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AEROSPACE RECOMMENDED PRACTICE

ARP6275

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Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System

RATIONALE

This SAE Aerospace Recommended Practice (ARP) provides insight into the factors to be considered for not only generating a cost benefit analysis but also the justification for implementing an integrated health management system to an air vehicle. With the considerable advancement of prognostics and health management (PHM) tools and capabilities in the past 10 years, more and more operators and fleet managers are asking for ways in which the overall value proposition of installing such a system, be it on in-service equipment or still-in-design systems, can be determined.

TABLE OF CONTENTS

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1. SCOPE

This ARP provides insights on how to perform a cost benefit analysis (CBA) to determine the return on investment that would result from implementing an integrated Health Management (HM) system on an air vehicle. The word "integrated" refers to the combination or "roll up" of sub-systems health management tools to create a platform centric system. The document describes the complexity of features that can be considered in the analysis, the different tools and approaches for conducting a CBA and differentiates between military and commercial applications. This document is intended to help those who might not necessarily have a deep technical understanding or familiarity with HM systems but want to either quantify or understand the economic benefits (i.e., the value proposition) that a HM system could provide. Prognostics is a capability within some HM systems that provides an estimation of remaining useful life (RUL) or time to failure and so Prognostic Health Management (PHM) is used where this predictive element exists. IVHM refers to an integrated vehicle level system deployed on a fleet of platforms and might, but not necessarily, include predictive elements.

1.1 Purpose

This ARP is not a standard or legal document because the approaches towards the end objective are many and varied. The document has been compiled to help the increasing number of people who want to compute a HM CBA prior to implementing such a system on a platform.

1.2 Approach

The approach taken was to identify the parameters that were relevant for consideration in a cost benefit analysis so that the boundaries of a specific problem could be defined from the outset. Several recent and worthy papers presented at conferences on the subject matter were studied and as much information as possible was obtained from the aerospace manufacturers and the DoD to identify tools and techniques that they might have used to good effect. The various methods were assessed by the SAE HM-1 Technical Committee team for their application to specific scenarios (e.g., military or commercial operation, legacy or new engines) and the parameters utilized by each scenario. The end result is a document that offers the reader various solution paths so that the one most appropriate to the specific situation can be used or adapted.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

Jennions, I.K., "Integrated Vehicle Health Management: Perspectives on an Emerging Field," SAE International, Warrendale, PA, ISBN 978-0-7680-6432-2, 2011, doi:10.4271/R-405.

Jennions, I.K., "Integrated Vehicle Health Management: Business Case Theory and Practice," SAE International, Warrendale, PA, ISBN 978-0-7680-7645-5, 2012, doi:10.4271/R-414.

AIR1871, Lessons Learned from Developing, Implementing, and Operating a Health Management System for Propulsion and Drive Train Systems

ARP1587, Aircraft Gas Turbine Engine Health Management System Guide

AIR4061, Guidelines for Integrating Typical Engine Health Management Functions Within Aircraft Systems

AIR4175, A Guide to the Development of a Ground Station for Engine Condition Monitoring

ARP4176, Determination of Costs and Benefits from Implementing an Engine Health Management System

AIR5871, Prognostics for Gas Turbine Engines

2.1.2 Other Documents

Reference 1: Army Implementation of CBM: 2012 Update, Presented by Chris Smith, Army Aviation & Missile Command. Annual Conference of the Society for Machinery Failure Prevention Technology (MFPT), Apr 25th 2012, Dayton OH. Available from Society for MFPT, 5100 Springfield St., Ste 420, Dayton OH 45431-1264 (937)-256-2285, www.mfpt.org.

Reference 2: "Metrics, Models, and Scenarios for Evaluating PHM Effects on Logistics Support". Presented by Joel Luna, Frontier Technology, Annual Conference of the Prognostics and Health Management Society, San Diego, 2009. Available from the PHM Society, www.phmsociety.org.

DO-160G "Environmental Conditions and Test Procedures for Airborne Equipment". Published by RTCA Inc.

DO-178C, "Software Considerations in Airborne Systems and Equipment Certification". Published by RTCA Inc.

DO248A "Final Report for Clarification of DO-178B". Published by RTCA Inc.

DO-254 "Design Assurance Guidance for Airborne Electronic Hardware". Published by RTCA Inc.

DO278B "Software Integrity Assurance Considerations for Communication, Navigation, Surveillance and Air Traffic Management (CNS/ATM) Systems". Published by RTCA Inc.

DO-330 "Software Tool Qualification Consideration".

3. ACRONYMS

ACARS Aircraft Communications Addressing and Reporting System,

ACMS Aircraft Condition Monitoring System

AHTMS Aircraft Health and Trend Monitoring System

AOG Aircraft on Ground

ATP Acceptance Test Procedure

CBA Cost Benefit Analysis

CBM Condition-Based Maintenance

DoD Department of Defense

DSC Digital Source Collector

FMEA Failure Modes and Effects Analysis

FMECA Failure Modes, Effects, and Criticality Analysis

HM Health Management

HUMS Health and Usage Monitoring System

IFSD In-Flight Shutdown

IVHM	Integrated Vehicle Health Management System
JSF	Joint Strike Fighter
LLP	Life-Limited Part
LRU	Line-Replaceable Unit
MEL	Minimum Equipment List
MRO	Maintenance, Repair, and Overhaul
NDI	Non-Destructive Inspection
NFF	No Fault Found
NRE	Non-recurring Engineering
OEM	Original Equipment Manufacturer
PoD	Probability of Detection
PHM	Prognostics and Health Management
PTCRB	PCS (Personal Communication System) Type Certification Review Board
ROI	Return on Investment
SER	Scheduled Engine Removal
TOW	Time on Wing
UER	Unscheduled Engine Removal
WIP	Work in Progress

