

# Identification and evaluation of the potentials of Prognostics and Health Management in future civil aircraft

Sebastian Torhorst<sup>1</sup>, Nico B. Hölzel<sup>2</sup> and Volker Gollnick<sup>3</sup>

<sup>1</sup>Master student Technical University Munich, Institute of Aircraft Design  
Research assistant DLR German Aerospace Center, Air Transportation Systems, Blohmstraße 18, 21079 Hamburg, Germany  
Sebastian.Torhorst@dlr.de

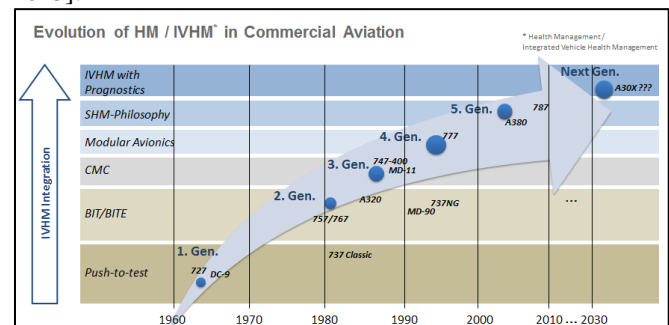
<sup>2</sup>Researcher/<sup>3</sup>Head of Institute, DLR German Aerospace Center, Air Transportation Systems, Blohmstraße 18, 21079 Hamburg, Germany  
Nico.Hoelzel@dlr.de/ Volker.Gollnick@dlr.de

## ABSTRACT

After the stepwise implementation of health management systems in form of diagnostic on-board maintenance systems in the latest generation of aircraft (e.g. AiRTHM (Airbus Real-Time Health Monitoring) – Airbus, AIMS (Airplane Information Management System) – Boeing, AHEAD (Aircraft Health Analysis and Diagnosis) – Embraer) and other technical equipment such as jet engines (Engine Condition Monitoring – MTU, Performance Based Logistics – GE) or trains (Remote Condition Monitoring – Future Railway), the pressure is high for an evolution of this technology. Integrated Vehicle Health Management (IVHM) represents a set of capabilities that enable sustainable and safe operation of components and subsystems within aerospace platforms. [Rajamani, 2013]. The next step in IVHM is the ability to give prognoses on the Remaining Useful Life (RUL) of a system or component and the structure of the aircraft. This approach is covered in the term “Prognostics and Health Management” (PHM). PHM in this context consists of Integrated Systems Health Management (ISHM) and Structural Health Monitoring (SHM). To put that step into practice in an industrial environment, it is inevitable to weigh up costs vs. benefits in a Cost-Benefit Analysis (CBA). This trade-off is subject of the following investigation. A methodology is presented with which it is possible to evaluate PHM on aircraft level and examples are given to show its applicability. The study shows that, under the assumptions made, a PHM system can benefit the design and operation of future civil aircraft. The dimensioning of structures can be modified, maintenance processes adjusted, system reliability, aircraft availability and safety increased. With the help of the results presented herein and further in-depth studies of the aircraft structures/systems of interest, a sufficiently well-founded evaluation of the possible costs and benefits of the implementation of this advanced approach on the PHM technology can be performed.

## 1. INTRODUCTION

Integrated Vehicle Health Management is a highly promising game changer for the design and operation of civil aircraft. Over the last 50 years, this technology has gone through major development steps. An overview of the evolution of IVHM in commercial aviation is given by [Hölzel, 2013]:



**Figure 1: Evolution of HM/IVHM in Commercial Aviation [Hölzel, 2013]**

Prognostics as the next level of IVHM integration is defined by [Goebel, 2010] as a prediction of “*damage progression of a fault based on current and future operational and environmental conditions to estimate the time at which a component no longer fulfils its intended function within the desired bounds*”. Prognostics can be based on the results of accurate diagnostic systems and data-driven and/or physics-based models. Depending on the level of integration, different implementation approaches for PHM systems are distinguished by [Hölzel, 2013] in Figure 2. This paper deals with the 3<sup>rd</sup> level, the integration in the conceptual design phase:

