amplitude fatigue loading set at a value that was anticipated to produce cracks within a reasonably short amount of testing. Additional acoustic emission signals were measured after 68,000 cycles (Figure 33) and visible cracks were observed around the rivets from 86,000 cycles onwards. The first cracks, of 5mm in length, were detected on the surface at 178,500 cycles. Sensor readings were taken every 5,000 cycles and crack propagation of around 1 mm per 1,000 cycles was recorded. The first method of analysing the sensor outputs was in a direct path between the upper and lower layers (Figure 32). Another option is to analyse the signal between each sensor and all those in the opposite row.

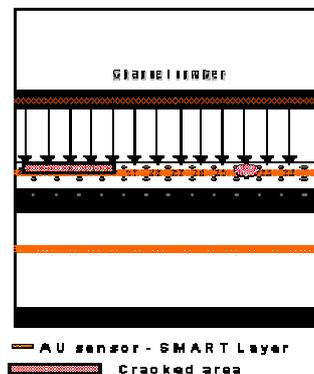


Figure 32: Direct signal paths between sensors

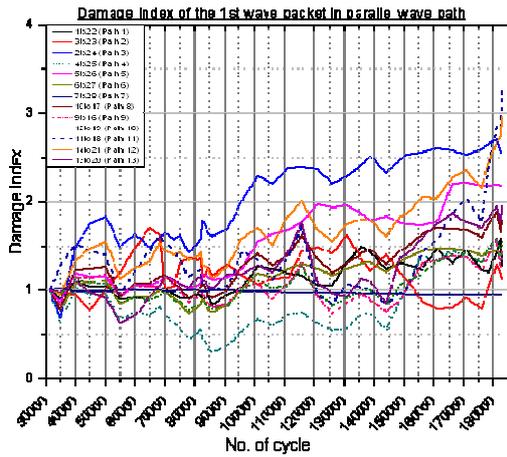


Figure 33: Signal transfer scheme 1 – direct path

One of the conclusions from this work is that structural health monitoring systems that were tested are not at the technology maturity estimated during the selection process. The testing has highlighted the deficiencies and feedback has been provided to the technology suppliers as the technologies do have the potential to be explored for aerospace application. The acousto ultrasonic was the most mature of the technologies used to detect cracks in metallic components and it allowed cracks from around 10mm and longer to be detected

The TATEM Technical Construct

To support the TATEM technical developments a global information system simulator called a Data Management Platform (DMP) has been developed this has been a backbone for the new technologies and techniques investigated by the project. Granting access to state of the art on-board and on-ground IT capabilities opens new possibilities of data transformation and presentation, such as adopting the ISO 13374 based Open System Architecture for Condition Based Maintenance (OSA-CBM) standard, as well as opportunities to share maintenance data on standardised formats which in turn opens the door to collaborative maintenance.

From health monitoring to information technology

In the Aeronautics industry today and for years to come, direct and indirect maintenance costs are a major part of operators' charges. A big research and development effort is dedicated to limiting these costs by anticipating the maintenance operations or by identifying more accurately the cause of a disruption. Aircraft health monitoring is one method to assist in achieving this and consists of gathering a large set of operational measurements and processing this data through several steps of transformation.

This need for data collection and subsequent management requires new information technologies that are different from traditional aircraft electronics. A wide variety of aircraft actors are involved in the health assessment; be it on-board - from the engine, to the landing gear, to the brakes, to the structure. Or be it off-board - from the Airline, to the maintenance repair office (MRO), to the original equipment manufacturer (OEM), to the Airframer. The most appropriate way to bring all these actors together is to use modern information technologies and standards to integrate all parties in a homogeneous and efficient framework.

In the TATEM project, in order to identify the benefits of enhanced Maintenance Integrated Systems (MIS) techniques, an environment providing such an information technology framework has been defined. It has been called the Data Management Platform.

One of the major goals of this platform environment was to evaluate the validity of the OSA-CBM standard as a condition based maintenance framework to solve the integration issues.

Combined with all of the other elements studied on the TATEM Project, the use of this platform takes a

step towards developing a fully Integrated Vehicle Health Management (IVHM) system for Aircraft.

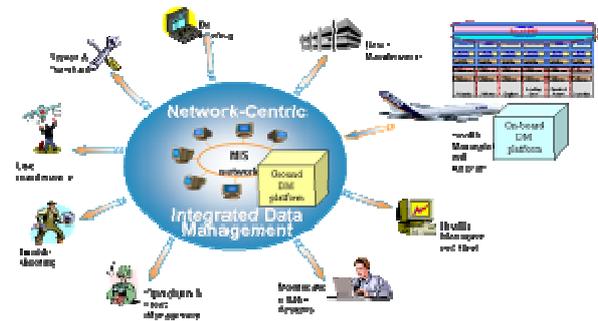


Figure 34: Overview of IVHM

OSA-CBM

The OSA-CBM standard is a layered approach to condition based maintenance, separating steps in data transformation to make them more manageable and data efficient at each level. The transition between each layer is supported through standardised protocols and data models

The primary goal of OSA-CBM is to define a non proprietary standard to reach inter-operability in condition based maintenance.

The OSA-CBM standard has been defined as an implementation of ISO-13374, by the OSA-CBM development group through the Dual Use Science and Technology (DUST) program in 2001. It is now supported by Manufacturers Information Management Open Systems Alliance (MIMOSA) to supplement their other Open Operations & Maintenance standard; Open System Architecture

Maintenance Action	Perform Maintenance Action
PR, Presentation / GUI	Used to display data or system information to user
AG, Advisory Generation	Automated decision making that uses patterns in the signal(s) or feature(s)
PA, Prognostics Assessment	Project future health of the system, taking into account estimates of past and future ops profiles
HA, Health Assessment	Determine current health of system or subcomponents
SD, State Detection	Compare features against expected values, or operational limits and output enumerated conditions
DM, Data Manipulation	Mathematical techniques that help extract the desired information from the energy received by the sensor
DA, Data Acquisition	Measure macrostate parameters (e.g. temperature, pressure, vibration)

for Enterprise Application Integration.

Figure 35 OSA-CBM Layers at a glance

The TATEM project decided to implement the OSA-CBM standard across the Project for simplification of algorithm/application design, integration, and for the evaluation of CBM in an aircraft maintenance management environment.

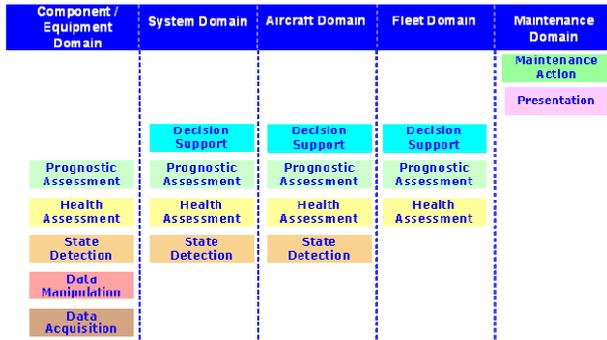


Figure 36: OSA-CBM coverage across TATEM functional domains

Data management platform architecture choices

Infrastructure functional architecture

As not linked to the criticality of Aircraft control, the response time required for health monitoring processing may be longer than in traditional avionics BITE calculators. So although real time processing at the component/equipment end has to occur, the timescales of subsequent processing can be longer. But how does a system deal with this differing of data urgency? Where do the boundaries lie? And what effect does this have on the overall architecture to manage this health data?

Real time processing is almost always required for data acquisition, manipulation or state detection (levels 1 to 3 of OSA-CBM reference model), whilst non real time processing lends itself towards health assessment, prognostics, decision support, presentation and maintenance action (levels 4 to 8 of OSA-CBM reference model) data transformation.

There is a grey area around the State Detection and Health Assessment layers depending on Domain and focus (Aircraft or System view) as to when real time or non real time processing is the most beneficial and efficient. This emphasizes the need for a flexible, adaptable, and configurable architecture to deal with the challenges this decision brings.

The TATEM DMP simulates the IVHM Information System covering primarily the levels 4 to 8 and thus runs nominally a non real-time software environment. This leaves levels 1 to 3 to the ownership of data concentrators; may they be remote, centralised or embedded in equipment specific computing.

However, as the domain data concentrators still need to be managed and there is advantage in merging data strands, a central on-board Information System environment is still of benefit.

Where appropriate, part of the processing can be operated on-board with a subsequent data link between the on-board and the ground elements allowing the transfer of data; be it during the flight or on approach to the gate (not just downloaded post-flight at gate). The transmission of Condition Data pre-landing is one of the tenets of the move from regular preventative (or corrective) maintenance to predictive/pro-active maintenance that CBM makes possible, ie. some maintenance actions may be anticipated on the ground after transmission of data during a flight, thereby minimizing Turn Around Time through preparation. So in order to simulate all the proper maintenance concepts, the DMP has been split in two dedicated platforms, an on-board and an on-ground platform both providing the same middleware and software ecosystem. A sample Air-Ground datalink has been defined to simulate the data transmission and to permit study.

Finally, a middleware providing access to the OSA-CBM implementation and a set of elementary IT services, to cope with a variety of applicative integration constraints, has been developed and installed across both platforms.

Interfaces to Remote Data Concentrators and to the human interface functions have also been designed in with display capacities and simple Ethernet network connectivity.

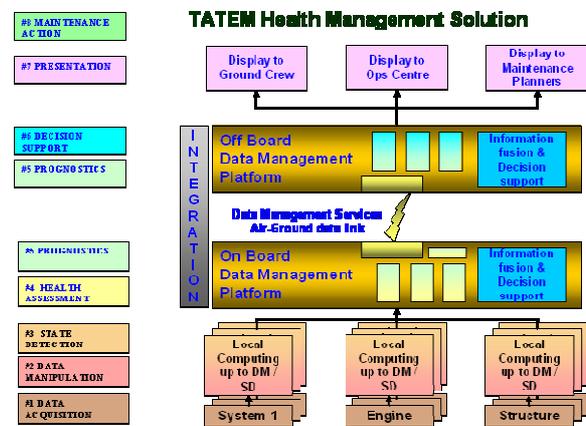


Figure 37: TATEM DMP functional architecture

Physical, network and software architecture

According to the functional objectives described above, the implementation choices have been set toward commercial off the shelf (COTS) components as much as possible and to open source software when appropriate. This allows the Project to capitalise on mature implementations and on widely used standards.

From a hardware point of view, the DMP half is made up of a COTS server unit with a multiple high processing and storage capacity. Each of the

halves (on board & off board) is linked to other parts of the IVHM by an Ethernet switch.

The Air-Ground link is demonstrated by a Wimax (IEEE 802.16) antenna. Wimax has been evaluated as an emerging technology in the Air-Ground link architecture, which has a medium range allowing installation of ground equipment outside of an airport whilst current gatelink solutions require Airport facilities. This would still allow earlier connectivity during the Aircraft approach.

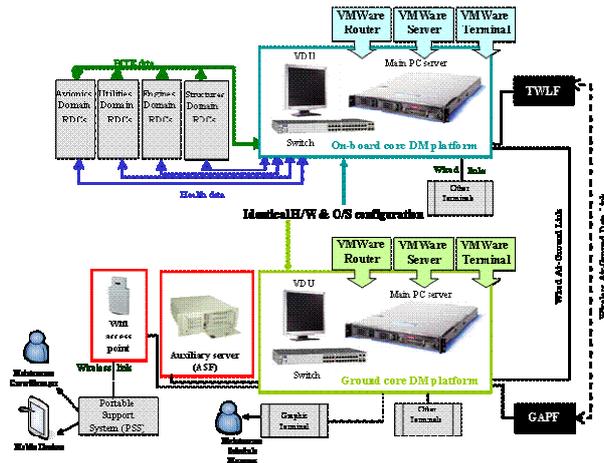


Figure 38 Physical architecture of the Complete DMP and its external IVHM links

From a networking point of view, in order to simulate a real architecture with several networks and peers connected to the data management information system, Virtual LANs have been defined. This allows the virtual segregation of network flows, with a representative IP addressing map and routing scheme. The networking standards maturity allows easy resolution of any interoperability issue.

From a software point of view, the interoperability is another story. Indeed, while network communication protocols are mature, there is no reference standard for software environments and application communications. For the software environment part, end users of the DMP developing the applications required a wide range of software environments. VMware virtualisation solution has been chosen in order to deal with the software environments heterogeneity. This solution allows the emulation, on a single machine, of individual virtual machines that can be linked to each other via virtual networking. In addition, Java has been integrated as a complementary virtualisation solution for applications with a limit on the languages that can be used in this case.

In the end, thanks to these virtualisation technologies, a wide range of programming languages were available on the DMP making it a

flexible environment for further integrations and for OSA-CBM layers implementation.

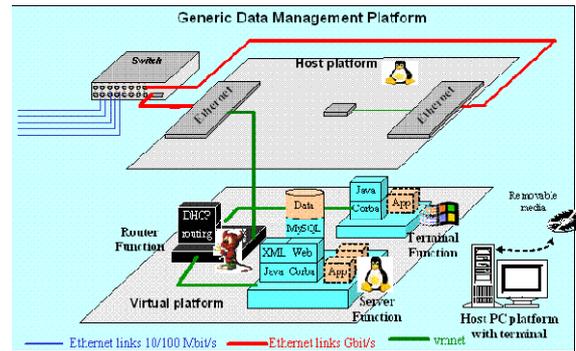


Figure 39 Virtual architecture of the Generic DMP

A set of OSA-CBM compliant communication services were used as a standardised inter-applicative communication means between each OSA-CBM defined layer. Although for common use services such as printing, installing, and database connection, a specific API method was used instead. The initial OSA-CBM implementation was done using CORBA middleware with IOP-based protocols, as at the time of the DMP architecture definition (circa 2005) it was the most advanced publicly available implementation of OSA-CBM in the research community. An XML parser/builder was then integrated on the platform between the CORBA and the CBM Applications to implement the data model for data exchanges between applications. Finally, for external communications out of OSA-CBM scope, to external systems (databases, or the Portable Support System (PSS) applications), or to the human user, the implementation used Web based or Java technologies; the associated services being provided on the platform.