4. INTRODUCTION

4.1 Motivation for Implementing an Integrated Health Management System

While aircraft condition monitoring has been utilized in various forms since the late 1960s (e.g., at the launch of Boeing 747 operations) and with steadily increasing capability since the 1970s, prognostics and health management (PHM) tools and capabilities have come from relative infancy in the early 1990s to now being sufficiently mature to implement on airborne systems. Additionally, modern aircraft components have become much more proficient at providing their health status to a higher management system thus allowing a PHM system to achieve its end goals of predicting necessary maintenance and reducing unnecessary maintenance activities. The components not only provide status indications but also operating data that can be analyzed. This rapid progress in “predictive” technology was mainly the result of the pull by the DoD’s Joint Strike Fighter (JSF) Program, which became the F-35 Lightning II aircraft. With affordability at the core of the program, the U.S. Navy agreed, for the first time, to accept a single-engine aircraft for carrier-based operations if a PHM system was able to provide warning of system failure at least one flight prior to the actual event. This predictive or “just in time” capability had been identified back in the late 1960s (ARP1587) but now there was a stated program requirement as opposed to a serious desire. In the case of the JSF for example, the ability to predict the need to do maintenance or remove an engine just before it is about to fail in service is sufficient justification to accept the implementation of a PHM system without further economic analysis, but it doesn’t consider the driving intent or original motivation for implementing a PHM system. For a commercial operator, the same is true for a major system component, such as a bleed system valve or an air conditioning pack. The base-line reason or initial motivation for considering implementation of a PHM system is where the analysis needs to start. The initial driving force for the JSF program was to maintain a previously experienced and accepted level of *safety* with the added benefit of reduced redundancy (one engine instead of two) and/or conservatism. In contrast, the commercial aviation world sees the benefits of a PHM system primarily in terms of *economics*. Commercial airline OEMs and operators typically meet or exceed the safety requirements put upon them by the regulatory authorities so PHM for increased safety is not a prominent driver for commercial operators. However, where safety can be improved as an associated benefit from some other action, then clearly this should be pursued by operators and manufacturers. This is most apparent in the rotary wing community, especially in oil and gas operations, where increased safety was the original driver, and still is the prominent driver, for a HUMS (Health and Usage Monitoring System). So, regardless of whether the driver is safety or economics, there are many aspects that are common to both when considering implementation of a PHM system on a platform, as discussed in the next section. The high level process flow (or architecture) of a typical PHM system is illustrated in Figure 1.

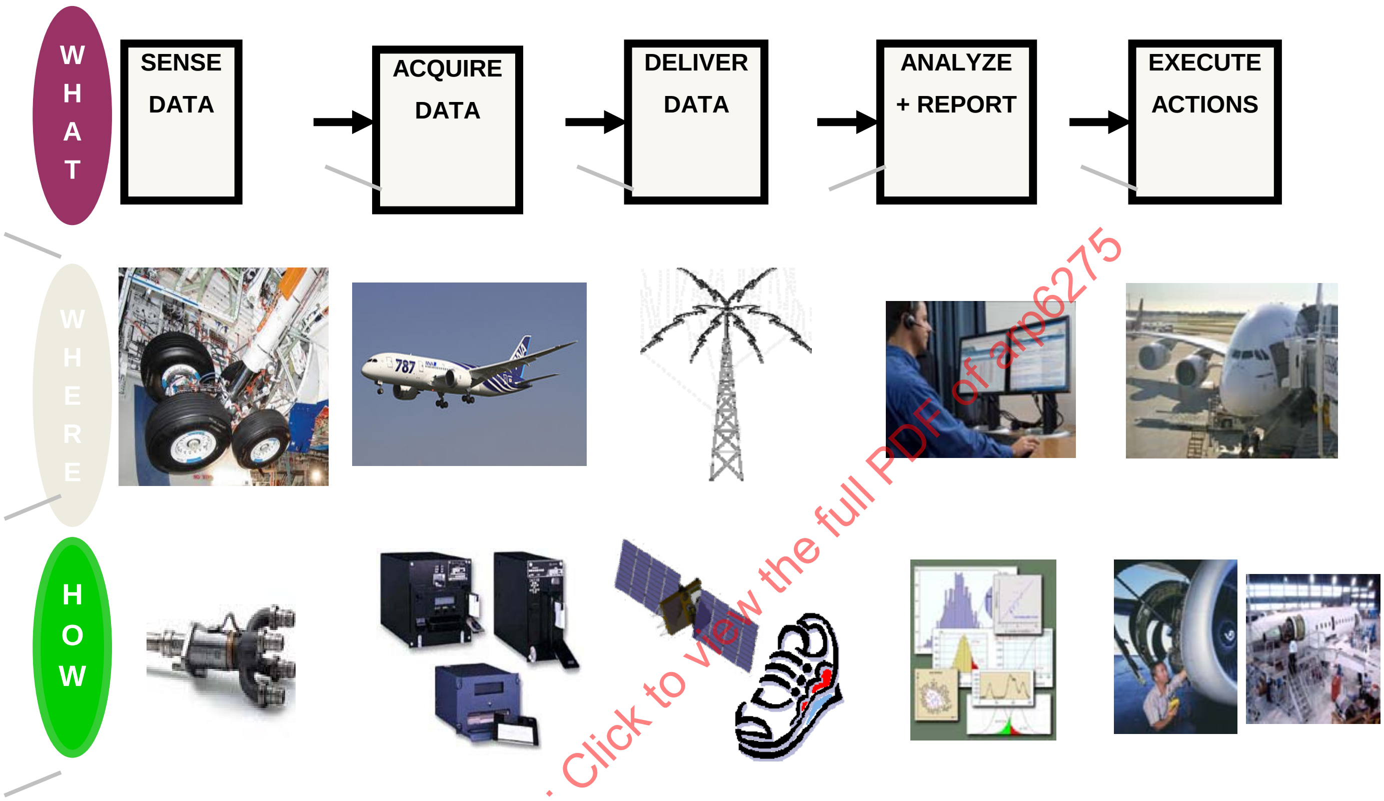

FIGURE 1 - A TYPICAL PHM HIGH-LEVEL PROCESS FLOW

4.2 Fundamental Considerations Preceding the Cost Benefit Analysis

The initial entry point for considering the implementation of a PHM system on any piece of equipment is to identify and define which specific failures or modes of failure should be detected. The PHM system will thus be configured to identify degradations that will lead to a failure that is either unsafe, expensive, leads to mission compromise or failure, or creates major inconvenience to the operator or its customers. Examples of such are engine disk bursts, or landing gear non-deployment, or sub-system failures that can lead to route diversions. These incidents are not only costly for the operator but also cause major inconvenience to the customers. There are many other failures which could be termed innocuous in that they are easily repairable, don't pose an in-flight hazard, or are inexpensive to fix, but it is important to evaluate possible failure propagation in the original Failure Modes and Effects Analysis (FMEA) or the more quantitative, Failure Modes, Effects, and Criticality Analysis (FMECA) to ensure they do not lead to larger costlier issues in the future. Many airline passengers experience such frustration with failures of their overhead seat lighting, and personal entertainment malfunctions. Other failures are typically remedied by "quick fixes" to the aircraft, conducted by maintenance personnel while the aircraft is at the gate, but which might nonetheless still delay the plane's departure. In the general aviation world, especially the business aircraft, many operators attach a high price tag to an unscheduled "event", especially one that causes the passengers to be delayed. It is proffered that any failure can be detected in its incipient phase if the parameters associated with the degradation that precede the failure are being monitored and analyzed. The reality is that many failures or modes of failure are not monitored because the designers, operators, or maintenance personnel have determined that to do so is not worthwhile, or not technically feasible. However, during the operating life of a fleet of aircraft, technological advances in data collection, fusion and analysis may now allow previously undetectable failure modes to be detected. Additionally, different failure modes come to light, or regulations change to affect maintenance and inspections, or the modus operandi of the platform/system changes that, in turn, can change the ways and means that components are monitored. In other words, PHM on a system is "a living thing" and needs to be flexible, adaptable, and easily updated to accommodate these continuous changes. Nonetheless, the unavoidable starting point is to define the failures in the system that need to be mitigated (for whatever reason), determine how those failures can be anticipated at a sufficiently early stage (from data generated during system operation), and identify the sensors and analytical tools (PHM) that will reliably provide the necessary information. From that point, a cost benefit analysis can be initiated.