	Legacy Aircraft	New Aircraft	
<b>Level of Integration:</b>	<b>1.</b> Retrofitting or Integration on System Level	<b>2.</b> Integration in A/C and System Design Phase	<b>3.</b> Integration in Conceptual Design Phase
<b>Potential benefits:</b>	<ul style="list-style-type: none"> <li>Advanced warnings of failures</li> <li>Reduction of unscheduled events and NFFs</li> <li>Improved trouble-shooting</li> <li>Reduction of operation interruptions and DMCS</li> </ul>	In addition to 1.: <ul style="list-style-type: none"> <li>Condition-based maintenance</li> <li>Reduced waste of life</li> <li>Increased operability and a/c utilization</li> <li>Reduction of maintenance downtimes and DMCS</li> </ul>	In addition to 2.: <ul style="list-style-type: none"> <li>Reduction of redundancies and safety factors</li> <li>Lower material consumption, production cost, weight, SFC, etc.</li> </ul>
<b>Expected effort &amp; challenges:</b>	<ul style="list-style-type: none"> <li>PHM design and integration</li> <li>Limited sensors, low integration</li> </ul>	<ul style="list-style-type: none"> <li>Certification of CBM for safety-critical items</li> </ul>	<ul style="list-style-type: none"> <li>Certification: PHM/IVHM would be safety-critical item</li> </ul>

**Figure 2: Implementation approach based on the level of integration [Hölzel, 2013]**

The main requirements for a complex system such as a civil airplane have to be decided on before the actual development starts in order to control the committed costs. In later development stages, the implementation of new technologies leads to higher investments. In an early design phase, major changes to the architecture of a plane are still possible and the greatest benefit is expected. With this approach, the amount of unscheduled maintenance and the number of No-Fault-Found (NFF) events can be reduced, while the components' use is safer and based on their actual condition. With the help of PHM, the overall platform safety and operational availability can be increased, whereas system redundancies and structural safety factors can be reduced. As a consequence, a decrease in the weight of the airplane is achieved. This allows for further savings by snowball effects such as the decrease of required thrust level or wing area due to lower weight and generates revenues in form of additional passenger or freight capacity and lower fuel consumption.

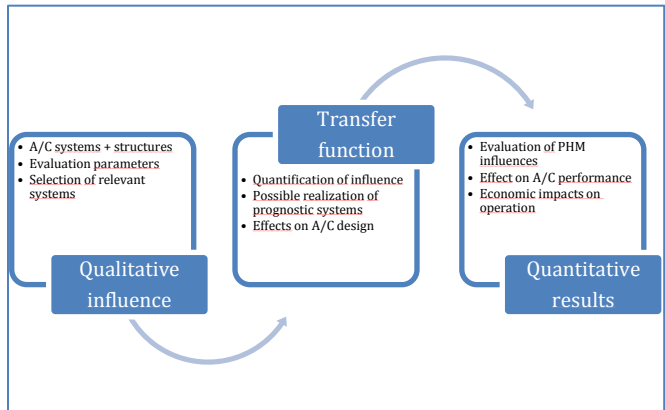
Benefits of PHM as found in various literature (e.g. [Wheeler, 2010] or [Banks, 2005]) include:

- Reduction of maintenance and operational costs, especially through reduction of unscheduled events and attributed costs for delays, cancellations and material (Condition-Based Maintenance)
- Faster and more accurate troubleshooting during maintenance events
- Ability to trend and predict the Remaining Useful Life (RUL) of a component prior to failure and resulting optimized component use
- Increase in operational/dispatch reliability and aircraft/fleet availability
- Inventory management optimization (spare parts) and intelligent aircraft route allocation (maintenance centers)

Examples of PHM systems for the analysis can consist of a PZT<sup>1</sup> sensor network connected with fiber optic cables generating & capturing guided Lamb waves, acousto ultrasonic patches, Eddy Current, thermography etc. with the respective data processing e.g. in the ACMS (Aircraft Condition

Monitoring System). A variety of sensors specialized on certain functionalities for Systems Health Management, such as sensors for current, vibration, flow, pressure are used for the evaluation. Especially on systems level, a lot of data can be retrieved from already installed Built-In Test Equipment (BITE) as shown e.g. by Taleris' "Intelligent Operations", a service by GE and Accenture focused on improving efficiency by leveraging aircraft performance data, prognostics and recovery [http://www.taleris.com/].