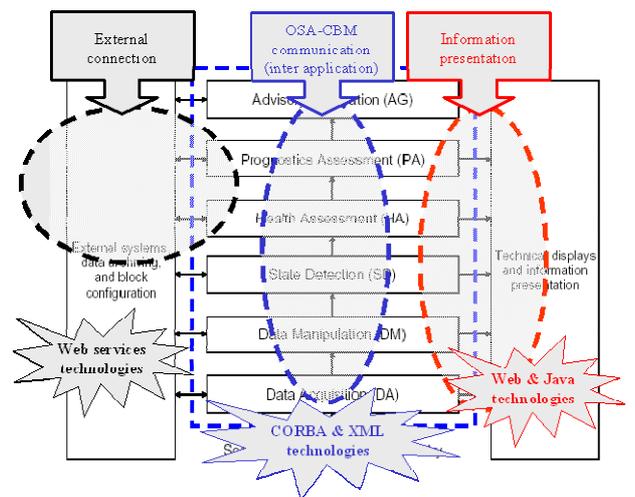


Figure 40: Technology implementation on the DMP

TATEM platform achievements

COTS and Open Source software

First of all, the building and use of the DMP in TATEM has confirmed the added value of COTS and Open Source solutions for avionics information system. Indeed, from the platform perspective, the maturity of these solutions allows to quickly set up an operational IT platform. This time effectiveness is a key issue for the reduced time to markets required as the industry cycles shorten.

In addition, Open Source solutions provide the same evolution flexibility as proprietary solutions, while showing a much higher in-service history in the so-called "open world". This in-service history in the "open-world" implies, from an application developer perspective, well known software environments to all development parties, and thus a universal skillset required for development which is easier to find on the skill marketplace.

The Pentium based architecture also allows ease to deploy the software environment to any third party developer in order to dispatch the integration risk in the development cycle.

Close attention should be given in the years to come to the emerging Open Source hardware components which may bring the same type of advantages.

Virtualisation and performances

Another key lesson learnt out of the TATEM DMP work is how virtualisation technologies help to relieve the integration constraints. It proved of major help in terms of network and software integration. Nevertheless, the performance overhead associated to such additional layers shall be closely taken into account for embedded targets, where the required performance is directly linked to key characteristics for the vehicle (weight, format, cost, consumption). This point also raises the issue of the board/ground processing allocation underlining the fact that no clear criteria is available for such an allocation and that it is closely related to the effectiveness of the board/ground datalink.

It shall indeed be kept in mind that a trade off between board and ground allocation for information system capacities bringing added value to the vehicle operations should be done systematically.

Standardisation and OSA-CBM

Standardisation is obviously of huge help in dealing with interoperability issues. It has been proven with the DMP at network level, relying on internet community mature standards. The

objective of OSA-CBM, aiming at the same level in interoperability at the application level is thus very relevant.

The CORBA implementation of the OSA-CBM principle for inter-application exchanges has nevertheless shown some limitations. Indeed, the lack of maturity in the implementation of this new standard and the lack of appropriation of a reference implementation has made it difficult to federate the applications in using this communication service.

Defining inter-applicative communications schemes in a multi-party information system is a difficult issue where no standard yet has taken the lead.

Considering the success of web technologies in the internet community, an OSA-CBM implementation with such technologies would probably have been easier to disseminate. The effort done in information systems urbanism with service oriented architectures (SOA) and associated standards could be mapped to OSA-CBM principles in later developments.

Finally, the data model side of OSA-CBM has not been well explored in the DMP. Nevertheless, using self explanatory XML technologies to describe data sets, which in turn are based on standardised data models, is a key step towards interoperability. It should be assessed whether OSA-CBM provides appropriate data models to federate all maintenance actors.

Platform Integration to the rest of Project

Two stages of Integration

The development and evaluation of the DMP was the first step in the Project to testing the platform's capabilities. The adoption of the OSA-CBM standard across the project was a parallel overarching design decision (where it was possible to apply it), and this helped define the framework of the DMP architecture towards a possible IVHM configuration as described in the earlier sections. This subsequently led to the design decisions in implementing such an IT platform.

Elements of service robustness and network resiliency of the Platform were tested at a local level, but the overall aim was to actually implement the DMP in a more realistic Health Management simulation. To this end, two stages of Integration were planned.

The first stage of Integration looked at hosting the on-ground applications. These collect aircraft health and condition from the sub-system and below quantifications, can process this in non-real time, and can then calculate and recommend

future use of the aircraft in a fleet management perspective.

This work collected representative samples of the algorithm and application development being done and hosted it on the combined (off-board) DMP environment. This would then trial the use of the upper layers of OSA-CBM and the associated middleware on representative hardware.

The interface links to “real” data coming from on-board are still present, as are the interfaces off the system; be it the appropriate Operator User Interface (Presentation layer), or to trigger the improvements/enhancements to the Maintenance Action process that TATEM was also investigating.

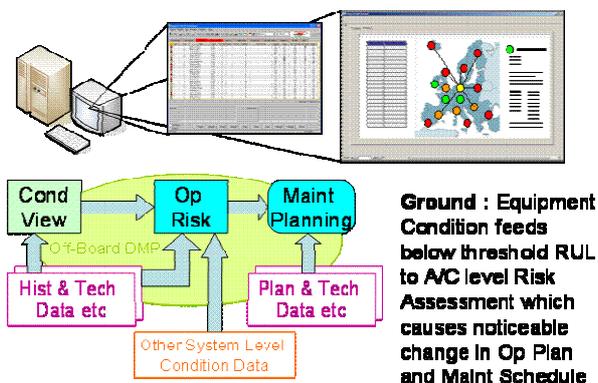


Figure 41: Example of applications hosted on Ground based integration

Although the front end of the new processes involved in the Maintenance Activities (ie. use of the Maintainers’ Portable Service System (PSS)) is a separate entity, much of the information required to drive it would be hosted within the DMP architecture (primarily hosted on the Windows O/S Auxiliary Server Function (ASF)8). Therefore this interaction was also be tested and evaluated during the culmination of the development of these new techniques and technologies.

The second stage of Integration included the use of the on-board DMP to demonstrate various types of End-to-End data flow and to demonstrate the first ‘complete’ picture. This is known as ‘Vertical Integration’.

Investigations into component/equipment/system level health; be it improvements in existing state detection, data analysis, or writing new applications to aid in prognosis of life, have been done on local lab machines; a practical research substitute for Remote Data Concentrators (RDC) or Remote Interface Units (RIU). By meeting the OSA-CBM design standard, it is possible to expand the running of the health monitoring applications across the RDCs and onto the central on-board DMP. This will not have been done in the local evaluations of the equipment.

The Vertical Integration demonstrates data coming in at the low levels, onto the on-board DMP for processing, and ultimately further onto the ground DMP.

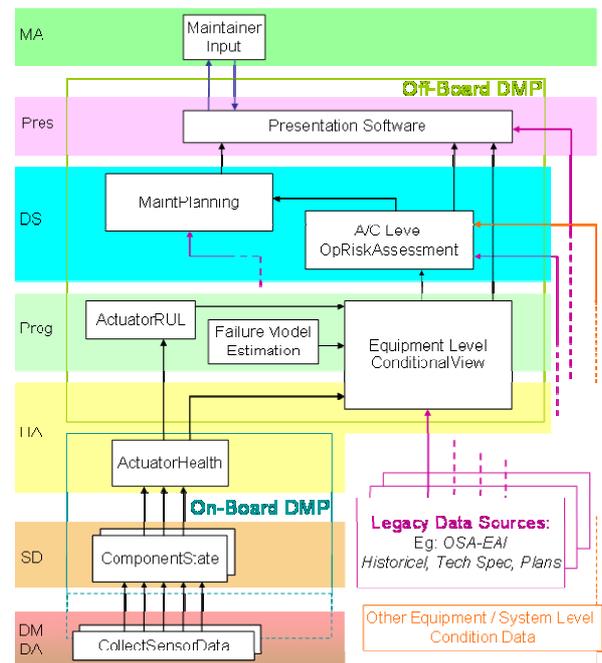


Figure 42: Example of applications hosted within a Vertical Integration functional Use Case

The effect of Horizontal Integration is also tested in this second stage of Integration using the DMP environment. ‘Horizontal Integration’ is the merging on data from parallel streams; generic data fusion is an example of the principle.

It is just another way to show the benefits of a modularised approach in building a flexible IVHM framework.

The second stage of Integration also looks at proving the robustness of the decisions made for adopting the OSA-CBM design standard. This was summarised as a set of ‘Integration Functions’ or concepts, of which ‘Vertical’ and ‘Horizontal’ Integration was also included. This list includes:

- Vertical Integration
- Horizontal Integration
- Architecture Robustness
- Architecture Flexibility
- Platform Independence
- Removable Media and Data Storage Compatibility
- Emergent Property Capture

These concepts were derived from Requirements Analysis techniques applied to the original Project TLRs and subsequently to the Level 1 Integration Requirements derived from them.

The encapsulation of these concepts in an IVHM perspective has not been done previously to such a scale on other Projects, nor internally within the

local evaluations elsewhere within TATEM. Therefore, this will be the opportunity to System Test the combined DMP, middleware implementation, and CBM applications as a working apparatus.

Middleware differences in Integration

Given the difficulties discovered in federating a CORBA based implementation of the middleware, the Integration task investigated further the use of Web based technologies utilising XML data structures to describe the OSA-CBM data sets being passed between applications (& layers).

A methodology was decided that to abstract the user from the complexities of client / server, XML formatting and parsing, etc., that the middleware developers created separate libraries to keep the standard OSA-CBM code separate from the specific implementation. The OSA-CBM library knows of only OSA-CBM types and calling conventions, whereas the other library is a wrapper library that uses the OSA-CBM library and adds support for networking and XML parsing. It is this wrapper that provides the user with simple calls to setup the library to work with the algorithms that have been written.

The wrapper library handles all the networking and XML parsing, whilst the user application will only communicate using OSA-CBM types. To make the networking/XML transparent to the user, it is necessary to use a 'Proxy Layer'. This proxy layer acts as another OSA-CBM layer to the calling application, ie. it mimics the destination. The proxy then converts the request into an XML message and sends it across the network to the real destination layer. At the other end, the wrapper decodes the XML and recreates the OSA-CBM types to be passed to the algorithm.

To make the system distributable, each user application references its request destination(s) by name. This name is checked against a configuration file that provides an IP address and a UDP/TCP port number of where the destination algorithm is running. This means that it is easy to quickly move different algorithm applications to different locations (e.g. off-board to on-board).

Admittedly, the use of a configuration file to hold topography data isn't scalable for a commercial product, and different Web-based methodologies could be adapted for tracking destination locations, it is nevertheless a neat and controllable mechanism for this scale of Integration Test Bed.

Limitations of CBM on the Project

The application of OSA-CBM across the design is not perfect. Certain elements within the TATEM Project's focus were just not practical to adopt it,

eg. Avionics modelling, or the PSS applications interactions. In reality the scope of TATEM was too large to contain just the use of OSA-CBM on improvements to Maintenance Management.

The Project also adopted the use of OSA-CBM when it was at v1.2 in 2005. Now the standard is at v3.1L and has been refined as it has matured. In fact, the experience in using the standard on TATEM has helped with this refinement as the project members have reported back to the Standards Working Group. One example of differences is that in v1.2 the higher layers (Decision Support & Presentation) were light in content in terms of defined data types.

The shortfalls in Decision Support layer data types have been subsequently further developed in the time between standards being issued, and additional questions asked about interactions beyond this layer have also led to the closer tie-in to elements of the OSA-EAI (Enterprise Application Integration) standard where cross-over of functions and required data become useful.

However, to aid application developers, the choice of version had to be fixed. Therefore it was fixed at v1.2 early on in the project lifecycle to enable algorithm developers to become familiar with the interfaces per layer before writing their code. It was quickly identified however, that new skills and knowledge would be needed, beyond the normal code writing skills to master this work style.

Version 1.2 does also suffer from being only a Client-Server communication service structure. This is fine for the higher levels; however two shortfalls were identified with this implementation:

- 1) What happens when the aircraft is in flight ie. there is a longer interval break in communications than a few milliseconds of a lost request message?
- 2) It really isn't practical to have a 'Pull Only' Request at the Data Acquisition layer. It is a lot more realistic (& practical) that a Push mechanism is in place at the monitoring level that generates the raw sensor data.

The Project ended up making a compromise during a design review to allow data to be 'Pushed' up from the sensor onto the RDC/RIU, but this isn't really conforming to the standard as was the original overall desire. The v3.1L standard however does allow other types of communication process within itself and gives guidelines on implementing 'Push' and 'Subscription' style actions.

Additional applications had to be written to fill the gaps in the communications flow where the Client-

Server logic did not work. But this would still have had to be done regardless of the version type.

The Operational Impact to the Maintainer

The overall objective of the project is to provide the means by which operators can reduce the maintenance element of their Direct Operating Costs (DOC) by 20% in the 5-10 year period and by 50% in the 10-15 year period. . The skills of the personnel and their equipment and tools, including planning tools, form a very significant part of the overall maintenance infrastructure. If costs are to be reduced, personnel must be able to work in the most efficient manner possible. This paper focuses on two aspects which are significant for achieving this goal:

The means to improve all ground crew activities related to maintenance, such as planning, procedures and technologies used, as well how humans interact in the maintenance environment and how the interaction should be taken into consideration. Improved Diagnostics and Prognostics are seen to be key performance indicators for improving ground crew support.

The investigations for both aspects have related to real working environments so that for human factors, workshops have taken place with a Maintenance Repair and Overhaul (MRO) company, while ground crew technologies were not evaluated exclusively in laboratory environments.

Ground Crew Support

The ground crew support work package has evaluated those technologies and techniques which can be used to reduce the time to perform maintenance tasks (inspections, installations and removals, repairs and trouble shooting), to support the deployment of condition based maintenance and to reduce the occurrence of human error in undertaking maintenance tasks. To achieve the objectives the activities in research have focused on the following key themes:

- The transition of maintenance activity from the current system-oriented approach to a process-oriented approach: This will necessitate delivering data, information and decision support, at each point in the maintenance action, through novel human-machine interface technologies.
- The application of proactive maintenance processes. Reliable proactive maintenance is a key issue for the development of new maintenance scenarios. Therefore the ground crew support work package has studied how the condition data and in-service experience provided by the diagnostic and prognostic technologies, or other existing sources, can be

used to develop reliable prognostic models to allow predictive maintenance planning or condition based maintenance.