5. FACTORS INFLUENCING COST BENEFIT STUDIES AND ANALYSES

5.1 PHM System Complexity

Nowadays, a PHM system can be as complex as a customer requires. Manufacturers at all levels (i.e., from component level to final integrator and provider of the platform to the customer) have an interest in providing a platform efficient operation especially if a “Power By The Hour”™ or Parts Management Contract is in place. Consequently, the amount of data the manufacturer needs, to achieve the contract terms, increases significantly. This is predominant in the commercial world. In the near future, PHM systems will be utilized to monitor and trend aircraft sub-systems. For example, landing gear retraction can be evaluated over time; if the time taken for the landing gear to retract is increasing, the interacting systems can be monitored to accurately diagnose the root cause. Similarly, slowly increasing asymmetry over time of flight control surfaces such as flaps, ailerons and spoilers and rudder positions is important to know not only from a flying perspective but also a desire for fuel efficiency, especially on long-haul flights. In the case of control surface asymmetry, airline operators are interested to the extent that they will monitor fuel consumption on a tail number basis and perform checks on the control surface positions of the planes with the worst fuel consumption because they see the need to do so; they are practicing Condition-based maintenance (CBM) based on fuel consumption changes. The cost benefit analysis of a PHM system is thus highly dependent on the requirements of the end customer yet, up to now, HM systems in general have been largely provided by the airplane manufacturers who have typically pre-determined the capabilities. However, ever changing priorities, such as an increased interest in fuel savings by the operators, is likely to introduce additional, new features or new functionalities to meet the operator’s defined needs. An example would be more sophisticated monitoring of control surface positions, especially any synchronization issues when they are being deployed. While the system would be operating satisfactorily, and safely, and meeting operating specifications, it might not be optimized for fuel efficiency. The interface to the aircraft will also need some degree of customization. This includes the degree of “on-board” analysis of the data and real-time action compared with downloading data at some later date and processing it in a ground software station. Thus, the user needs to determine, at the outset, the desired capabilities of a PHM system and build a CBA from that base-line. If the specific needs are not able to be precisely defined, then several scenarios could be created and a CBA computed for each, which would reveal the trade-offs between system complexity and return on investment.

In the propulsion arena, which has historically tended to be the lead sub-system for HM, mandated vibration monitoring resulted in vibration monitoring systems installed on engines and aircraft in the seventies. In more recent times ETOPS (extended twin engine operations), drove the need for an EHM system in commercial fixed wing operations, especially those across water, as was also the case for rotorcraft operating in support of oil rigs in the North Sea. For airframe systems, the drivers are not so clear cut and there are no mandates to equip a fleet with a HM system. Instead, once the HM capabilities are visible and demonstrated to the airplane OEMs or the operators, then business cases start to be generated because the capability has generated new, perceived needs. In other words, capabilities sometimes generate needs as opposed to needs generating the development of new capabilities. However, some regulation-driven PHM functionality does exist today on airframes. For example, for emergency battery backup systems, there is a requirement to show the state of charge (SoC) indication before a flight so that the flight crew can be assured that the battery can be used during an emergency to restart the engine or to provide power for other essential electrical functions. This is an example of a PHM system specific to the airframe.

5.2 Usage: The Considerations and Differences between Categories of Operators

It is well appreciated that military and commercial aircraft operate in starkly contrasting flight regimes and this makes a large difference when considering the cost benefit approach to take. First and foremost, commercial operators fly similar operations every day, whereas military aircraft are typically conducting flying training and preparatory operational missions on a normal basis until a major exercise or combat/war scenario is brought to bear, at which time the intensity of operations increases significantly for an unknown period of time (could be several days to several years). Generally, military airplanes fly into and out of the same base on a daily basis whereas commercial planes are typically crossing the country or world where maintenance facilities at non-hub locations are often less comprehensive. A combat military PHM system is generally more complex (with armament systems, sophisticated radar and self-defense measures, etc.) and will in many cases take into account many more failure modes, even though some might have a very remote probability of occurrence. The commercial carrier, on the other hand, would typically want a less complex system, capable of detecting gradually changing trends with a well understood and predictable set of failure modes but with extremely high reliability so as to minimize false alerts. Additionally, the “detection window” required for commercial aircraft is likely to be much longer than military (maybe 25 to 50 flying hours compared with five to ten for military) because of the higher usage rate and the longer flight durations. An aircraft on the ground for a commercial operator is earning no revenue; a military aircraft on the ground, while not available for its intended use, has no monetary loss attached to it. In short, the military is focused on mission success and the commercial operations are most interested in schedule reliability and cost of operations. For these reasons, and others that can similarly be identified, the rationale and approach to PHM cost benefits are vastly different between commercial and military operators. Business jets and cargo operations, while subsets of commercial-type operations, are sufficiently different from airline passenger operations to necessitate the design of their own health management systems. Factors such as fleet size, the unique demands of the business jet passenger and the non-human payload on cargo airplanes drive quite different requirements from a HM system. For business jets, availability, which is driven by reliability, is the most important factor, certainly more so than cost considerations, and arguably higher than for either military or other commercial operations. For any of the four main types of airplane operations cited above, different cost-benefit models and approaches are needed so that one which best suits the specific circumstances can be utilized. While it is recognized that the differences in operational scenarios across the various types of operator could be addressed by a generic CBA model, in which the importance or weighting of different cost benefit elements could be adjusted, there are many other factors, such as those covered earlier, that necessitate the building of a customized approach.