Most of the current literature is focusing on the technical feasibility of PHM solutions on component level or Systems Engineering approaches for requirements and implementation but only few authors show its quantitative benefit. To fill this gap, the following thread is chosen for this project:



**Figure 3: Project thread**

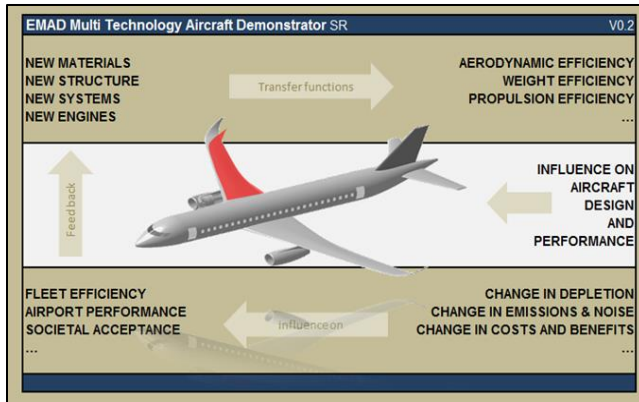
[Speckmann, 2008] states:

*“Due to current maturity level of the SHM technologies, the economic benefits are not yet available for customer and cannot be realistically reached before 2008.”* Six years later, the PHM technologies are more mature and the awareness for this technological evolution in aircraft design and operation is growing. Now is the time to make the stakeholders aware of its economic benefits and potential gains in order to foster innovation.

**2. APPROACH**

The methodology implemented in this project makes it possible to evaluate the effects of PHM on different levels. The aircraft systems as well as the structure are examined separately according to ATA-chapters. In order to achieve representative results, the qualitative influences of PHM are translated into a “Transfer Function” to show the economic benefit by means of Cost-Benefit Analysis (CBA). This analysis can be used as an argument for the quantitative evaluation of the implementation of the new PHM technology. The improvements of a PHM system for aircraft structure, systems, maintenance and availability are estimated with the help of the DLR-internal CBA-tool, the “Multi-Technology Aircraft Demonstrator” (MTAD) (Figure 4):

<sup>1</sup> Lead zirconium titanate



**Figure 4: Multi Technology Aircraft Demonstrator [Weiss, 2007]**

With this tool, it is possible to evaluate new technologies in terms of costs, emissions and socio/eco efficiency. The new technology in form of innovative materials, systems or structural layout is translated into a Transfer Function to compare its effect on aerodynamic, weight and propulsion efficiency with a reference aircraft. With the integrated life-cycle calculation, it is possible to compute economic values such as the Net Present Value (NPV) or Internal Rates of Return (IRR) for the aircraft operator and ecological emissions in form of CO and NO<sub>x</sub>. The base of comparison for the studies is a single aisle short-range aircraft such as the A320. The scenario is the application of PHM on future aircraft, e.g. an A320 successor.

### 3. RESULTS

After a thorough literature research on the mentioned topics and performance of respective CBA calculations, results of the project include:

- Qualitative evaluation of Prognostics and Health Management on structural and system level → Benefits in terms of weight savings, Operational Interruption (OI) reduction – availability increase, maintenance task escalation, effective use of RUL, Direct Maintenance Cost (DMC) savings, Non-Recurring Costs (NRC) & Recurring Costs (RC)
- Long-term benefit: Reduction of redundancies on system level and changed structural design principles (damage tolerance, allowables, safety factors) based on better knowledge of structural state and prognostic capability; verification and specification of 10 % acquisition cost reduction potential ([MacConnell, 2007])
- Quantification of benefits concerning aircraft design and operation on ATA-level based on Transfer Function and advanced CBA; verification and comparison with 30 % life-cycle cost reduction potential ([MacConnell, 2007])

### 3.1. Structural Health Management

The possibility of Structural Health Monitoring on aircraft-level is evaluated parametrically from an operational (sensors, cables, power and data transmission) and economic point of view (added mass, higher fuel consumption vs. reduced structural reserves, higher availability, reliability) and response surfaces are created.