- With the introduction of new maintenance concepts it becomes necessary to develop new training programmes. The project has therefore studied the applications that will enable maintenance operators to train in the use of the process-oriented maintenance approach.

The research activities have been grouped into the following main areas:

- Technical Data
- Process oriented maintenance
- Embedded Training
- Proactive maintenance
- Local Integration

Technical Data

With recent developments in IT technologies, Aircraft Maintenance Documentation has now been digitalized. However, its organization is still inherited from the paper format: the transition from a 'document oriented' philosophy (in which the documentation is organized in monolithic manuals) towards a dynamic 'process-oriented' approach (in which the requested contents are properly processed to be provided for the process at hand) remains to be fully achieved.

Thus, to reach this goal, data structures and formats better aligned with the customer business processes needed to be developed.

In order to develop this new data structure and formats, a conceptual data model was first established – called the "Process-oriented Data Map". It focuses on the "Maintained Object", to which information regarding physical description, configuration, maintenance triggers, and maintenance actions are related.

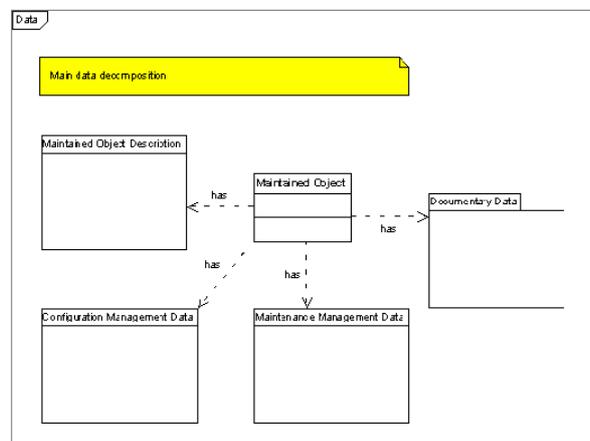


Figure 43: Data Map

This Data Map was then "translated" into a practical XML Data Structure for actual implementation – the Data Structure contains all the data identified in the Data Map, and is the specification for the final Data Samples to be produced for testing purposes in TATEM (covering one fault isolation procedure and the subsequent repair, of a Brake Unit).

In order to reach the process-orientation objective, this Data Structure contains a much higher level of information than current technical documentation. A specific software application, called the "Process-Oriented Information Application" (POI), has thus been developed to process this richer TATEM technical data.

From the user's interface point of view, Process Orientation means to be able access information needed at a certain process step to perform a specific task.

For TATEM the concept as shown in Figure 44 has been chosen.

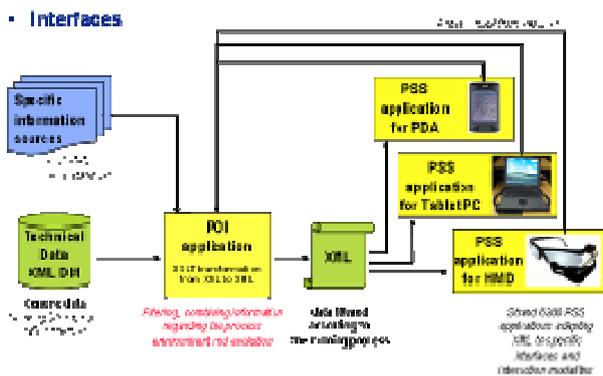


Figure 44 TATEM Concept of Process oriented Maintenance Support

The concept consists of the following three components:

- The Technical Data including Multimedia
- The Process Oriented Interface Application (POI)
- The Human Machine Interface (HMI)

The POI application basic functions are:

- Information filtering regarding applicability (data only applies to actual A/C MSN, SB, defaulting part)
- Information filtering regarding actual process (tasks already performed, status reached)
- Information filtering regarding available consumables
- Information fusion (tools, warnings...)

- Information provision (packaging and delivery of the "next" data set from a Decision Point perspective)

The source information is embedded in the XML files of the S1000D standard Data Modules, which have been adapted for TATEM. The filtering function optimises the end user presented data. For other filtering information, external files have been designed to simulate databases needed to perform some of the filtering activities.

Regarding the Multimedia aspects, an initial selection was first made, which was then narrowed down to the most promising technologies. This was followed by detailed analysis, with testing of currently available production software and evaluation of their maturity for the TATEM purpose, and benchmarks to evaluate their respective technological performance. This has allowed both the final formats to be select for implementation in TATEM, and for the proper tools to be selected. The finally selected formats are:

- 3D: X3D (ISO/IEC 19775)
- Line Art: WebCGM (ISO/IEC 8632)
- Photographs: JPEG2000 (ISO/IEC IS 10918)
- Video: MPEG4-10, also known as H264 (ISO/IEC 14496-10)
- Audio: MP3 (ISO 11172)

The final multimedia samples are being authored, and are used with the source XML files, in the same use case tests.

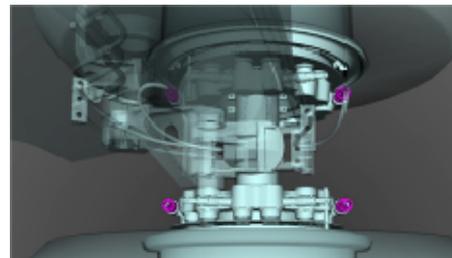


Figure 45 Example of Multimedia Content

Process oriented Maintenance

The scope of research has been focused on providing human machine interface technologies, which enable process-oriented applications to be used in different maintenance scenarios, as well as to specify a process-oriented human machine interface for implementation based on the selected technologies. The objective was to evaluate human machine interface technologies, which can be used to provide process-oriented information to the operator at the point of operation. The tasks to be undertaken to achieve this are:

- Identify the maintenance process interface to each of the principal maintenance applications

(Inspections, Installations and Removals, Repairs Trouble Shooting, Retrofit Modifications).

- Specify the hard and software integration requirements for the Portable Support System (PSS)
- Specify the functional and the HMI requirements for the Portable Support System
- Evaluate the selected HMI technologies
- Specify the requirements for the human machine interface technologies to meet these needs.
- Adapt the OSA-CBM architecture for the various PSS components
- Specify and provide the required applications to support process oriented maintenance execution.

A Basic Set and an Enhanced of technologies has been considered. Of the Basic Set, the following technologies have been selected for demonstration:

- Tablet PC or a Laptop/Notebook PC
- Wearable Computer (option 2)
- PDA/Hand Held PC (option 1)
- Pocket Sized Display (as part of the PDA – option 1)
- Notebook Sized Display (as part of the Laptop/Tablet),
- Touch Screen and Stylus (as part of the Laptop/Tablet or PDA)
- Keyboard (as part of the Laptop/Tablet)
- Mouse (including Scroll Wheel)
- Touchpad (as part of the Laptop/Tablet)
- Wireless Data Transfer
- Data Exchange Standard
- Multi-Platform Data Conversion
- Online Electronic Documentation
- Electronic Signatures
- Data Encryption and Security

Of the Enhanced Set the following technologies have been selected for demonstration:

- Head Mounted Display
- Digital (Video) Camera
- Speech Recognition System
- Microphone
- Speech Synthesis System
- Headphones

The operational context of the PSS with adjacent TATEM elements is presented in the next figure:

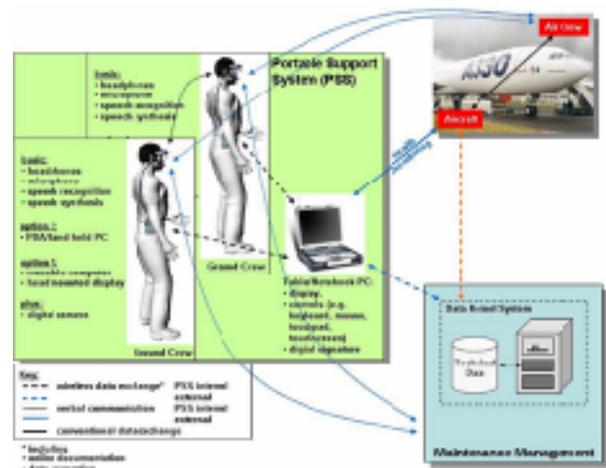


Figure 46 Operational Context of the PSS

The PSS is intended to work as follows: The tablet/notebook PC serves as the core of the PSS. It is intended to provide the data link to the maintenance management system, transmit and receive technical data and planning/organisational information to/from the data kernel. For cases where the data link is interrupted the tablet/notebook PC holds the information necessary for the maintenance crew to continue their work. The tablet/notebook PC also provides a wired interface to the aircraft health monitoring system, in order to access maintenance relevant aircraft data. The PC is carried by one of the technicians to the aircraft. It is placed in a position where it can be connected to the aircraft interface and from where wireless data exchange with the (two or more) members of the ground crew is possible. It is not envisaged that the PC is constantly carried by a person throughout a work shift. The PC also is intended to be used by the technicians if they need to examine information which cannot be adequately viewed on the displays they carry (the PDA and the HMD). Moreover it is designed to be used to fill electronic forms and to confirm the input by a digital signature. Another function of the PC is data encryption.

The truly portable equipment carried by the technicians consists of two variants:

- a) a PDA or hand held PC, and
- b) a wearable computer together with a head mounted display.

Both variants are supplemented by headphones and a microphone. Via these interfaces it is not only possible to communicate with people in remote areas of the maintenance system (e.g. the MCC – Maintenance Coordination Centre) but it is also possible to operate the PSS via voice and receive audible feedback and or additional (non-visual) information from the system. This feature

allows hands-free operation when required by the task. The PDA variant can also be operated manually using a stylus or the fingertip. The portable part of the PSS is not very well suited to input large amount of data. This should be possible via the PC which includes a conventional keyboard. The PSS is completed by a digital camera, which allows the ground crew to take pictures (still or moving) and sound, and load them into the PC for analysis or documentation purposes.

The PSS is intended to be used as a modular kit providing the technician with the flexibility he needs to perform his task in the most effective manner.

The functional description shows how the PSS works from the user's point of view. It describes the features, the menus, dialogues and the information displayed on the screens of the PSS elements in a generic manner.

The technical specification describes the PSS hardware in detail and also the "common look and feel" of the PSS elements, thus providing a guideline for the implementation of the above functions on the selected hardware.

Functional Description

The method which was used for the definition of the PSS functions is based on the "function analysis" process described by the standards NF EN ISO 21351:2005 "Functional and technical specifications" and NF EN 12973:2000 "value management".

For the analysis of the PSS functions a template was created to capture the following main parameters:

- ID identifies the function by a single and unique identifier
- Function name describes the function using a short and direct sentence
- Criteria describes the properties of the function in quantifiable terms
- Level identifies the constraining value applicable to the criteria, taking into account the user needs
- Flexibility is defined by the "flexibility class" and the "importance".

In order to achieve an efficient functional description of the Portable Support System, the main boundaries and the interfaces to adjacent systems had to be defined. The PSS is composed of several functions used by a team of maintenance technicians.

Moreover, the PSS is included in a higher order management and general maintenance solution, called the Process Oriented Maintenance Application (POMA), that also manages other PSSs. The following picture shows an architecture example. Five teams of technicians are working on two aircraft "A" and "B" (3 teams on "A" and 2 teams on "B"). The teams are independent from each other and each team has its own PSS. Communication between PSSs is normally not required. If yes, it will go via the Data Management Platform.

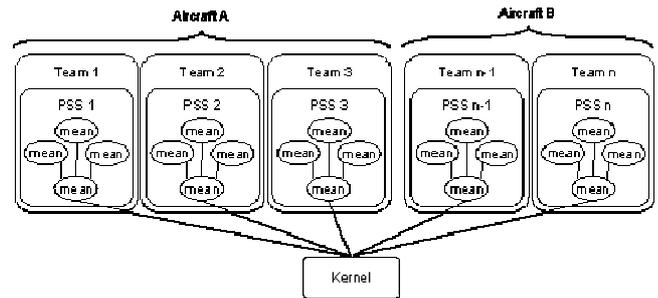


Figure 47/ PSS – DMP Kernel Architecture

The PSS Functions apply to several main and additional scenarios:

- Main scenario: "start the day job"
- Main scenario: "work appropriation"
- Main scenario: "task to carry out"
- Main scenario: "end of day job"
- Additional scenario: "analyse unusual situation"
- Additional scenario: "gather information"
- Additional scenario: "communicate"
- Additional scenario: "report".

The analysis of each scenario is structured as follows:

- Aims and Description: A textual description of the scenario is provided in sufficient detail to understand the necessary functions, within the context of aircraft maintenance
- UML Use Case Diagram A textual and graphical analysis of the interrelations between the various activities and the stake holders of the scenario is also provided
- Functional Analysis describes in detail the individual functions of the scenario and the elements of the scenario responsible for the performance of the functions.

Technical Implementation

The technical implementation represents the translation of the functional requirements into technical and concrete terms.

The PSS application has integrated Open Source technologies wherever possible to interpret and visualise the XML which is used to integrate the PSS and Data Management Platform. The

selected open source technologies also had to be capable of running on the wide range of selected devices which have different capabilities and functionality. For example, a Pocket PC device is only capable of running a slim down version of the Windows OS (Windows Mobile) which has limited features. Selected open technologies include NanoXML for parsing of the maintenance process representation and the Light-Weight Visual Components Library for provision of a highly interactive GUI not normally available on low powered mobile devices.

In addition other technologies have been selected, in particular Wireless LAN. One area of concern is the selected WLAN (Wi-Fi) performance. The use of multi-media technologies is at its most critical when high integrity and high Quality of Service data transfers are required. It is this combination, which needs to be investigated under realistic conditions. Therefore it was decided to carry out preliminary investigations before the formal tests are carried out. As planning proceeds and preliminary investigations demonstrate the realities of using the technologies, the Use Case tests will be refined for the formal tests. Some embedded training activities will be carried out in a similar fashion using similar equipment. Thus it will be tested how a maintainer can effectively carry out process oriented maintenance, using electronic documents such as diagrams and schematics, and also how the maintainer can train or prepare for such activities using such multi-media facilities like video. If necessary alternative WLAN technologies may be considered such as Wi-MAX

Embedded Training

The Embedded Training application supports a user in checking and learning the applicable process for maintenance work, that requires the operators to follow strict procedures. The Embedded Training system consists of a UMPC or PDA device and a Head Mounted Display (HMD), which support the maintenance process while allowing personnel to stay in their normal operating environment. The personnel can practice tasks by interacting with a computer-based virtual model of the target maintained object. The personnel will be able to inject commands, using speech recognition features. The user is allowed to operate and practice tasks regardless of the environment, either natural – the real object - or Virtual – a 3D mock-up, and to put the information/data belonging to the maintenance process delivered by the training application on top of the maintained object using the see-through HMD.