5.3 Legacy versus New Platforms

There is a big difference in approach between applying a PHM system to a mature or legacy platform compared with one still in the design stage. Firstly, older “legacy” platforms typically have more antiquated databus and data recording capabilities, requiring investment in more complex ground systems to do off-board processing. Newer platforms have more centralized data collection, processing and computing power, and are thus able to perform more HM functions on board. Ground systems to support these types of platforms can also be complex, as they strive to implement more complex algorithms to deal with the exponentially growing data that is available for analysis on modern vehicles. Secondly, while the legacy platform has, depending on age in service, typically demonstrated some failure modes and certainly generated a wealth of data, there is understandable reluctance (because of the cost and disruption) to retrofit a PHM system to such an operational fleet. While one can gain a sense that the qualitative cost benefits are reduced by the mere thought of fleet modification, the PHM system could be specifically designed to address the sub-system failure modes that had been demonstrated in operational service, as opposed to those defined at the outset. Moreover, the available fleet data provides insight into the number of occurrences of the various failure modes and an experience base of the resulting costs or disruptions. These data enable the cost benefit case to be not only more carefully computed but also more believable based on the fact that the data are “real” as opposed to conjecture. For a fleet that is still to be introduced into service, implementation of a PHM system in the design stage is undisputedly the optimum time, both from ease of embodiment and ROI. However, there is likely to be neither operational data on which to help define the PHM system design nor real reliability data to predict the number of failures that the PHM system is going to “prevent” or predict. This makes a cost benefit analysis more difficult to not only compute but also to generate with sufficient fidelity. On the other hand, many of the hardware costs of a PHM system may be already cost justified, based on other business needs or at least shared with other needs making the effort much easier. The earlier reference (4.2) to a PHM system being a “living thing” as opposed to a “fit and forget” capability is thus apparent for both new and legacy systems. The sustainment, which includes the continual evolution of the PHM system, is therefore a cost element that needs to be included in the CBA for both.

In legacy commercial platforms, ACARS (Aircraft Communications Addressing and Reporting System) has been the traditional and world-wide system for notifying degenerations or sudden faults that breach a pre-set threshold of acceptability. Additionally, FOQA (Flight Operations Quality Assurance) is a process which uses data captured in flight at around 1 Hz, and subsequently trended on the ground, to monitor how the plane is both flown/handled and operating. Software development to capture the data sets has been necessary and, in some cases, modifications to the flight data recorder or ACMS (Aircraft Condition Monitoring System) have been pursued to capture data in a particular format so as to be sent over the ACARS. This has required software modifications on the aircraft and on the ground operations hardware to enable the data to be received and handled. Some airplane OEMs maintain that retrospective addition of sensors or HM algorithms is still viable, depending, of course, on the motivation. One particular OEM cited the addition of a sensor to collect an extra parameter onto the databus that was driven by HM needs. It is thus important not to over-generalize and assume that retrofits are not economically practical. While it will usually be a tougher case to justify, the ease of installation onto a legacy system and the benefits derived can conspire to make the case. The situation can be further complicated by which party is perceiving the benefits. Once again, the motivation can be OEM driven or operator inspired and while both will have different perspectives, it matters little; if one of them sees the benefits sufficiently to propose the introduction of a PHM system, then the two parties collaborating to explore the optimum scope, the system’s degree of complexity and its implementation will probably generate the best end result.

Consider, for instance, adding an “embedded reasoner” to an unmanned air vehicle (UAV) which will basically perform prognostics and health management for all the systems on the platform. While improved availability and reduced maintenance benefits can be computed, the negative effect on the platform’s range or “time on station” can also be determined, based on the additional weight of the on-board system and the reduced fuel load capacity. Herein is the complexity. If the embedded reasoner is retrofitted to an existing platform, resulting in added weight, then the downside is the reduced number of minutes that the UAV can loiter at the area of interest; this has to be weighed against the qualitative benefits of improved availability, reduced maintenance, etc. But if the reasoner system is implemented during the design of the UAV, then it might be that the redundancies and conservatism inherent in the original design can be removed or reduced (e.g., single flight control actuators instead of dual, vehicle structural weight, etc.). The end result could be that introducing a PHM system and its associated weight, actually *reduces* overall platform weight and possibly cost of manufacture and *improves* platform capability and performance (such as time on station). That said, the Safety Assessment process exists in civil aviation to guarantee that the probability of occurrence of faults is proportional to the inverse of its severity. One way to guarantee that is to add redundancies. It is currently not an acceptable procedure to take credit for PHM in the Safety Assessment process, i.e., the regulations that define the Safety Assessment process do not comprise the use of PHM in that way. On the other hand, HUMS, which has been established for decades, has enabled at least one operator to be granted maintenance credits (which is an earlier step than being able to remove a redundancy) and has occurred because there are regulations that define the possibility of getting maintenance credits by using HUMS. This is important for those considering to perform a CBA for IVHM to understand that the potential benefit is currently a long term possibility. Additionally, building in capacity at the outset for introducing smart software updates that would increase PHM capability in the future, depending on how the new platform performs as it ages, would be prudent as software is typically easier and cheaper to retrofit than hardware.

5.4 Impact on Design

In the current era, the aircraft manufacturer needs to design the aircraft with PHM in mind, and, in so doing, press suppliers of LRUs or sub-systems to ask themselves these two questions: “What data would I need to determine whether my LRU/sub-system is failing?” and “If I could collect data to trend my LRU/sub-system over time, would I be able to remove and replace the faulty component just prior to a failure?” These questions impact how engineers design their systems on a more detailed level than just taking into account the weight and cost of a PHM system. It is not easy to do, but it is a necessary step if the PHM system is to be at its optimum effectiveness. It also generates more initial costs, but these should be seen as an investment as they will generate a greater set of benefits. As discussed in the prior paragraph, the benefits are likely to be shared, albeit to varying or different extents, by both OEM and operator. Interestingly, besides the OEM and operator, third parties may also benefit (e.g., by providing IVHM related services). If a third party is going to provide services, instead of the OEM (because the OEM may not be willing or interested in providing IVHM services), then the OEM might have a lesser interest in adding PHM features to the aircraft, so the level of the OEM’s interest in the after-market activities might well influence the design of the PHM system. Additionally, the business case must be clear for suppliers. Sometimes, suppliers are risk-sharing partners in the development of a new aircraft. If the business case to suppliers is not clear, than adding PHM features to components and sub-systems may become excessively costly.

5.5 Performance versus Reliability or Sustainment

For commercial platforms, increasing a fleet’s performance and capability is not usually as important as cost-effective sustainment of the fleet throughout the life cycle. For business aircraft, increasing dispatch reliability and availability is a key focus area. For military systems however, technology upgrades and increases in performance or capability usually trump fleet modifications, even if those modifications might greatly benefit life cycle costs. Such an example is fleet implementation of a new radar for the F-15E in the 2005-2015 timeframe at a cost of about $800M, a program that for the available funding competitively beats out other sustainment initiatives (such as replacement of pyrotechnic bomb racks with pneumatic bomb racks despite the highly attractive cost benefit analysis, or implementation of PHM systems). The point is that the strength of a CBA is not the only thing that determines whether a PHM system is implemented on a platform or not. An extremely strong CBA case could still be insufficient to win the necessary funding for implementation. Other considerations can come into play including affordability, public perception (e.g., of a safety issue), contractual commitments, customer acceptance, etc. As discussed in 4.1, civil/commercial operators will be more driven by economics than in the military world, where maintenance is measured by labor-hours per flight-hour, but not necessarily paid for by the hour (the military personnel are seen as a sunk and set cost, irrespective of hours worked). Winning the military fight against adversaries is uppermost. Nonetheless, the complex interaction of these two contrasting scenarios can be easily sensed and vigorously debated. A PHM system could be advocated in military applications based on the system’s contribution to “win the fight” through reduced or zero “surprises” during the operation of the weapon system (i.e., improving “mission assuredness” and/or “readiness”), a meaningless factor in commercial aviation. Calculating or assigning a monetary cost benefit to, say, a one percent increase in platform availability, readiness, or mission success is extremely complex and arguably the most nebulous factor to calculate. This is because the value of availability is surrounded by subjectivity; understandably, availability means different things to different operators and entities. The issue is discussed more in 7.7.2.