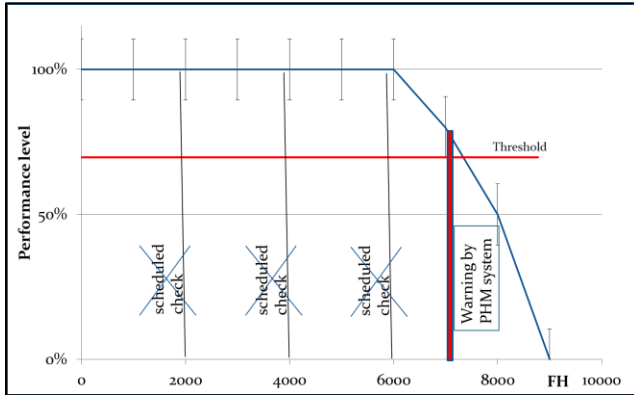
One example for the alternative structural design with PHM is the dimensioning of stringers in the fuselage. According to current design principles, stringers have to be assumed broken if the skin is torn. With a PHM system, e.g. in form of a network of PZT sensors and Lamb waves, the stringer can be monitored intact above a skin crack and therefore this design constraint is no longer valid. According to [Assler, 2004], the allowable stress level can be increased by 15 % which leads to 15 % weight savings (assumed linear correlation between weight and stress level [Speckmann, 2006]). The saving sums up to around 190 kg. The weight of sensors and cables for this SHM is approximated to be 15 kg which reduces the savings to 0.04 % of the aircraft Operating Empty Weight (OEW). Through snowball effects, the wing weight can be reduced by 0.01 % and the fuel consumption drops accordingly. A trade-off study shows that this corresponds to a delta of app. 1.5 \$/kg OEW. This reduction of 1.5 \$/kg for an OEW of 41,680 kg results in 62,520 \$ per aircraft. Multiplying this by the number of expected sales gives an idea about the margin for NRC and RC for the implementation of the PHM system. Assuming a market of 1,000 aircraft results in a budget of 62,520 k\$, or 43,764 k\$ with a profit margin of 30 % for the OEM (Original Equipment Manufacturer). An approximation of NRC & RC via percentage values from [Curran, 2004] and [Lammering, 2012] shows that a completely new design of the stringers can be possible with this saving but a partial re-design due to changed constraints is more cost-effective. False alarm events have to be taken into consideration, reducing the overall benefit. On the other side, an increase of the flight safety is a clear benefit which cannot be expressed in monetary value.

Another benefit of PHM is the escalation of maintenance intervals. The inspection interval (II) is derived from “lives”  $n_i$  (number of flights) and a ‘life factor’  $j_L$  as explained in [Teske/Schmidt, 1999]:  $II \leq \frac{n_2 - n_1}{j_L}$

As an example, the life factor for bearings in service doors can be reduced from three to one due to the new SHM inspection method that guarantees continuous monitoring, e.g. in form of oil debris and vibration analysis (see [Goebel, 2005]). Thereby, the check interval can be increased from 13,500 to 40,500 FH which leads to the escalation or even deletion of the maintenance task.

Assuming similar factors for other inspections, the escalation of the entire structural inspection check from e.g. 12 to 13 years leads to an NPV increase of about 4 % within 16

years. This however requires a thorough assessment of all carried out tasks. The ultimate goal regarding scheduled maintenance is a complete performance monitoring with a warning from the PHM system when the performance drops below a certain threshold (see Figure 5):



**Figure 5: Escalation of scheduled maintenance tasks**

This way, scheduled checks can be reduced to a minimum and unscheduled events become predictable.

### 3.2. Systems Health Management

On ATA-level, systems that are particularly suited for PHM and have a great effect on reliability/availability, installation, maintenance effort, operational costs (e.g. avionics, hydraulics, air conditioning) are analyzed parametrically. In this “top-down” approach, parameters such as the weight, functionality and numbers of parts of a system are used to generate a function for the necessary sensors and the possible impact on NRC, RC and weight on the cost-side opposed to benefits such as reduced maintenance effort and Operational Interruptions. This parameterized approach will have to be validated and improved by a detailed analysis of the respective aircraft systems.

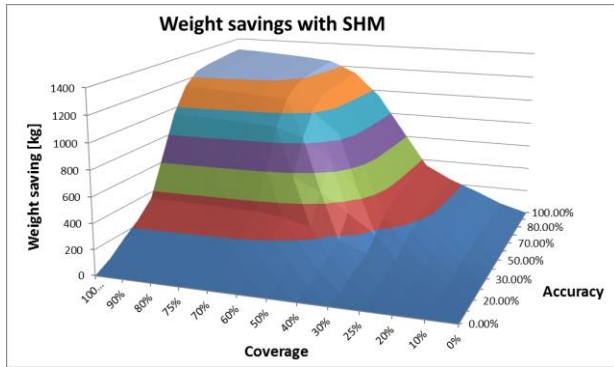
A paradigm shift in system redundancy can be triggered by PHM systems. If failures of systems can be predicted with a sufficiently high reliability (depending on the Failure Effect Category), redundancies can be reduced in order to save weight, complexity and potential failure causes. Examples are air conditioning packs (~82 kg), one of the three hydraulic systems (~290 kg each) or parts of the oxygen systems. An explicit consideration of the respective failure categories per component/function is hereby inevitable. For the systems, a major benefit of a PHM system is expected through a reduction of OI rates. These interruptions lead to delays and cancellations which can be reduced with the help of PHM. Another benefit is the DMC reduction through less scheduled & unscheduled maintenance tasks, troubleshooting times and spare part logistics.