The activities have been focused on the design of the Embedded Training System and to start its implementation through the integration of the selected hardware component, the realization of

the designed software items and the adaptation of the virtual model for the reference maintained object, that is the “landing gear assembly”.

The software items were integrated in order to build a framework supporting the process oriented maintenance execution as an on-site training tool for ‘Mobile Maintenance’ tasks. The system design has been derived from Embedded Training requirements specified in a associated document.

Since this “Training Tool” allows the technicians to practice with their standard ‘Mobile Maintenance’ Portable Support Systems’ (PSS), the development of the embedded training also took the PSS requirements into account (common feel and look).

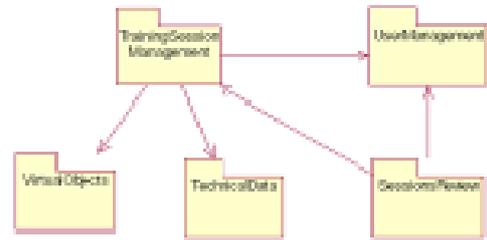
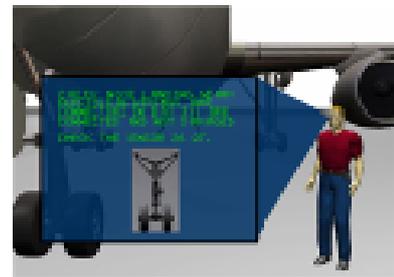


Figure 48/ Embedded Training Design

Proactive Maintenance

Condition_View

Whereas reliability data, trend parameters and physical models are the basis for current health assessment of an aircraft component, prognosis based solely on these parameters may be too imprecise, and any additional source of information that may be used would be very welcome. Uncertainty related to health assessment models increases rapidly as remaining useful life (RUL) estimation is projected into the future, and may offer few benefits over standard, conservative ‘preventive maintenance’.

Given this, the provision of additional data to narrow uncertainty bounds needs to be considered. First, an operational plan may have some influence on the input parameters of a degradation model, if based on physical analysis

and/or trend information. Second, aircraft and fleet related field experience may prove very valuable to improve RUL estimation for any model. A Conditional View module is then responsible for retrieving current component status estimation, and translating this into a bounded estimation of future degradation that may be a valuable part of the operational reliability assessment, following step in the prognostics process. This module should also permit the adaptation of RUL models as real feedback is available to assess previous estimations.

Within TATEM, two different models for conditional view estimation have been deployed, corresponding to different sources of information available.

The first one is based on existing physical degradation models. These models offer an estimation of the degradation process (i.e. degradation of the brake wear) with respect to A/C flight data, such as A/C weight, A/C velocity at landing, etc). However, it is difficult to forecast degradation from these input data, unless there is a (causal) relationship that relates certain model input data (i.e. weight, velocity, use of brakes) to certain characteristics of the operational plan (runway conditions, flight length..). Given this, a Bayesian Networks (BN) model has been developed to forecast the degradation process. This type of network has been chosen due to its remarkable characteristics for integrating expert knowledge as well as feedback data. If no operational plan is available, this model mimics the physical model with respect to health status estimation. However, if operational plan information is known, the operational characteristics serve to forecast the degradation process in a more accurate manner. The model finally provides an 'uncertain' estimation that corresponds to the level of information available.

The second model has also been deployed, when there is no degradation process, but the only information available corresponds to probability of failure (reliability). This model is based on the component lifetime analysis using a Weibull distribution; the most widely used for this type of analysis, due to its flexibility of fitting real failure distributions. In this case this is important, as we expect to re-assess and improve the reliability distribution with feedback information. In operation, an initial assumption of exponential distribution is made (usual for electronic components). When new data is available the current failure distribution can change and the algorithm re-computes the Weibull function characteristics. In order to achieve this task, the model uses Goodness of Fit test (chi-squared test) to check if new data is a good fit with the current distribution. In case of being true, the model re-computes confidence levels, otherwise it

re-computes the whole model (confidence levels plus distribution's parameters).

This methodology has been applied to different use cases, such as brake wear and avionics..



Figure 49: Different conditional view estimation models have been deployed depending on the type of information available

Operational Risk Assessment

The operational risk assessment, in the scope of aircraft operational support, calculates a set of discrete probabilities of operational interruptions and their estimated costs for a given operational plan for an aircraft, as input for economic decision-support.

Concept

Operational risk in the context of this paper is seen as the risk of an unscheduled maintenance occurrence during the operation of an aircraft. Such incidences disrupt the itinerary of the aircraft.

The operational risk assessment in this context describes the calculation of probabilities of operational interruptions caused by unscheduled maintenance events and the estimation of costs caused by them (based on specific cost functions of the point of occurrence - these points being the bases within the flight network where operational schedules can be interrupted).

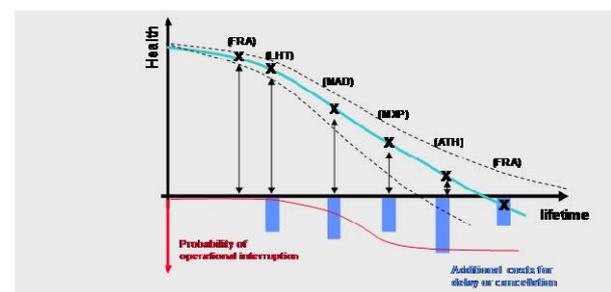


Figure 50: Operational risk assessment principle

Root causes of operational interruptions are, non-deferrable maintenance actions, which prevent the aircraft dispatch in time. An aircraft loses its dispatch ability, if mandatory components listed in the MEL are out of specified function. The fundamental concept therefore is the modelling of the aircraft as a set of "managed" components with individual failure (behaviour) models and structural interdependencies representing the MEL

constraints for aircraft dispatch ability. The failure of one component does not necessarily cause an operational disruption, if redundancy is implemented.

The process of operational risk assessment starts with the estimation of the “survival rate” for each “managed” component as well as the complete aircraft for an operational plan. The operational plan is defined as a sequence of flight segments, the itinerary. The “survival rate” for each flight segment indicates the probability of operational disruption.

The capabilities of each base along the itinerary can be different with respect to repair resources (e.g. availability of spares and maintenance personal), repair time and costs. So the risk of delays or cancellations and costs will vary. The second step of operational risk assessment is the calculation of the probability for delays or cancellations and of related costs for each base along the itinerary.

Theoretical Background

The estimation of “managed” components and aircraft level “survival rate” uses an implementation of the Maintenance Free Operating Period (MFOP) approach. It allows the reliability assessment of complex technical systems by calculation of the survival probability for a discrete time period with regard to a given level of risk for the availability of the technical system. In addition, the MFOP approach considers the structural interdependencies of complex systems. The resulting MFOPS (Maintenance Free Operating Period Survivability) parameter describes the probability of survival operational cycle and defines the lapse of time the system will be able to perform its function accordingly.

The second step of operational risk assessment deals with the calculation of the probability of possible occurrences as well as their resultant costs. Using these probabilistic parameters and the components and aircraft MFOPS along the itinerary, the calculation model (implementation as a Monte Carlo simulation) estimates the probability of occurrences and the related expected costs.

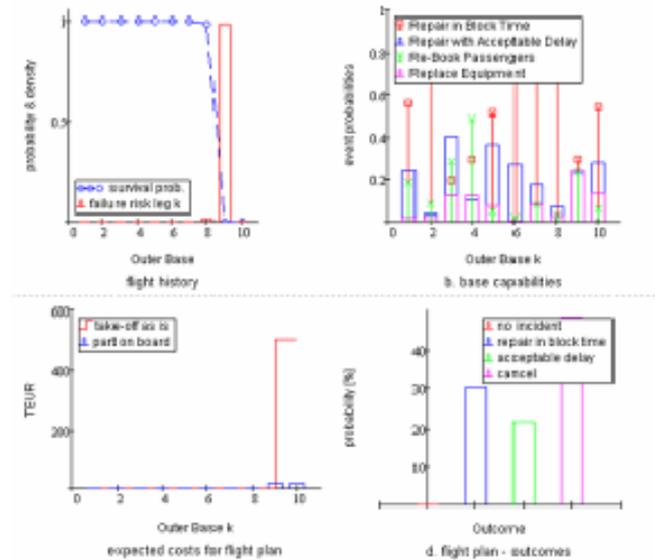


Figure 51: ORA calculation example

The above figure shows the results of calculating the operational risk for an itinerary with 10 flight segments. The upper left chart contains the survival rate / probability of failure for the “managed” component (or aircraft) on each outer base for the given itinerary. These parameters are provided from the MFOP model. The upper right chart describes the probability of delays or cancellations as a result of the defined base repair capabilities. Finally the expected costs and occurrences are shown in the bottom charts. In this example, an unscheduled event is expected at the end of the itinerary. Due to the low base capabilities the probability of a cancellation is high.

Implementation

The described operational risk assessment functions have been implemented in a laboratory prototype for further evaluation. The prototype evaluation includes:

- Evaluation of the specified operational risk assessment functions and their algorithms
- Integration into OSA-CBM architecture and proof of concept for operational risk assessment and decision support for operation

The prototype is based on technologies for the remaining lifetime estimation and determination of the conditional view. The modelling of the operational risk uses component failure and probabilistic cost information and MFOP models and technologies for decision support using multi-criteria decision-making, utility theory and simulation.

Economic decision support

The economic decision support module provides a short term planning methodology of line

maintenance activities, in the airports, during Turn Around Time (TAT). The proposed methodology supports decision making for deferring maintenance actions that affect the dispatch of the aircraft, aiming at high fleet operability and low maintenance cost. Based on health assessment information as well as on any additional information on operational and economical constraints, at the operators' fleet level, a multi criteria mechanism evaluates whether maintenance actions should be executed in the current airport or in successive ones.

The proposed approach includes the use of an Artificial Intelligence framework, taking advantage of concepts and techniques originating from the multi-criteria decision making, utility theory and simulation, in order to produce and assess different maintenance plans

The following steps are followed at each decision point, when an allocation decision should be made for the aircraft's maintenance tasks

- Identify required maintenance tasks
- Determine decision criteria and weights for evaluating alternatives
- Form alternatives
- Determine the consequences of the different alternatives and their utility

Four criteria have been identified as being suitable for the evaluation process of the alternatives: Cost, operational risk, flight delay and Remaining Useful Life - RUL. For each criterion, a parameterised function is identified in order for the performance to be calculated. Costs related to aircraft maintenance encompass a number of different factors which can be classified. A "technoeconomical" model is used, for modelling the impact of the maintenance attributes on the cost of aircraft maintenance. The RUL function models the utilisation of the expected remaining useful life for a component/subsystem. Modelling the Operational Risk (OR), the expected gain of a maintenance task allocation regarding the operational risk could be a measure of the cost of the scheduled and unscheduled events of the respective allocation, weighted by the probability of failure and aircraft operational reliability. A probability for a delay measure is used to assess alternative performance in terms of A/C delay due to maintenance action. This criterion assesses the performance of the airport to respond efficiently to a maintenance request.

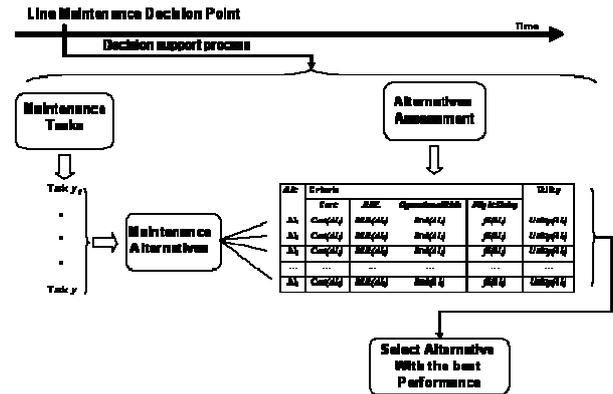


Figure 52 Maintenance alternatives generation and evaluation

Based on the list of tasks for which a decision should be made, a set of feasible alternatives are identified. The possible execution of each alternative results in different economical and operational risk consequences. The alternatives are simulated and their performance against each criterion is estimated in the form of a decision matrix. The alternative with the best utility is the one eventually proposed by the system

Local Integration

The objectives of Local Integration in the context of Ground Crew Support are:

- To validate the maturity of functions and technologies which supports process oriented maintenance and maintenance planning.
- To validate the technology integration capability to support an "end to end" information service provision.
- To verify that the Ground Crew functional requirements related to pro-active maintenance planning and process oriented maintenance are met.

The validation will be done through selected Use Cases which are:

- Use Case #1: Process Oriented removal and re-installation of Brake Unit
- Use Case #2: ILUC#2 Operational Risk Assessment (the advisory that has been generated is related to the condition determined by a combination of actuator, fuel pump and brake wear),
- Use Case #3 Usage Based Maintenance Planning (maintenance planning based on overall health status data).

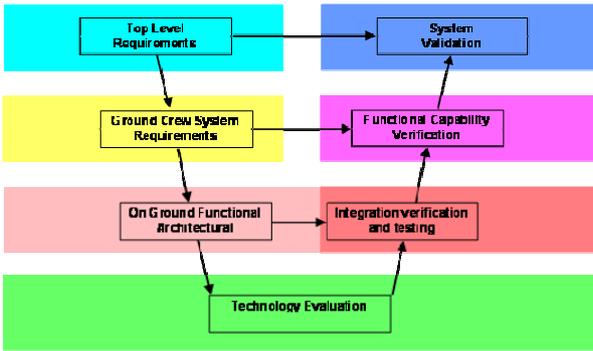


Figure 53 Validation Cycle

Use Case #1: Process Oriented removal and re-installation of Brake Unit

LIUC1 is an example of Vertical Integration and includes the validation of the PSS functionalities by using the approach shown in Figure 54.