5.6 Cost Savings versus Cost Avoidance

When calculating all the total financial benefits (referred to in this document as *cost reduction*) it is important to distinguish between cost savings, where the actual costs of an activity are saved in true currency, and cost avoidance, where a cost that was being incurred is “saved” but doesn’t actually show in the bottom line of the financial statements. Cost avoidance is also used for warranty expenses which are estimated and accrued as future risk but not part of an operating budget. Practically, savings in warranty cost do come to the bottom line eventually. By way of simple examples, the military does not recognize maintenance reductions or labor-hour reductions as monetary savings, but they can be book-kept as cost avoidance. This is true for commercial operations as well. It is hard to quantify cost avoidance of a delay, cancellation or air-turnback that did not occur. To address this, one OEM recently implemented a way for customers to record this type of “benefit” in the HM system (e.g., delay avoided) to aid in quantification. Additionally, many business-jet operators place a high dollar value, which can reach six figures, on missing a scheduled trip due to unscheduled aircraft system failure. Cost savings are clearly easier to measure, and can usually be done via some simple quantifications around work-flow (e.g., less manual research, more efficient troubleshooting, and reduced no fault found rates). The commercial operators typically have a lot of data on removing, say, an actuator versus the cost of a 4 to 5 hour delay or a diversion. The operators maintain that the cost of the delay always exceeds that of the actuator. Proving the true worth of removing and replacing a component which is still technically serviceable, but for which a PHM system recommends removal, requires considerable human resources to relate the post repair report for the removed component to the HM system data that called for the removal. Often the human bandwidth is not available but the exercise is sometimes carried out depending on the criticality of the component and the quantity, frequency and “pain factor” of the maintenance. Thus, what can be claimed as an accountable “benefit” is not necessarily set in stone and needs to be determined and agreed ahead of time both by the compiler and the reviewers of the business case. Lean six-sigma provides a lot of insight into cost avoidance; the same parallel can be made for HM systems to show the soft savings and the hard savings. As will be discussed in Section 6, the CBA can become extremely complex partly because the factors that are “allowable” are in the eye of the beholder. It is thus imperative that the compiler of the CBA understands what factors will be favorably regarded by the decision-makers within the organization and whether the benefits are regarded as cost savings or cost avoidance.

6. COSTS FOR CONSIDERATION IN AN AIRCRAFT PHM COST BENEFIT STUDY

For a comprehensive cost benefit or business case analysis, the costs of the following elements (not in any suggested order of priority or sequence) of the total PHM system need to be considered. While the myriad of elements have been sorted into logical areas, many of them will be applicable to multiple areas as opposed to solely one specific area. The main intent is to identify all the possible elements that might apply to a specific case study, so that the person generating the cost benefit analysis can decide how to best address each and under the most appropriate categories for the case in question.

6.1 Impact on Cost and Weight

The impact on the platform of the relative cost and the weight to implement a new PHM system is a good starting point. One OEM addressed this aspect and the outcome of their specific example is illustrated in Table 1. This Table is meant to show how such an exercise can be efficiently completed by the team performing the study and is largely based on qualitative evaluation. Hence, neither the *specific content nor the scope* shown in the Table should be construed as fact for all similar assessments. Note that in some cases, sensors can inherently reduce the weight of structural material (e.g., embedded carbon nanotubes) and so the relative impacts are far from universal.

TABLE 1 - PHM SYSTEM IMPLEMENTATION, RELATIVE COST AND WEIGHT IMPACTS (ESTIMATED)

		ELEMENT	SUB-ELEMENT	WEIGHT IMPACT	COST IMPACT Civilian or Military		
					Retrofit	New Dev.	
					Non-Recurring	Non-Recurring	Recurring
Onboard	Engine	Sensor	Pressure (air, oil, fuel, hydraulic)	HIGH	HIGH	LOW	MED
			Pressure Delta (oil / fuel filter, metering valve)	HIGH	HIGH	LOW	LOW
			Temperature (air, oil, fuel, hydraulic)	MED	HIGH	LOW	LOW
			Vibration	MED	HIGH	LOW	MED
			Debris (oil, inlet, exhaust)	HIGH	HIGH	HIGH	HIGH
			Condition (oil, airfoils)	HIGH	HIGH	HIGH	HIGH
			Position (solenoids, actuators, switches)	HIGH	HIGH	LOW	MED
		Sensor Port or Mount	Tubing	MED	HIGH	LOW	LOW
			Casing	MED	HIGH	MED	LOW
			Casing	MED	HIGH	MED	LOW
			Bracket / mounting block	LOW	MED	LOW	LOW
		Wiring		HIGH	HIGH	LOW	MED
		Signal Conditioning / Power Supply		HIGH	HIGH	MED	LOW
		Data Capture Hardware	EEC / FADEC	LOW	HIGH	MED	LOW
			Other Box (CEDU, PHMU, etc.)	HIGH	HIGH	MED	MED
		Airframe Interface		LOW	HIGH	LOW	LOW
		Software	EEC / FADEC	LOW	HIGH	LOW	LOW
			Other Box	LOW	HIGH	LOW	LOW
		Testing		N/A	MED	LOW	N/A
		Certification		N/A	MED	LOW	N/A
	Aircraft	Signal Conditioning / Power Supply		HIGH	HIGH	LOW	LOW
		Engine Inferface		MED	HIGH	LOW	LOW
		Snap Shot Data Capture Hardware	FDAU, DMU, DFDR, etc.	HIGH	HIGH	LOW	LOW
		Streaming Data Capture Hardware	QAR, DFDR, eFAST, etc.	HIGH	HIGH	LOW	MED
		Data Storage	Hardware	HIGH	HIGH	LOW	LOW
			Software	N/A	HIGH	LOW	LOW
		Data Reduction / Analysis	Hardware	HIGH	HIGH	LOW	LOW
			Software	N/A	HIGH	HIGH	LOW
		Data Transmission In Flight	ACARS	HIGH	HIGH	MED	HIGH
			Satellite Narrow Band	HIGH	HIGH	MED	HIGH
			Satellite Broad Band	HIGH	HIGH	HIGH	HIGH
		Data Transmission On Ground	Cellular	MED	HIGH	LOW	MED
			Wi-Fi	MED	HIGH	LOW	LOW
			Manual - Removable Media	LOW	MED	LOW	LOW
			Manual - Download	LOW	MED	LOW	LOW
		Testing		N/A	HIGH	HIGH	N/A
		Certification		N/A	HIGH	HIGH	N/A
Offboard	Ground Station	Data Receipt		N/A	MED	MED	LOW
		Data Unencryption		N/A	MED	MED	LOW
		Data Decompression		N/A	MED	MED	LOW
		Data Storage		N/A	MED	MED	LOW
		Data Analysis	Steady State	N/A	MED	MED	MED
			Streaming	N/A	HIGH	HIGH	MED
		Information Delivery to End user		N/A	HIGH	HIGH	LOW
		System Upgrades		N/A	MED	MED	MED
		System Maintenance		N/A	LOW	LOW	LOW