The possible benefits of PHM for ATA21 – Air Conditioning are discussed in the following example: With an assumed amount of parts with different part numbers of 67, seven basic functionalities (compression, distribution, pres-

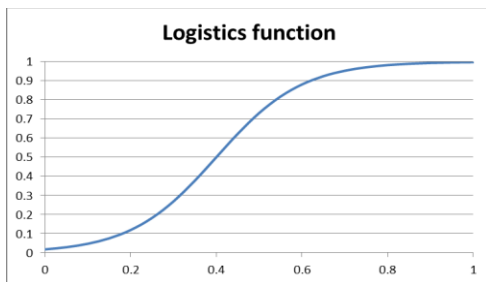
surization control, heating, cooling, temperature control, moisturize/air contamination control) that need to be covered. Temperature, flow, pressure and hygrometer sensors are necessary to guarantee the functionality and the amount of sensors adds up to 13 (without already installed BITE) (no. of parts \* 0.2; Pareto approach: 80 % of failures caused by 20 % of components/functions) with a corresponding weight of 0.938 kg. As most of the systems are already supplied with power and data transfer, no additional effort will be assumed. A typical OI-rate (per 100 revenue flights) for ATA21 as mentioned by [Feng, 2013] is around 0.044. On the basis of the Pareto distribution (80 % of failures covered by 20 % prognostic capability), a new OI rate of  $0.044 * 0.2 = 0.0088$  is approximated. The corresponding mean saving per 100 flights (mean delay of 63 min with costs of 8,000 \$/hour) is estimated to be around 296 \$. Considering flights over 16 years with 4.5 flights/day, app.  $296 \$/100 * 26280 = 77,789 \$$ , which corresponds to an NPV of 38,037 \$ after 16 years with a constant discount rate of 0.1, are expected. Multiplying this with the number of expected sales of 1,000 aircraft results in a budget of 38,037 k\$, around 26,625,900 \$ with a profit margin of 30 % for the OEM. This expected gain justifies the costs for development and RC for the PHM system. Approximated via the weight and number of parts of the system, NRC (development & installation) are estimated in relation to the approximate costs of 1 B\$ for a new aircraft development and account to app. 10 M\$ for ATA21. The remaining delta can be used for the inevitable recurring maintenance costs which are approximated via percentage values taken from [Lammering, 2012]. Reduction of redundant features such as the second air conditioning pack allows for further weight savings of 82 kg with respective snowball effects, around one extra passenger. The corresponding reliability for the functionality of the pack has to be guaranteed by the system.

### 3.3. Response surface

As the examples shown here are assuming a perfect PHM system and no technical system can guarantee 100 % reliability, a trade-off for uncertainties and failure possibilities has to be carried out. For this project, the approach is to show this interdependency by means of response surfaces for different degrees of reliability and coverage of the PHM system (see Figure 6). The run of the curve is approximated with a logistics function as used for many statistical problems (Figure 7). It is based on the assumption that very low coverage as well as low reliability lead to low savings due to high risk and lack of credibility. Respectively, very high coverage and reliability are required for according savings as dramatic improvement opportunities are exhausted.



**Figure 6: Response surface for weight savings plotted against coverage and accuracy**



**Figure 7: Logistics function for response surfaces**

Other relations, such as combinations of logarithmic, linear and exponential functions are possible.

#### 4. CONCLUSIONS

A methodology for the assessment of costs and benefits of PHM systems for future civil aircraft is presented and its applicability is shown on the basis of case studies. Exemplary business cases on structural parts such as stringers and systems like air conditioning prove that the potential benefits in terms of weight reduction, increased availability and reduced maintenance efforts can outweigh additional weights, costs for the development and maintenance of the diagnostic/prognostic system. By using a parametric approach, the analysis can be further refined. The uncertainty of prognostics and failures of the PHM system is represented by the use of response surfaces for the potential benefit.

#### 5. OUTLOOK

In order to state the costs and benefits for respective structures and systems more thoroughly, a dedicated assessment on component level is suggested with the FMECA process and decision metrics as justification method, also for future certification. The potentials of already installed BIT/BITE and the architectures for new sensors, data transfer and processing will have to be evaluated. A detailed economic assessment with different scenarios for the various systems/structures and complete analysis of task escalation/deletion for respective components can take place in order to implement PHM for the most cost-effective systems.

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