The left side of the figure 12 shows the generic functional analysis. The result of this analysis is a set of functional specifications that define the PSS in general. The right side of the figure presents the storyboard specific functional analysis which will form the basis for the PSS prototype. This prototype will demonstrate how the selected HMI technologies can support the functions defined in the storyboard. This double description of the PSS characteristics is necessary due to differences between the "ideal" PSS solution and the "real" prototype which has been developed within the scope of TATEM. Due to the fact that the storyboard covers only a very small sector of aircraft maintenance situations and that it only focuses on the true maintenance functions the more general functionality of the PSS must be obtained by generic analysis.

The first step of the process consists of a use case analysis. It consists of these three different actions:

1. Draw the overall PSS use case diagram including initialisation. We only consider how the main system will interact with actors outside the system boundary.
2. Consider the main functional steps that the PSS must perform in order to make the use case happen.
3. Consider the type of data that is saved or passed around the system. We determine the type of data that each functional area deals with, or the parts of data that those functional areas have access to.

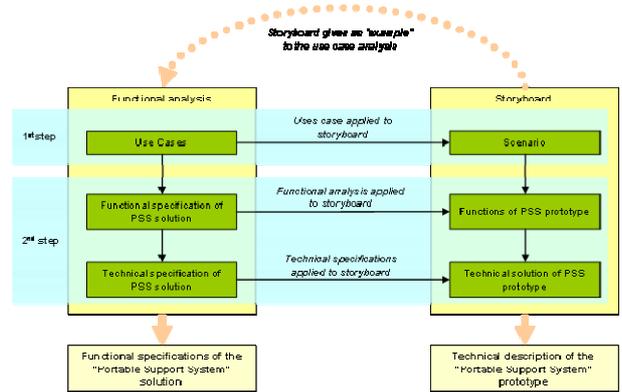


Figure 54 Approach Consolidation

The second step is split into two main parts. The first part consists of analysing the system and subsystems according to their functionalities identified in the first step, in order to describe the functional and the technical specification of the PSS. These functionalities, illustrated by the use case, could be translated as user related functions or product related functions describing the major and alternative items of the solution. The analysis of the system aims to specify (i.e. to describe) all the functions. This specification includes a description of each function, a presentation of their technical requirements (the criteria), their performance level and their flexibility. The second part corresponds to the translation of the functional specifications into technical requirements for each function of the PSS. This technical specification describes the allocation of technical solutions to functions. In fact, it describes how the functions specified are implemented. Therefore, the technical specification shows the selected solution (a technical part of a system or a subsystem) that will ensure a function.

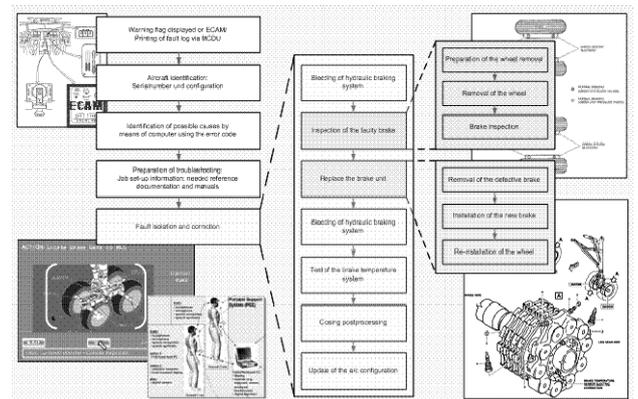


Figure 55: Use Case / Storyboard.

The maintenance action can be tried out using the embedded training facilities.

Results

PSS has been developed and deployed using a variety of mobile technologies. Functionality supported in the developed PSS system includes:

TATEM: Technologies & Techniques for New Maintenance Concepts

- Interfacing capability to a remote POI for technical data retrieval.
- Retrieval of XML representation of technical data for interpretation.
- Translation of XML for visual display tailored to capabilities of mobile technology used by the engineer.
- Visual display of procedure adhering to defined standards and common 'look and feel' defined within TATEM.
- Complete user interactivity for walk through of process, selection of instructions, sub task calling.
- Interpretation of user decisions (e.g. Yes/No) to walk through user defined process.
- Data capture through user input and RFID/Bar code scanning.
- Access to supporting multimedia from individual maintenance steps. Multimedia retrieved for display as technical data from remote POI.
- Ability to be deployed and tested on a variety of mobile platforms i.e. Laptops, UMPC, Tablets, Pocket PCs, HMD.
- Ability to practise and train for the activities using the embedded training facilities (similar equipment to PSS)

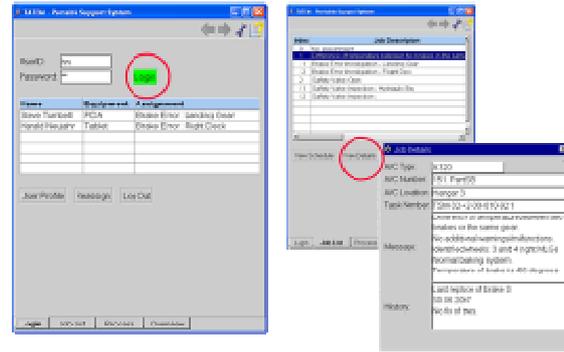


Figure 57 Login and Identification

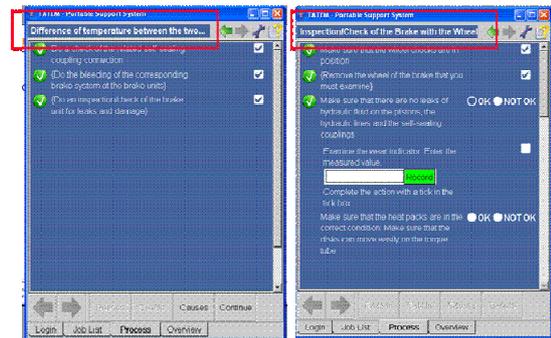


Figure 58: Two technicians carry out the procedure

The validation of the full functions are done by using the equipment sets as shown in Figure 56

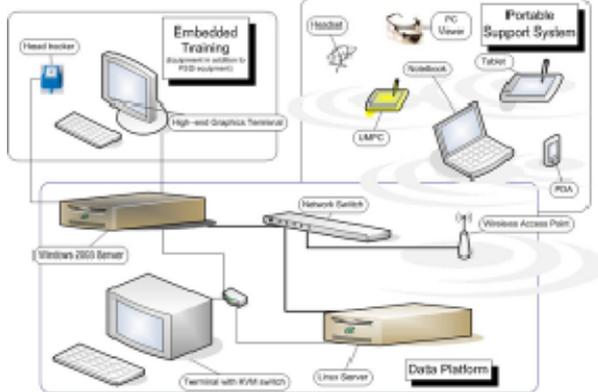


Figure 56: Complete use case#1 test equipment

The following activities were required:

- integration and deployment of process oriented technical
- integration of the process oriented interface functions
- integration of Multimedia content
- integration of HMI requirements
- The figures below show some aspects of the PSS display:



Figure 59: Process oriented HMI support, with multi-media

Use Case #2 and #3: Operational Risk and Usage Based Maintenance Planning

The local integration has to be OSA-CBM compliant and has to support a smooth and easy integration of the ground crew support applications. To achieve that compatibility, a software framework was developed and provided for implementation of all functions specified in tasks ground crew support. Figure 60 shows the overall TATEM software framework packages structure. The framework consists of four packages supporting the applications developed in the local integration (OSA_CBM, XML Parser, Utility and Communication).

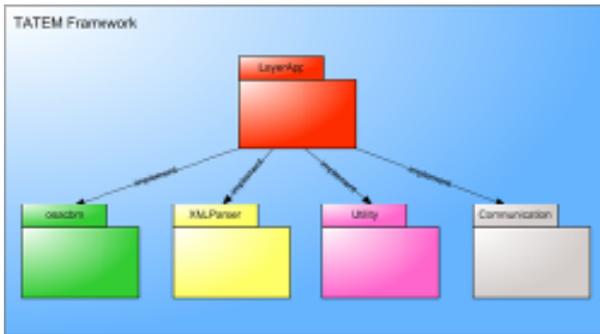


Figure 60: OSA-CBM software framework packages

The implementation concept of OSA-CBM, especially the access to external data not covered by OSA-CBM standard (e.g. legacy data, function specific data) is shown in Figure 61. The Sapphire MIS system has a central role in providing some basic functions and data to the local integration. All available data, like aircraft component structure, maintenance tasks, etc. have to be accessed using Sapphire services. Additional data is stored and is accessible in an additional database.

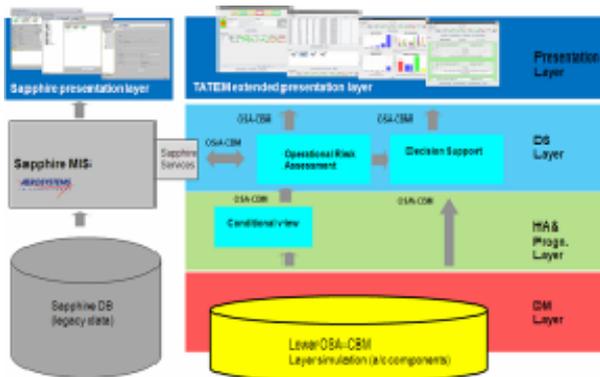


Figure 61 Components for testing Use Cases #2 & #3

Results

In the context of the local integration framework, the Use Cases #2 & #3 application provides functions to cover the maintenance management activities, especially the decision support processes during the turn-around-time (TAT) of a commercial aircraft. The application supports the following tasks:

Generates and visualizes the conditional view of the a/c (package “a/c conditional view”)

- Predicts the Remaining Useful Life (RUL), based on degradation or failure models, for the a/c by means of the operational plan characteristics that influence the models
- Updates RUL prediction models by the analysis of fleet statistics (history data)

Calculates and evaluates the operational risks for a/c and fleet operation (package “operational risk assessment”)

- Reshape the long-term maintenance plan based on a/c and fleet conditional view
- Evaluates the impact of virtual maintenance plan on alternative future operational scenarios (alternative usage profiles/ operational plans)
- Provides quantified operational risk indicators for further decision support

Provides decision support to the maintenance management staff (package “decision support”)

- Supports decision making for deferring maintenance actions that affect the dispatch of the aircraft, aiming at high fleet operability and low maintenance cost

The “Conditional View” provides estimations of the Remaining Useful Life of a given aircraft. It is the first part of the Operational Risk Assessment, where results from Health Assessment and Prognostics are reviewed and updated. It generates an operational view of the a/c taking into account component health status and Remaining Useful Life, and updating this information with specific information concerning future usage of the a/c aircraft that can be derived from the operational plan. The resulting condition view is thus provided to the “Risk Assessment” module for further processing. Finally, as an off-line effect, this conditional view can also be updated from the existing historical data and fleet statistics, related to health degradation or component reliability.

The “Risk Assessment” in this context describes the calculation of probabilities of operational interruptions caused by unscheduled maintenance events and the estimation of costs caused by them (based on specific cost functions of the point of occurrence - these points being the bases within the flight network where operational schedules can be interrupted). Root causes of operational interruptions are non-deferrable maintenance actions, which prevent the aircraft dispatch in time. An aircraft loses its dispatch ability, if mandatory components listed in the MEL are out of specified function. The fundamental concept therefore is the modelling of the aircraft as a set of “managed” components with individual failure (behaviour) models and structural interdependencies representing the MEL constraints for aircraft dispatch ability. The failure of one component does not mandatory cause an operational disruption, if redundancy is implemented.

The process of operational risk assessment starts with the estimation of the “survival rate” for each “managed” component as well as the complete

aircraft for an operational plan. The operational plan is defined as a sequence of flight segments, the itinerary. The “survival rate” for each flight segment indicates the probability of operational disruption. The capabilities of each base along the itinerary can be different with respect to repair resources (e.g. availability of spares and maintenance personal), repair time and costs. So the risk of delays or cancellations and costs will vary. The second step of operational risk assessment is the calculation of the probability for delays or cancellations and of related costs for each base along the itinerary. The following figure depicts how these results are presented to the user.



Figure 62: Conditional View and Risk Assessment capabilities

Making use of the results of Risk Assessment module, the “Decision Support” module provides a short term planning methodology for line maintenance activities, at the airports, during Turn Around Time (TAT). The proposed methodology supports decision making for deferring a maintenance action that affects the dispatch of the aircraft, aiming at high fleet operability and low maintenance cost. Based on health assessment information as well as on any additional information on operational and economical constraints, at the operators’ fleet level, a multi criteria mechanism evaluates whether maintenance actions should be executed in the current airport or in successive ones. The selected decision making criteria are Cost, Remaining Useful Life (RUL), Operational Risk (OR) and Flight Delay. The proposed approach includes the use of an Artificial Intelligence framework, taking advantage of concepts and techniques originating from the multi-criteria decision making, utility theory and simulation, in order to produce and assess different maintenance plans.

The next figure depicts how the results are presented to the Line engineer to support the decision making process.

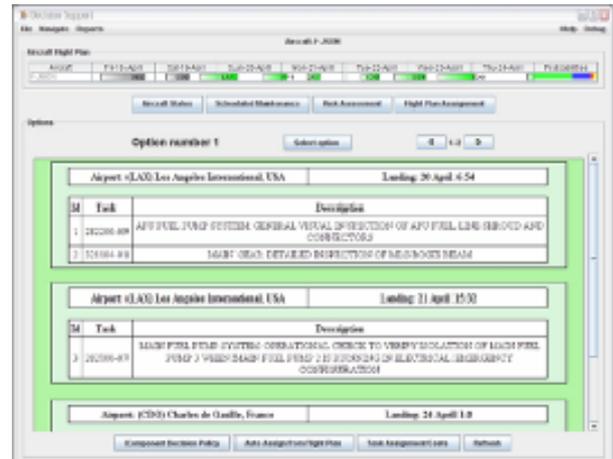


Figure 63: Short term maintenance planning capability

The developments concerning usage based maintenance planning are based on the request to perform the scheduled maintenance coming from fleet management or as result of the operational support (reshape of maintenance planning due to deviation of usage and/or degradation of aircraft and its components from previous planning predictions).