6.2 PHM System Scope and Complexity

6.2.1 Data Generation and Acquisition

The following statements are a good rule of thumb but are not absolute. Raw parametric data comes from sub-system components such as controllers and sensors that have already bought their way onto the platform (i.e., they are performing an essential function). Making as much use as possible of the data from these devices will minimize costs, and system complexity, and increase the effectiveness of the desired HM system. Determining which failure modes need to be detected and anticipated requires a strategy as to how the data will be obtained. It’s likely that some additional sensors will be needed on the system. Adding sensors also adds weight, be it from the sensor, its mounting provision, the associated wiring/plumbing, and the interface to the recording device, etc. It can also reduce system reliability and increase maintenance costs since it is possible for some sensors to be less reliable than the equipment to which they are mounted or intended to monitor. Consider too that sometimes, sensors might be neither feasible nor available and so the wish or need to detect a specific failure mode might be an unachievable challenge, in which case, reversion to scheduled inspection and hard time removals might be the only option. Clearly, the best scenario is to rely as much as possible on the sensors that are necessary to manage and ensure the process of safely operating the aircraft and minimize the introduction of additional sensors purely for PHM purposes. Retrofitting additional sensors on legacy fielded aircraft is considerably more expensive and more logistically challenging than designing them in from the beginning. The anecdotal “rule of ten” applies: If a change in the initial design phase costs one dollar to implement, then that same change will cost ten dollars if made in ground testing, one hundred dollars if made in customer flight testing, and one thousand dollars if made after the aircraft is in service. Note also that with the advent of Central Data Computing, some LRUs can report their own health/status back to a central control station; in some cases, they might also be able to report the health of their next higher assembly. Finally, Integrated Health Management is more than sensing and predicting failure modes; remote diagnostics is also a feature.

6.2.2 Data Recording

Is it adequate to record/capture periodic “snapshots” of data or should the entire flight be recorded, and if so, at what rate? Are all available parameters required or will a smaller subset suffice? Immediate data processing is inextricably linked with data capture. What is the capacity of the IVHM system to not only capture but also store, buffer and forward the data? On a business jet, there are around 63 000 parameters of relevance to a PHM system; on a large long haul commercial airliner, this figure is typically larger. So, one needs to consider the cost, the practicality and the necessity to capture and record all this data and the optimum sampling/capture rate. How does the cost of the on-board processors for the initial data processing increase with the complexity or fidelity required; a trade-off will most likely become apparent. Finally, to what extent should future unknown requirements be accommodated when considering capacity? How long will the captured data need to be stored on the air vehicle? Determination of the data capture requirements is part of an overall assessment of the best method to optimize the IVHM system.

6.2.3 Data Format Compatibility

While the compatibility of data and the hardware with which it interfaces should have been addressed at the design stage, it is nonetheless important to be aware of how this issue might influence cost of operating the HM system once implemented. Consider the scenario where multiple vendors provide their own sensor and processor data to a centralized on-board HUMS processor, made by a different vendor. This processor is required to process and retain all the data generated on board and then be capable of downloading the data to a ground station which performs further processing. It could well be that the different data formats create compatibility issues which will need addressing, with inevitable associated costs. If the data formats are proprietary, then translator software might need to be purchased and implemented on the ground station or, alternatively, all the sensor/processor vendors could be required to provide their data in a specified format, compatible with the ground station software. Hence, it would be prudent for the person undertaking a CBA to ascertain whether the data being generated on board is compatible throughout the data handling and management system.

6.2.4 On-board versus Off-board

What is the strategy for data analysis? The more analysis done on-board, the less data is required to be transferred to, or on, the ground, thus reducing the cost of data transfer and increasing response time. However, processing data on-board is more costly than off-board, due to hardware and software costs and upgrade costs. Processing the data on board provides a much faster response but there is still a need to retain the data on board and then download it later. Both the on-board and off-board processing needs configuration control of software and hardware across the fleet of aircraft. The magnitude of making a change, especially software on an LRU and then rolling it out to the fleet should not be underestimated especially on a system that is often considered as non-essential. Generally, on-board software updates are considered a major change and so a certification effort is probably necessary. It might be that a mere maintenance enhancement (such as fitting a parameter recording device that is not used for primary or critical maintenances) will have a minimal impact on software and not require (re)-certification.. Rolling out changes to off-board systems is invariably quicker and cheaper than to on-board systems. In some cases, off-board may have the advantage of using external information such as fleet-wide data or perhaps more sophisticated processing options which make it a better overall solution. However, the same level of design assurance is needed for both on-board and off-board software (as per DO-178C), when the software is used as an analytical or verification tool, unless a manual data review process is implemented for the raw data prior to implementing the maintenance.

6.2.5 Vehicle/Platform Integration

What is the impact of the PHM system on the equipment to which it will apply? How will it be integrated on the system and what are the effects on the platform? For example, it is recognized in the industry that, for every kilogram of weight added to the platform, the aircraft weight increases by four kilograms, referred to as a weight compounding effect. How the HM system is to be used will affect the level and thus the certification of the software. The trade-offs between higher level certification and the costs involved need to be considered (see 6.3).

6.2.6 Communications (including Satellite and Other Relay Provisions)

How will the collected data be delivered or transmitted? It is inadvisable to assume that existing communications systems will have available bandwidth to cater to the initial (and future growth) of PHM system data communications, so suitable allowance for this should be included. How often does the data need to be off-loaded? This can range from near-real-time in-flight (very expensive) to post-flight, to daily or weekly. Is automatic download required or are manual means acceptable? All of these factors drive system architecture and cost. For commercial aircraft, available bandwidth may increase significantly in the future to meet infotainment needs and then be able to also support PHM, whereas for military aircraft, a security need not to transmit during flight might preclude full exploitation of this capability. Whatever the platform, “piggy-backing” on other systems wherever possible is invariably a benefit. Finally, is sufficient security built into the communication system to ensure that sensitive, proprietary data is safe from third parties, malicious or otherwise? If not then adequate encryption or other means of protection will be needed.