The proposed approach provides the capability to shift maintenance tasks among A, C, D checks and heavy maintenance on demand equalizing the workload over time (traditionally there can be a big workload on C-checks requiring a longer downtime of the aircraft) and packaging them in a cost-effective way (e.g. zonal checks) for reasons such as accessibility.

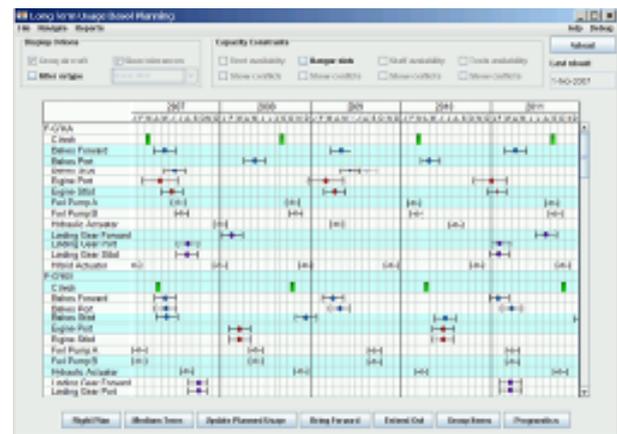


Figure 64 Long term maintenance planning

Human Factors

The ultimate goal of health management is to increase operability. This in turn is a key concept within the TATEM project. However, its

understanding is very much based in thinking in terms of business models and commercial benefits. So far it has not been researched in very much depth what this concept entails from a Human Factors point of view. This is all the more alarming because aircraft maintenance is a process that is mainly driven by people interacting with technology. The formally defined process of accomplishing maintenance tasks in alignment with technical and regulatory requirements does only happen because of maintenance personnel engaging in a complex network of human-human and human-machine interactions. These interactions and their importance for the maintenance operation have to be understood in order to design technology that ultimately improves operability.

Therefore, Human Factors research has to be build into the technology development lifecycle. TATEM provided a first opportunity to approach this goal. The basic idea is to transform the typical V-shaped design process into a learning process. Where design and technology development projects usually look into user requirements for specific applications our human factors approach would argue for also generating an understanding of the wider operational context and its demands on the targeted users. In a second step this context has to be subject to thorough human factors orientated research. This includes mapping out and documenting the formal, proceduralised aspects of the operational process as well as capturing all human activities necessary to put this process into practice. Based on this step it will be possible to identify areas within operational processes that need better support and that are accessible for new technologies. This will define technology requirements that feed into the central task of architectural design and technology development. The envisaged solutions then have to be brought back to the users, and users and designers together will have to assess in how far they fulfil the requirements and what process changes they will entail; i.e. what is required is getting users and designers to extrapolate in a joint exercise how new designs affect the whole relevant operational context, not only specific tasks. Essentially the system under development has to be validated within the real operational system by the operators. This step of knowledge transformation allows deriving a model of the future process that can be compared against the current process. This comparison will show costs and benefits of the envisaged innovation.

In the following sections we are going to show in how far this process has been applied to TATEM and what results have been achieved in doing so. Additionally, we will introduce the main concepts of human factors orientated operational process

modelling as it has been developed by the APRG thanks to the opportunities provided by TATEM.

Human factors in maintenance today

Aircraft maintenance today is characterised by complex sets of co-ordinated tasks that are managed by people. Although the maintenance technician is the central person of this nexus – through executing maintenance actions and manipulating the aircraft – his success ultimately depends on contributions by a wide set of stakeholders. Operational staff thus has to manage the considerable ambiguity and uncertainty designed into the operational system. The main sources of instability are not located in the task but how the planning and support that lead into the tasks are managed and how their requirement for parallel activity is realised. Managing this information flow in an adequate manner will provide companies with the necessary competitive edge.

Human factors are at the core of the system. While outcomes can be observed at the operational sharp end, the root sources can often be located in the upstream processes of the organisation. This relationship is not well managed in current processes, key reasons being (a) the dynamic – and thus ad hoc – management of unscheduled tasks and (b) insufficient utilisation of information available about the system. Solutions are sought locally in the organisation without an integrated view of the system. This is what our proposal for a new approach to human factors analysis aims to tackle.

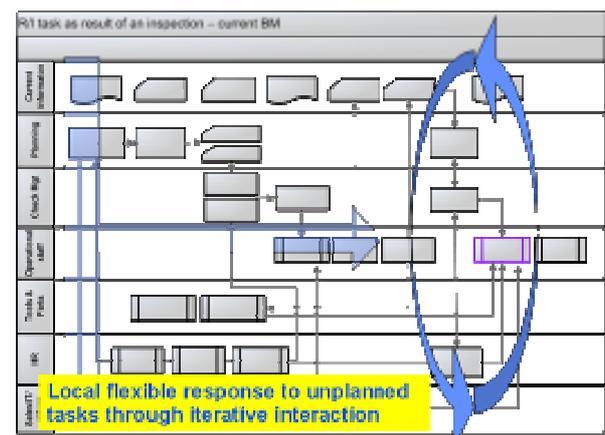


Figure 65: Local management of distributed inputs.

In short, the main activities of planning and preparation for a check currently are not well integrated with the local effort in managing the operational task. The operational staff executing a plan is left to manage the residual ambiguity and changes that are introduced when confronted with changing requirements (e.g. new findings). This

requires a local team effort that depends on good relationships and a shared understanding of what is an adequate response in such situations. This can be summarized as follows:

- **TEAM:** Human factors analyses have to explore to which degree local teams and their success in completing a task depend on iterative co-ordination. It also has to be examined on what social techniques such mutual adjustment teams have to rely.
- **TRUST:** Further, human factors analyses have to address quality and stability of social relationships, which are characterised by trust in others and the system. Here local personal relations have to be measured against segregation of support and operational departments on a more global level.
- **COMPETENCE:** Human factors analyses also have to examine professional as well as, often untrained, social skills relevant in this specific context as for example, e.g. communication for flexible problem solving with adequacy of outcome negotiated per situation.

Many of human factors issued in today's processes can be seen as consequences of how the system is designed and operated. Requirements for local adjustment forward pressure and responsibilities onto the people working at the aircraft. With the system being under constant strain, people are critical for the operation to perform well in these systemically adverse circumstances. The lack of serious incidents and accidents reflects that the active process management of the people involved maintains sufficient stability most of the times. The occasions on which the system strain exceeds the available mitigation resources lead into so called 'human errors' which are rather instances of system failure.

The Knowledge Space Model: Analysing the operation

The Knowledge Space Model (KSM) captures knowledge about how operational systems actually work in practice and it provides a framework for analysing events and undesired outcomes within operational processes. Furthermore it provides a logic for examining processes and events within those with respect to risk mitigation and technological innovation and change opportunities.

The KSM is designed to enable stakeholders in an operational system (across the lifecycle 'space' from new design to planning, management and operation) to join each other in a process of constructing a common understanding of how a new technology or operational concept could change or transform that operational system in order to deliver a radically different outcome. This

outcome could be a step change in efficiency or it could be an improvement in safety, reliability or operability. The KSM can be described in three ways:

- **The KSM as a model**
It comprises a model of the operational process, which incorporates rich layers of knowledge about how that system really works. Building on the functional logic of the analyses within the social process analysis modules of the KSM it also allows constructing potential future models of the process, e.g. as a result of new task support technologies brought into operation.
- **The KSM as a methodology**
It is a methodology for analysing the impact of new technologies or operational concepts on the operational process, but also for identifying and mitigating against the potential impact of threats and risks within the process. In doing so it focuses on the human/social structure of that operational process.
- **The KSM as a process**

It is a process for facilitating the transformation of knowledge about that operational system, held by the stakeholders (across the lifecycle), into a common understanding of the operational implications of new concepts and the envisaged changes. It is this knowledge transformation process, using the KSM methodology, which supports the development of a model of future operations.

The operational process model component of the KSM

A core component in the overall Knowledge Space Model framework is the Operational Process Model (OPM); a comprehensive model which (in a generic way) describes process activities and models their underlying causal logic. The OPM provides the basis for the social process analyses to be performed in other KSM modules and it serves as a baseline for measuring performance and risk in the current context. It also allows comparing this to future models as results of change and improvement processes.

The Operational Process Model

- Stores and manages data, information and knowledge about the current system
- Represents the system graphically in different ways (system level, process activity, stakeholder relations, dependencies & critical path – see Figure 66), based on that data;
- Supports transformation of the operational process into future or alternative versions

The OPM approach differs from standard process modelling in (a) the scope of what is considered as critical elements and (b) consequently, how the relations between these elements and their underlying mechanisms are expressed.

In summary, the system activity is systematised in the process model around the following elements:

System Level

Any operational process is embedded in a wider system context. Outcomes of activities at each level in the hierarchy of an organisations’ system feed into subsequent levels. The system level overview diagram depicts this hierarchy, its main processes and basic dependencies. It provides an entry point from which to access all other elements of the OPM.

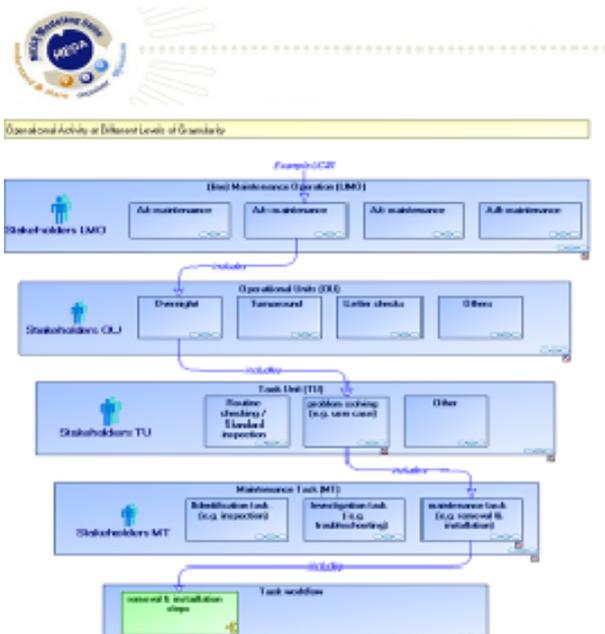


Figure 66 The OPM system level diagram – modelled using the MEGA® suite software (see www.mega.com).

Process activity

The process activity diagrams not only map out the process as it is defined by e.g. manuals and procedures or company policies, but integrate the additional human activities that enable the formally identified process to work. The diagrams distinguish between technical activities as required to manipulate the technology object and co-ordination activities that are critical to understand how outcomes are produced in processes.

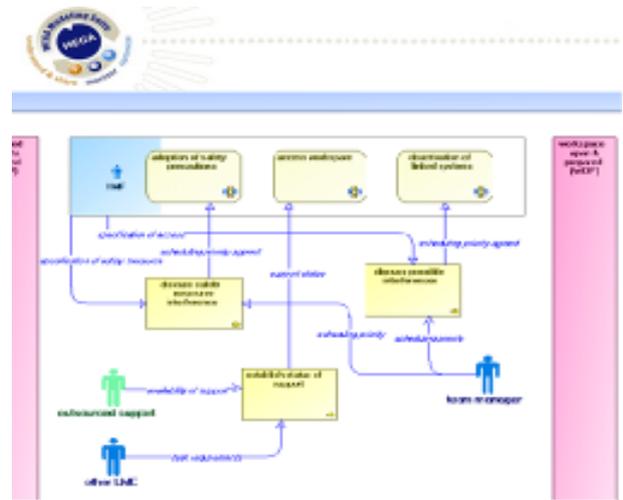


Figure 67 The OPM process activity diagram (detail).

Dependencies

States are gates in the process progression at which the status of the process is consolidated to provide a stable platform for its progress. In order to achieve a state certain resources are required. These demands can be expressed as a set of dependencies. These dependencies can be located within a process, span across process levels, or arise outside of the operation.



Figure 68 OPM dependency diagram (detail).

Stakeholder

It is not sufficient to review individuals’ activities. One has to include the pattern of their relationships. The notion of stakeholder includes every role that has a direct or indirect contribution to defining the system constraints.

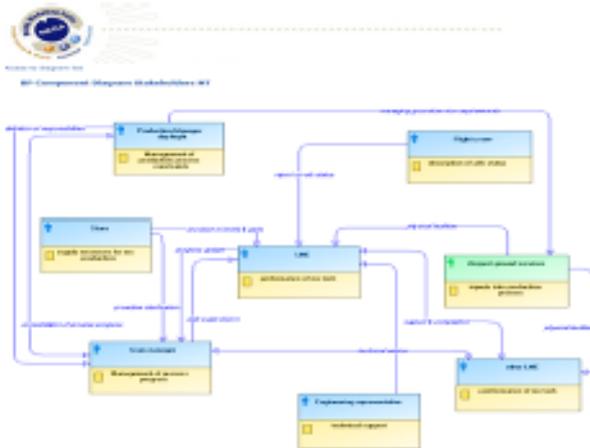


Figure 69 OPM stakeholder diagram.

The KSM as methodology for human factors analyses

The KSM as a methodology defines a set of dimensions that are critical to the understanding of the interaction between the social/human and the technical structural elements of the process. The evaluation of the operational system serves two purposes: (a) feeding back into the process model, e.g. for comprehensively identifying risks in the system, and (b) driving a comprehensive vision of the future system and its requirements for improvement and change. The analysis will be steered through a set of modules dealing with the following topics:

- **Operational system**
The operational system module reviews the functional coherence of the processes and tasks that deliver the system’s outcomes. It is not restricted to the core operational processes but also evaluates interfaces with direct support processes. Interfaces are a critical element which links to coordination activities.
- **Information system**
Information integration is a critical dimension. Here the information notion includes all information used in the operational process, some of it being formally defined and exchanged, some of it being linked to standard ways of facilitating the process that are not prescribed in any documentation or procedures.
- **Team system**
The Team system module examines the extent to which the participants in the task and coordination activities possess the essential characteristics of a team, and how well these team characteristics are supported by the process design and organisational context.
- **Competence**
The Competence module reviews the knowledge, skills and abilities, the

understanding of the work and the performance and evaluation dimensions which are driven by the process logic.

- **Relationship quality/Trust**
The quality of social relationships has a fundamental conditioning effect on the way in which those relationships are worked out, not only in terms of how people conduct their everyday tasks in the processes, but also in terms of social processes in organisations between different levels and groups in the organization.

The KSM as a methodology guides the analysis strategy which includes the following steps:

1. Selection of relevant OPM and review of its information
2. Initial evaluation of critical/vulnerable points
3. Utilizing these principles in the knowledge transformation process to facilitate the transformation into change and improvement initiatives and requirements
 - a. Process activity changes; this includes an assessment of what process activity becomes obsolete, what is going to change, what is shifting to another process, what are the overall organisational opportunities in this transformation of the process.
 - b. Stakeholder relationships
 - c. Instantiation of dependencies
4. Secondary evaluation of the impacts on the human-social structure
 - a. Consolidation of implications of detailed transformation for key dimensions: Operational system, information structure, team, competence, relationship quality/trust
 - b. What are improvements of the current situation? What are potential risks introduced in the system?
5. Compilation of overall results; this includes a future process model and analysis reports to be used in other activities, such as design innovations or organisational change initiatives.
6. Transfer of results into specific activities, such as inputs into functional requirements for technology solutions

The KSM within a knowledge transformation process

The KSM framework is designed to support a process that uses its elements for knowledge transformation. While the KSM methodology is a set inquiry following established principles, the OPM provides a conceptual process framework which is populated according to the scope of the research or organisational management application it is used for. The Knowledge Space Model as a methodology facilitates the Knowledge

Transformation Process, from the initial diagnosis of the state of the system to the production of useful knowledge for implementation. The knowledge transformation process facilitates closing the existing gap in knowledge sharing and transfer in the lifecycle between the design phase and the operation of the systems.

At the same time the knowledge transformation process gives end-users a perspective to learn about the rationale and constraints in technology development. This enables organisations to reflect on their potential and prepare for the implementation of new products in a way that facilitates the use and maximises benefits.

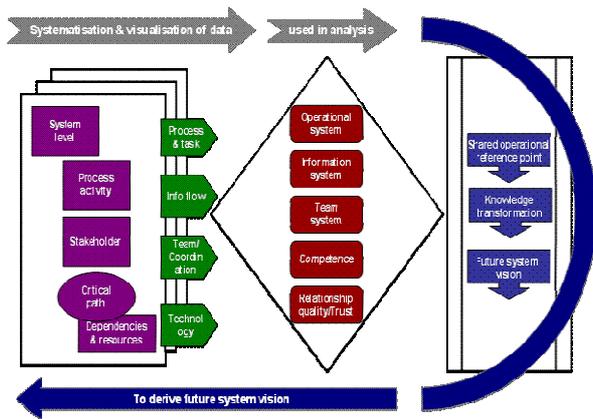


Figure 70 The KSM processes.

Sample results of human factors analysis

This section discusses some of the implications for the dimensions that have been defined in the KSM modules as being critical in assessing and evaluating the wider transformation implications.

Information integration

The TATEM health management (HM) approach improves the understanding of the aircraft status and thus increases the control over the maintenance production requirements. The main mechanisms to deliver the benefits into the maintenance operation (and also to other stakeholders) are (a) data management following the OSA CBM standard (from data generation to information presentation) and (b) the integration of information across onboard and off-board information systems (Maintenance Information System – MIS). The benefits of the information integration are realised at each process level. Process orientation and mobile maintenance are concepts that further facilitate and improve the information flow into the processes. However, the following sample analyses, which focus on the team managers situation, show that HM and its supporting technologies deliver higher quality inputs into specific task contexts, but (a) their implications go beyond just a change in

information quality and (b) full advantage of this new quality can only be taken when the information is managed holistically throughout the organisation. The analyses based on the KSM concept and thus expressing a new understanding of human factors clearly point towards these issues and indicate where organisational change processes need to intervene to reap the full benefit of the TATEM solutions.

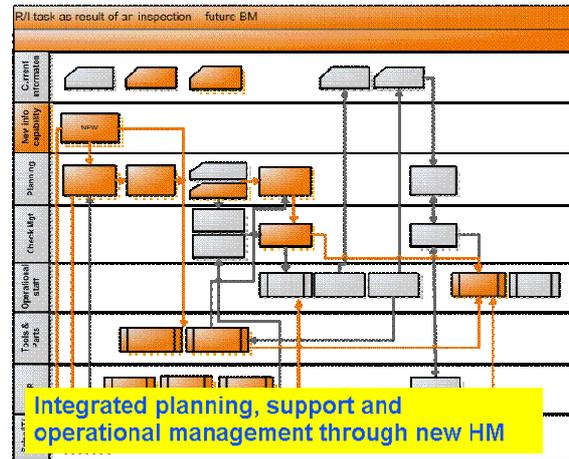


Figure 71 Streamlining the process flow through information integration.

At the level of the maintenance task sequence the main benefits are

- Increased transparency of the current status (e.g. of the process (via PSS functions)), of the aircraft (via HM functions) etc) through real time information management
- Clear definition of a set of tasks and their role in the overall context provided from upstream
- Standardisation of information in information flows in and out of the process facilitated amongst others by PSS functionalities
- Information may be pushed at e.g. the team manager which reduces the risk of oversight of critical developments; this also leads to less effort spent on information access, search and integration by the team manager
- Support of workflow in the process execution by adequate information: all in all the team manager will have to search less for information be it on appropriate team composition or material resources due to scheduling and planning capabilities.

One major advantage of the new TATEM information capabilities will be that information is for example presented directly to the team manager – potentially through only one channel. This releases his capacity to better monitor and supervise the process. However, it has to be taken care that the information actually reaches the team manager because creating and packaging the

information higher upstream without direct involvement of the team manager could imply that he will have no other way of accessing relevant information. It is an open question, too, how existing informal information flow patterns will be affected by new technologies and if their continuous existence will pose a threat to new information architectures.

Operational system

The introduction of health management gives the opportunity for a formalisation of processes that can be traced into the operation and monitored in daily practices. The reduction of local management due to increased control over the aircraft status and thus its current and emerging maintenance requirements enables a standardisation of inputs and outputs. This overcomes the current situation where formal systems do not necessarily reflect the daily practices which are driven by a requirement for flexibility within an operation characterised by constantly changing/updated requirements.

Today, local coordination activities add essential value to the current process because of the constraints of the existing operational system such as changing requirements or short lead times for decisions. Furthermore, downstream levels of the operation are today often left with the challenge to manage and monitor supply chain aspects of the operation that would formally belong to planning and scheduling processes. This process relies heavily on interpersonal relationships and informal ways of management. This operational deficit is due to a lack of – technological – support of the organisational units that would be responsible for these issues. A major problem here is that integrated monitoring and management (support) tools are currently missing. Future systems for decision support and scheduling/planning should step into this breach and thus this effort should be reduced or shifted to a central function and will then be remote from the local management due to increased control delivered by HM information.

The implication for the team manager is that he will still perform crucial interface functions between planning and production management on one side and task execution on the other. But his activities will no longer be a partial reduplication of planning and production management work. Instead he can supervise and support the execution of this planning work at task sequence level. Thus his actual role in ensuring process flow and stability will in future indeed be at the core of his activities.

On this basis clearer performance indicators for specific roles can be derived since the formal process is closer to the activities as they happen. Formalisation of interfaces also includes the

identification of responsibilities, aspects of which are currently distributed or cascaded down, e.g. supply chain management: from a central planning effort to a local management to deal with changes. (Team, competence) For the team manager in particular this however leads to an open question: A key responsibility is to sign off work cards and thereby ensuring that maintenance work has been done according to specification and regulations. If now the maintenance engineer has greater control over the sign off process, then the role of the team manager in this process has to be adapted accordingly. Further, it has been said that some of the team manager's capacity could be directed towards on-the-job-training for example. Again, this then needs to be formalised – probably even in terms of KPIs – and needs to become part of his official role and thereby skill profile.

Overall the transformation promises to reduce ambiguity which is part of the current system at different levels.

One concern: The HM approach provides the opportunity to transform the operational system. These potentials can only be maximised if adequately backed up in the organisation by wider process and system changes. An example is the opportunity for redesign of the supply chain around the new parameters introduced by the HM solutions (increased lead time; root cause knowledge etc).

Competence

The information integration and subsequent change in the operational system have an impact on the human/social dimensions of the system such as competence, team and trust (in organisational relations).

The Team Manager is currently involved in coordination activities that are a response to the ambiguity in the operational system (in form of e.g. task mushrooming, changing scheduling priorities in response to events). Today this involves personal communication and negotiation (around e.g. access to equipment) that extend the technical skills that the person has been mainly trained in.

In the current situation the team manager has to draw from a very diverse skill set to cope with his complex tasks. However, as stated earlier a certain part of these tasks is not formally part of his responsibilities and only fell into his area of work because of system ambiguities and insufficiently supported information flow.

Roughly the following changes to his required KSAs can be anticipated: Perhaps the least changes are to be expected on the technical level. He should however be in a better position to play to them, because the operational changes affect

the social and organisational profile of his position. Organisationally he will need to be less skilled particularly in resource management and logistics. Currently he is taking these aspects on board, because of system instabilities that undermine higher level planning work. The most important change will then be on the social skills level. Instead of fire fighting unexpected situations on behalf to the maintenance engineer who is too busy doing his assigned work to cope with the complexity of emerging additional tasks or support shortfalls, the team manager will be able to monitor his team's progress and that of each individual which gives him the responsibility to recognise potential problems early on and to provide specific support. This can be done personally or by triggering e.g. training sequences on the PSS. To do this appropriately the team manager has to have people management skills and training skills. For this he may need additional training and education amending his technical expertise. In this respect the new competence requirements put an onus on the organisation to prepare their personnel properly for the new challenges.

currently in the proposal phase of the 7th framework programme.

Conclusion and outlook

Ground Crew Support potential technologies have proven to be at the forefront of increasing efficiencies in the maintenance environment. To be able to move around and have the necessary information or instructions at hand, based on health monitoring and management capability, when carrying out a task, has revealed a considerable potential for automising fleet processes and reduction of work load. Furthermore integrated health monitoring and management has the potential for direct operating cost savings and the deployment of a Condition Based maintenance strategy. Condition Based maintenance will be efficiently performed when supported by integrated enterprise management. A further important part are the fleet support processes, which are strongly dependent upon human factors.

TATEM provided the first opportunity to highlight the importance of a wider understanding of human factors in order to develop and successfully introduce technological innovations. However, as the sample analysis have shown, not all issues arising out of new technological developments, both problems in implementing them as well as opportunities to improve process within an sector of the industry, can be covered at the technology level alone. Some of these issues require structural changes in the organisational set up of companies or even a whole industry. Some of these aspects are currently being taken up by Framework 6 projects such as HILAS. Others will hopefully become the topic of new projects that are

The Value Proposition

TATEM develops techniques and technologies in different domains (Aircraft, Data Management, Ground Crew Support) for enabling value-driving concepts including Health Monitoring and Management. One challenge in the project is about assessing the operational benefits that can be expected from an integrated implementation of these techniques and technologies in maintenance.

The 'value proposition' is developed through a model-based approach; for evaluating operational benefits in terms of impacts on aircraft operational reliability, availability and maintenance related cost. The project could not directly assess the benefits directly resulting from TATEM actual research results because by construction the project could not generate all required quantitative data. The model-based assessment rather looks at a projection of TATEM concepts potential in the middle term.

Methodology for assessment of operational benefits

TATEM methodology for assessment of operational benefits, as shown in the figure below, is based on models in which comparisons between as-is and to-be scenarios implementing TATEM results can be performed.

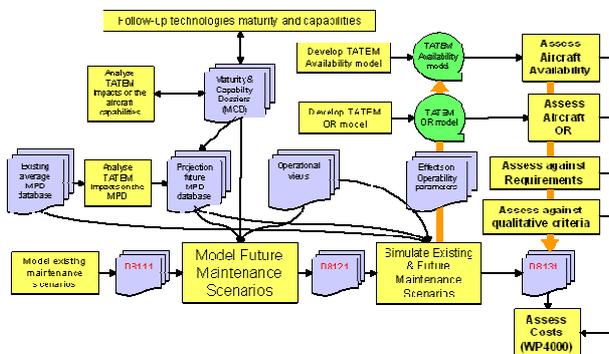


Figure 72: Flow chart for assessment of operational benefits

It consists of the following main steps:

- Identifying strengths and weaknesses in the existing maintenance
- Identifying end users operational needs and deriving major requirements
- Producing a reference model of the global maintenance processes and their major components
- Understanding and assessing the potential of the TATEM techniques & technologies
- Assessing the impacts on the aircraft Operability

- Assessing the global impacts on Costs

Modelling of maintenance processes and impacts from TATEM research results

Modelling of maintenance processes

As a first step the major maintenance processes were modelled. The reason for that is if one considers a particular technology under development in TATEM, it is not easy to understand what could be the potential of this technology once implemented in maintenance, since technologies may be used at different places, they may integrate with other technologies and they may even change the processes. Modelling of maintenance processes allows a better understanding how TATEM may impact aircraft operations.

The existing processes were modelled using MEGA and the following aircraft situations were considered:

- **Aircraft in service:** flying, having turn-arounds or stops. This is the typical Line Maintenance situation.
- **Scheduled Maintenance:** this process goes from generation of the Maintenance Planning Document to execution of scheduled maintenance tasks through to Engineering and Planning processes.
- **Shop maintenance.** This process was modelled only for the aircraft computers repair process.

As an example the figure below shows the 1st level of modelling of the aircraft GO-NOGO analysis process, within a Turn Around. modelling also identifies the major activities and allows better understanding of the roles of the corresponding centres of competencies and their exchanges.

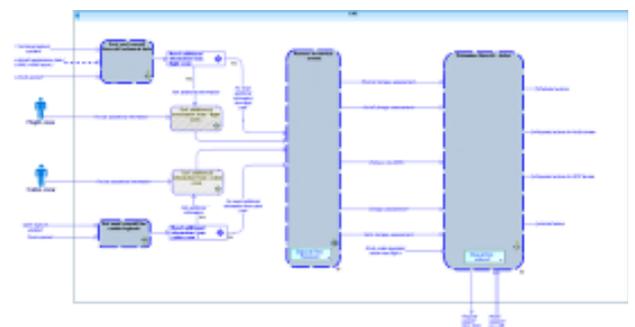


Figure 73: Aircraft GO / NOGO analysis process.