6.2.7 Ground Station

What hardware and software will be needed to receive, validate, decompress, decrypt, and analyze the data? Depending on the type of analysis performed (critical versus non-critical), this can change the software/hardware requirements. The cost of acquisition, training, and sustainment of the ground based system needs to be determined and included. Most ground based systems will be running off-the-shelf operating systems and application software. It is imperative that the designer considers the use of COTS software on the safety of the overall PHM function and be ready to defend its use to the regulators if needed.

6.2.8 Data Storage and Archiving

Data Storage and Archiving applies to both on-board and off-board. What is the data storage requirement of the on-board system? This ties in directly with the communication strategy highlighted above. The more often data is downloaded, the less on-board storage is required. What quantity of data will need to be stored from the fleet and for how long? Is it likely that archived data will need to be reprocessed later due to, say, life usage algorithm changes? While data storage has become relatively inexpensive, it is inadvisable to assume that existing data processing systems will have available capacity to provide for the initial (and future growth) of PHM system processing requirements, so suitable allowance for this should be included. With any data storage system, provision must be made for a backup in a location physically separated from the original source.

6.2.9 Information Delivery

How will the processed and analyzed data, and the actionable alerts, be delivered to end users, i.e., those who will make maintenance or mission decisions? Will delivery be Web-based or integrated with some other existing system? Will it be a push or pull approach? What is the impact on the end user? Will it require them to update or implement new software/architecture to support the system?

6.2.10 Data Security

Data Security is very important from an operator perspective, especially if flying into certain countries. Using a wireless strategy requires an infrastructure; some HM systems use cell phone technology which can be expensive but transferring to a Wi-Fi system requires, again, an infrastructure to support it. Airlines typically have a gate-link with terminal wireless/broadband capability but, again, an infrastructure on the ground to collect the data is needed. As mentioned above, additional data encryption may be needed over and above what is provided by commercial systems.

6.2.11 Software (including Software Maintenance)

While improved capabilities are continually being sought by end users, health management hardware (sensors, recorders, storage, processors, etc.) are typically plentiful and readily available off-the-shelf. The software system(s) to analyze the data and seamlessly deliver reliable answers is generally not as available off the shelf. Robust, enterprise-class, PHM software is very difficult and expensive to develop and, without it, the system will be useless. Compared with hardware, the software, even if it exists in a mature form, will most likely need customizing to suit the particular application and the costs associated with this customization will be significant and highly variable depending of the degree of customization required. System certification and approval needs to be taken into consideration when designing these systems because these could significantly affect their cost.

6.2.12 System Availability

How critical is the PHM system to the end user operation? The response to that answer will drive the system availability requirements. A ground system with very high availability will drive cost but will ensure that its availability will meet the potential need for it. However, a ground system with a lower availability will cost less but will have more often unplanned downtime.

6.2.13 Technical Support and Training for Users

Technical Support and Training are elements relevant to both the initial and recurring cost elements. Much of these costs will depend on how the training is perceived, developed and implemented and it will thus be a significant and complex piece of the cost equation.

6.2.14 Continuous Upgrades

System upgrades to accommodate emerging fault modes that arise with the aging of the fleet and address evolving needs are a necessary element of sustaining an implemented system; this also helps ensure that the system does not become outdated as the fleet ages. Upgrades to the data analysis capabilities should also be considered under this element.

The above elements can also be assigned within the categories of development, production, and sustainment costs (as covered later) and while these elements do not constitute an exhaustive list, some may not be relevant (not applicable, unaffected, or insignificant) to the specific case being made. It is recommended that, in the process of selecting and using a cost benefit model(s), judgment and sensitivity analysis is used to select the main cost drivers for the application. Also the particular concerns of the reviewers of the analysis need to be addressed. In other words, every individual cost analysis will be different, depending on the system and the personalities/needs of the eventual decision makers.

There are likely to be "unknowns" that add uncertainty to the estimates. Aerospace systems are seldom delivered into service with all, or even most of, the known failure modes already identified. Some failure modes will emerge with service experience, usually spanning the full service life of the equipment. PHM systems must therefore be able to cater to the emergence of unanticipated failure modes to fully meet users' needs. The size and impact of this "immeasurable" necessitates some degree of conservatism in the form of management reserves for the future or explicit provisions for notional change driven by this class of risks, over and above the normal challenges of development and subsystem obsolescence. Providing this flexibility may drive and dominate system architectures, capabilities, and features. It might be that significantly long tail costs for ongoing change are needed to provide specialist engineering support, field usage, and maintenance data acquisition and analysis, all potentially leading to eventual and continual PHM system modification. While PHM systems have tended not to provide for explicit integration of information from shop floor (or MRO) and incident investigation findings, there are no technological barriers to so doing and these sources of data might well provide valuable input to justify the changes and cost to the enhanced PHM system. While not wishing to convey a "gold plating approach, which is inconsistent with modern day program management practices, the analogy to the above discussion would be building a new overpass with a larger than initially-needed span because it is confidently predicted that the road beneath will almost certainly be widened within the lifetime of the overpass.

Assessment of the above costs, versus those of conventional mitigation of these long tail risks, may be crucial to justifying PHM systems, while neglecting these considerations will undermine the credibility of the cost benefit analysis with experienced users.

6.3 Development Costs

While most elements being considered throughout this section will have developmental costs, the elements have been addressed in their more prominent category. So, rather than repeat them all in this section, it is recommended that the cost-benefit analyst considers and identifies the development costs for every element discussed. The one major and overarching element considered specifically under development costs is the requirements definition.

6.3.1 Requirements Definition

Even if the customer is looking to procure a PHM system that is "off the shelf" and already utilized on a similar application, a requirements definition will be necessary that will include some form of FMEA or FMECA, and determination of specifications such as size, weight, power, false positive and false negative rates, robustness to withstand the expected operating environment, and certification requirements. Before embarking on a FMECA approach, the cost of such an approach needs to be addressed as the cost of the FMECA itself could be more expensive than the benefits that are likely to be obtained. Other alternate approaches could be to use bench testing or simulation models. While much of this work might have preceded the CBA, the cost of completing a FMECA sufficient to meet the needs of the PHM system being considered might need to be included and will likely be a significant effort. Another key requirement, particularly in commercial applications, is determination of the end use of the output: will it be used to make solely economic decisions (e.g., when should I do maintenance to minimize my costs) or safety-related decisions (e.g., I want to use my PHM system to manage a safety-related issue on an engine or in the fleet)? If the customer wants to preserve the ability for the PHM system to provide benefit in a flight safety scenario, then the regulatory certification requirements and costs increase substantially. Historically, most PHM systems have only been used to influence economic decisions. However, today, there is an increasing desire to use PHM in safety-related applications, for example to mitigate safety inspections. In this case, a much higher level of software assurance would be required. A typical on-board PHM system is Level D or E software whereas to use the system for maintenance credit or safety mitigation would require higher levels depending on use. Clearly this is much more expensive to accomplish and may also require ground system certification. The Design and Development costs will then be based on the above requirements definition.