Analysis of TATEM results and construction of future maintenance processes

The construction of future maintenance processes is based on implementation of TATEM impacts on existing processes. These impacts may change

the organization of activities, the interfaces between activities as well as the performances of these activities; some activities may be removed or some new activities may appear.

Prior to modelling future maintenance processes a series of TATEM workshops were held in order to gather and analyse all information related to the Maturity and Capabilities from the research results achieved by TATEM. In particular their impacts on the activities of the major maintenance processes were analysed.

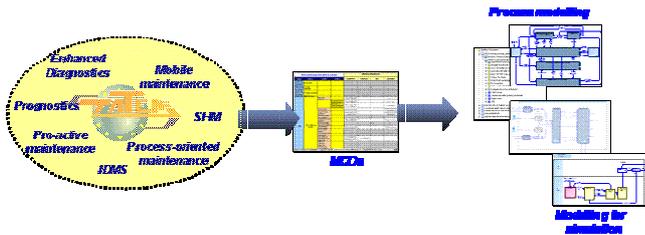


Figure 74: Maturity & Capability Dossiers -MCD

Traceability within this process was ensured by use of a Maturity & Capability Dossiers (MCD), as shown in the figure above. Research results were analysed in the following areas:

- Integrated Data Management System
- Process-oriented maintenance
- Mobile maintenance
- Operational risk assessment
- Enhanced diagnostics
- Prognostics of electronics
- Electrical systems diagnostics and prognostics
- Actuation systems diagnostics and prognostics
- Engine fuel pump
- Engine Variable Stator Vanes actuation
- Engine vibration
- Engine performances monitoring
- Data fusion of Engine and Environmental Control System (ECS)
- Brake wear
- Shock absorber servicing
- Airframe structure monitoring

As most of TATEM results are related to specific domains and use cases and address precise pieces of systems or structure, it is necessary to make a middle term projection of these results at aircraft level. This projection relies on TATEM results but also on assumptions based on experts' judgement. It means the construction of the future maintenance processes doesn't result directly from TATEM research results; it is a work based on what could be the potential of TATEM concepts in the middle term (<10 years). The most significant benefits that were identified through the modelling

of the future maintenance processes are as follows.

- Enhanced diagnostics
A new BITE concept (Built-In Test Equipment) could be successfully tested in laboratory environment, as well as a better systems failures correlation at aircraft level. First analyses show it should reduce the durations of the activities related to the aircraft GO-NOGO analysis and trouble-shooting in a typical Turn Around.
- Prognostics
TATEM investigations in Prognostics are quite promising though tests demonstrated it is technically very challenging. However in the middle term one can envisage Prognostics to be implemented on a reasonable portion of the Operability-driving component. It has to be noticed that most Prognostics techniques will require some in-service experience for getting sufficient maturity and accuracy. Prognostics should allow a significant reduction of unscheduled maintenance in Turn Around. At the same time it is likely to bring additional workload to the back-office functions in charge of maintenance engineering and planning.
- Airframe Structural Health Monitoring (SHM)
From the tests, the SHM technology maturity is currently felt to be below initial expectations. In addition, the integration of this technology in airframe structures remains an issue. However SHM is expected to bring significant benefits in particular for accelerating assessment of certain in-service damages. SHM should be an interesting option for certain structural inspections (Specific Detailed Inspection, Detailed Inspection) particularly in aircraft areas that are difficult to access. Also, the use of SHM together with an aircraft usage and fatigue monitoring is felt to be promising for reduction of the overall burden of structural inspections.
- Mobile and Process-oriented maintenance
Mobile technology has reached a good maturity level, though its seamless integration in legacy information systems remains challenging. Process-oriented maintenance was felt to be a longer-term objective. The perception is these concepts should accelerate most of the activities, both during maintenance preparation and execution. Significant time savings are expected especially when performing complex tasks, like installation of a landing gear.

Assessment of TATEM impacts on Operational Reliability

This analysis is performed using the Airbus tool ORA: Operational Reliability Analyser. Major steps are as follows:

- Development of functional breakdowns for Operational-Reliability-Driving systems that are impacted by TATEM concepts
- Definition and setting of ORA parameters both for the existing and TATEM baselines
- Execution of ORA and comparison between AS-IS and TO-BE baselines

As input information ORA takes into account the functional architecture of a system including its redundancies. A parameter list is used to enter the characteristics of each component of the system with regard to its operational performances: MTBUR, MEL action time, Mean Time To Restore Function, etc.

Probabilistic rules are implemented at every node of the model for reflecting the evolution of the system's status over the time, taking into account related maintenance actions. An aircraft mission profile has to be set and ORA can be run on a high number of iterations, as an example 10,000 take-offs. This allows calculating the operational interruption rate of the system and of each component.

Some benefits are expected from TATEM, in particular with application of the enhanced Diagnostics, Mobile and Process-oriented Maintenance concepts. The related study is still on-going and no quantitative results can be provided for the time being.

Assessment of TATEM impacts on aircraft availability

The assessment of TATEM impacts on aircraft availability is achieved using a model that compiles aircraft downtime. Since there is not a standard definition of aircraft availability, the tool has been developed with flexibility in mind, to allow the calculation of various key performance indicators (KPIs) for differing operational scenarios.

For downtimes caused by unscheduled maintenance, the model will be fed with some inputs provided by the OR assessment (ORA), but also by the Turn Around simulation (see hereafter). For downtimes caused by scheduled maintenance, the inputs will be provided by a separate analysis of TATEM impacts on scheduled maintenance.

Analysis of TATEM impacts on Scheduled Maintenance

A thorough analysis of TATEM impacts on all tasks of a Maintenance Planning Document (MPD) would be difficult in the timescales of TATEM. Consequently, it was decided to perform this analysis on a subset of tasks. A typical C-check was selected because it makes the comparison easier with the 'AS-IS' situation.

To this purpose a analysis grid was developed, which functioned as questionnaire for collecting relevant data. One central question is the ability to electronically monitor the degradations that are expected to be detected when performing scheduled maintenance tasks both on systems and structure. The analysis is ongoing. However there are provisional statements.

- Zonal inspections

TATEM brings no significant benefit because of the nature of General Visual Inspection tasks (GVI) that are used in zonal inspections. These tasks aim at detecting many types of potential defects or degradations that can occur in an aircraft area, and the 'human' remains the best "sensor" for that.

- Structural inspections

Some tasks are found to be good candidates for condition-based maintenance using SHM. In some cases it is beneficial to use SHM in areas that are difficult to access (avoid inspections with no findings). Using SHM for monitoring of particular areas prone to cracks is found also beneficial as long as it can avoid costly and labour intensive repair work. It is also beneficial for usage and fatigue monitoring in order to trigger the time of the first heavy visit.

- Systems checks

First analyses show that Systems health monitoring may allow replacing some MPD tasks with on-aircraft automatic tests or with extended coverage of Diagnostics and Prognostics. Mobile and Process-oriented maintenance may also help for complex systems checks.

Assessment of TATEM impacts on aircraft availability is ongoing. At this stage of the project no precise figures are available.

Simulation of a Turnaround

The existing maintenance processes are modelled and simulated in MEGA. The simulation aims to assess the Line Maintenance efficiency in a Turn Around with regard to aircraft systems failures, in a probabilistic way. To this purpose a simulation model of a Turn Around is developed from the "Aircraft in service" model.

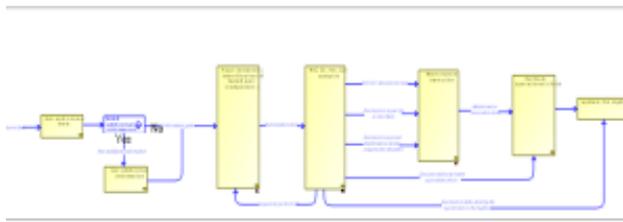


Figure 75: Simulation model of a Turn Around Simulation settings

The simulation runs the Turn Around process on a high number of cycles (probabilistic approach). At each cycle, some systems failures are generated according to a set of probabilities. These probabilities can be set for reflecting failures occurrences for a typical mission profile, based on in-service data. 'TO-BE' scenarios can be defined, taking also into account a more robust aircraft design.

The impacts from TATEM concepts are tuned via a set of performance parameters. These parameters will change the performances of the different activities within the Turn Around process. Some KPIs, such as the number of delays, are defined in order to make comparisons between AS-IS and TO-BE scenarios.

Cost Benefit Analysis

The following figure depicts the way the assessment of TATEM operational benefits is conducted. The results coming from the assessment of TATEM impacts on OR, Availability and in Turn Around (simulation) will feed the Cost benefit Analysis (CBA). The CBA model will be used in a way to directly assess cost impacts at aircraft level.

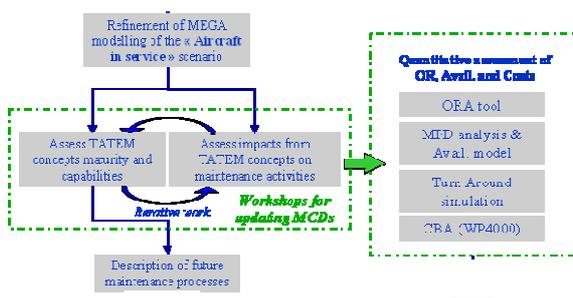


Figure 76 Assessment of operational benefits

More details about the development of the CBA tool are given in. The CBA tool supports the early pre-selection of maintenance technologies of interest within the different TATEM technology streams. Besides the CBA tool supports also the cost assessment of final TATEM research results against the project initial objectives. To this purpose the CBA is implemented in a way that

allows comparison of TO-BE maintenance scenarios with AS-IS scenarios.

Approach to cost assessment of innovation

The approach that was selected for cost benefit analysis is inspired from the classical approach used in capital investment decisions. It compares additional costs of an investment with its expanded benefit. For measuring the cost and benefit of a new technology the CBA compares one future use case against a reference, i.e. an existing use case. As shown in Fig 77 hereafter it consists of a step-by-step comparison, from an initial state to a final state, of an existing scenario with a future scenario implementing TATEM innovative concepts.

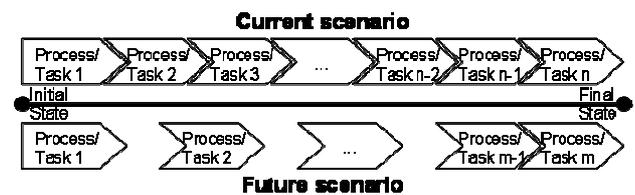


Figure 77 Principles for comparison between future and current scenarios

Maintenance related costs, reference aircraft and airline operational concepts model

It is essential that the CBA include a relevant model of maintenance related costs. The maintenance related costs are derived from an airline's total operating costs. The total operating costs are composed of the Direct Operating Costs (DOC) and the Indirect Operating Costs (IOC).

The DMC relate to labour cost and materials cost directly spent when performing maintenance tasks, i.e. in maintenance execution. The IMC relate to costs of managing maintenance, i.e. costs related to all back-office functions: administration, engineering, record keeping, planning, supervision, tooling, test equipment, facilities, etc.

In addition a reference aircraft and airline profiles have to be selected in the CBA tool prior to analyses. The tool contains a representative set of reference aircraft and airline profiles for short and long haul missions and various types of airlines/operators (e.g. premium, low-budget, charter, cargo etc.) are identified, captured and modelled. The following figure shows the various models used for entering the parameters.

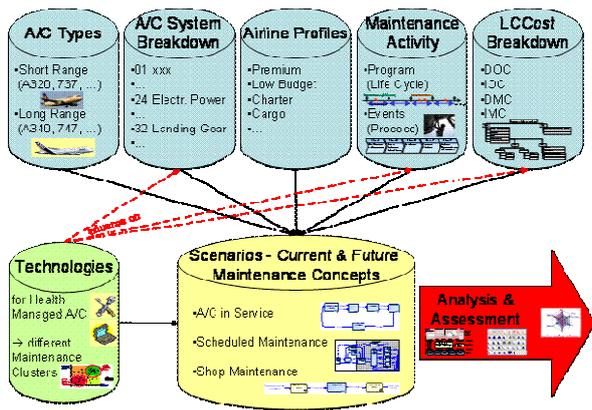


Figure 78 Input models used in the CBA

As explained the CBA has been used successfully on some specific scenarios. As an example a 30% time saving could be demonstrated for the “Brake replacement using mobile and process-oriented concepts” scenario.

It should be noted that the model-based assessment performed in TATEM will provide results at aircraft level. This may be extended to the fleet level but this is beyond the scope of the project.

Projecting the TATEM research results into aircraft operations is a challenge. Some assumptions had to be made however as described here, the selected approach provides some strong elements for a value proposition of a future health managed enterprise, supporting the top line TATEM objectives.

TATEM Conclusions

TATEM has taken important steps in demonstrating the key technical, cultural, commercial and infrastructure capabilities that will underpin service provision in a future health managed enterprise is ongoing. The TATEM project has shown that it is technically feasible and the challenge going forward is to build upon this and others successes to realise the promise of new enterprise and operational solutions.

1. New services and products are emerging to satisfy the growing demand of both military and commercial customers. Customers are keen to embrace more sophisticated contracting regimes for larger and more complex systems.
2. Developing open standards and protocols for support functions will be essential for market penetration and customer acceptance. Successful solutions will offer integration across the value chain.
3. Gaining an understanding of the interactions (intended or otherwise) of complex systems can be as important as monitoring individual equipment or sub-systems. This is an area of

work that requires serious attention if the full capability of aircraft health management is to be unlocked.

4. Managing the technical complexity of the interactions of people, organisations, technology, policy and economics remains one of the biggest challenges in deploying a future health managed enterprise.
5. The key to success is the acquisition, exploitation and management of data.
6. The first part of the TATEM project analysed current maintenance practices and identify major weaknesses and strengths. In parallel the project developed a shared understanding of operators and MROs operational needs.
7. Based on these investigations the project is confident that the TATEM concepts are strong enablers to achievement of these operational needs.