6.4 Build and Qualification Costs

Qualification of software and associated hardware needs to be considered during the PHM development phase.

For software qualification and certification, DO-178 ("Software Considerations in Airborne Systems and Equipment Certification") is generally adopted.

There are other standards that may be applicable for software qualification such as DO-330 ("Software Tool and Qualification Consideration"), DO248 ("Final Report for Clarification of DO-178B 'Software Considerations in Airborne Systems and Equipment Certification'"), DO278 ("Software Integrity Assurance Considerations for Communication, Navigation, Surveillance and Air Traffic Management (CNS/ATM) Systems"), and DO-254 ("Design Assurance Guidance for Airborne Electronic Hardware").

On-board hardware needs to fulfill the requirements for qualification tests, which includes DO-160 ("Environmental Conditions and Test Procedures for Airborne Equipment").

PHM software or hardware that is located off-board may also have standards that affect qualification resulting in additional costs. Additionally, costs will be dependent upon the level to which the software/hardware is qualified.

While the examples cited here are not extensive, they represent the need to address the specific costs of initially qualifying the PHM system.

6.5 Production Costs

These costs include those of fabricating hardware, its initial installation on the platform, provision of spares, and the build of ground software support station/infrastructure. Additionally, the costs associated with initially creating the PHM system and its operation, maintenance, and training documentation needs to be included.

6.6 Operational Costs

6.6.1 Labor for Data Handling, Analysis, Storage, Back-Up and Transmission

Labor to take care of the data, at all junctures from initial collection to access and archiving, is self-explanatory and needs no further embellishment. The costs associated with this continuous “overhead” need to be considered as the costs will be significant.

6.6.2 Data Transmission and Storage Costs

Satellite-based data delivery is very expensive, broadband capability even more so. Streaming satellite data will require leasing of transponder capacity from a satellite provider. Ground-based methods such as cellular for a global commercial customer will require an agreement with a global provider and compliance with transmission requirements in every country of operation. For example, operation on a cellular network in the United States requires that the transmission device be certified by the PCS Type Certification Review Board (PTCRB). If the signal is encrypted for security, then other rules come into play, particularly in countries which may require the encryption keys to be provided to the government. Wi-Fi data delivery is available at some airports when the aircraft is parked at the gate. Arrangements must be made and fees paid, and this capability is not, and unlikely to ever be, universally deployed. Storage costs can be partially mitigated by archiving solutions, however, this impacts the response time of the ground system if archived data is needed for analysis. The proper compromise needs to be made between how much data can be archived and the data that must be transmitted while en route. Increasingly, broadband data connection is becoming ubiquitous at least in the U.S. using mainly line-of-sight ground links. It is possible to use this medium for PHM communications as well, at least for the non-critical parts of this data.

6.6.3 Additional Fuel Costs

It is probable the IVHM System adds weight to the platform, and therefore, displaces some other payload element, even if it is merely its own weight in fuel, and will have some adverse, calculable impact on range, duration, etc. More than ten years ago, an interesting metric quoted in Aviation Week and Space Technology was that one pound of weight on an airplane creates an increased cost to an operator of $1 million over the life cycle of the platform. While this figure has no doubt changed, and is highly dependent on the price of fuel, the point is well made that every pound of weight on a platform comes at a cost and needs to be addressed in a CBA. In theory, the problem is decreasingly exponential; the elements are not only the fuel to carry the additional IVHM system weight but also the “fuel for the (extra) fuel” and potentially extra structure or strength to carry the additional load (weight compounding, as discussed in 6.1.4). However, if a system is being introduced at the design stage of a platform, then it might be that the addition of a IVHM system actually *reduces* overall platform weight because of redundancy that might be designed out at the outset (see 5.3.1). As discussed in 4.1, the U.S. Navy adopted PHM based on the fact that the redundancy of two engines could be eliminated, yet maintaining equivalent safety.

6.6.4 Unnecessary Maintenance Due to PHM System “False Alarms”

As no system is perfect, an element of “false alarms” can be expected from a IVHM system. But, against what base-line should this imperfection be compared? There are two choices. First, the system’s performance can be measured against a perfect record and so any false call will be a strike against it and the costs associated with unnecessary maintenance counted against it (how to compute those costs, especially in terms of airplane downtime, delayed passengers, damage to on time departure statistics, is clearly complex, somewhat subjective, and becomes an additional issue). The second option is to compare the PHM system against the current “human based” maintenance system where some diagnoses turn out to be “the wrong guess”. Whether records and statistics exist for the occasions that unnecessary maintenance was carried out is organization-dependent and, if not available, could be difficult and/or laborious to determine. The reasonable perception is that a PHM system will improve on the understandable degree of human “guesswork” and the well-intentioned, experienced-based, maintenance decisions that are subsequently found to be the “wrong call”. The IVHM system has the advantage over the human of non-emotionally examining and fusing all the data over a period of time and making “clinical” determinations and prognoses which should increase the rate of “correct first time fixes” and reduce No Fault Found (NFF) occurrences. Hopefully, the system being considered for fleet implementation has a history based on some sort of trial, or verification and validation, which provides a starting and believable base-line from which to try and compare against the status quo. Balanced against this is the number of “false positives” that the IVHM system detects, thus generating unnecessary maintenance and “down the line” costs. The subsequent danger of false detections is the risk of the IVHM system being ignored or marginalized such that it is no longer utilized by the maintenance managers. For instance, in the infancy of engine condition monitoring, there were occurrences of maintainers permanently disconnecting accelerometers due to repeated false vibration alarms. While as low a false positive rate as possible is desired, the best currently achievable levels are 5% or higher. Health monitoring sensors are like a (continuous) non-destructive inspection and so using the same metrics for probability of detection (PoD) and an associated confidence level that defines the capability of NDI sensors is logical. Typically, NDI sensors for aircraft and engine structural inspections are quoted as having a PoD of 90% with a confidence level of 95%. Of course, the converse of a IVHM system missing a real fault (a “false negative”), is worse than a false positive as it adversely affects safety as well as reducing user confidence in the system. Designers and implementers of IVHM systems thus have a delicate and skilful balance to find in their quest for a “perfect system”.

6.7 PHM System Sustainment Costs

Some of the elements shown below were also included in the operational cost section as there is a degree of unavoidable overlap between operations and sustainment activities.

6.7.1 PHM System Training

In a well-designed system, usage should become almost intuitive, minimizing the need for training. However, this ideal is difficult to achieve and some training will be required, both for operators and maintainers. The cost of a well-designed training program, probably web-based, needs to be estimated and included. As mentioned in 6.2.12, the training elements are complex and intertwined at all stages of the HM system design, implementation and operations and it is likely that specialist help will be needed to accurately compute the cost elements.

6.7.2 PHM System Upgrades

Inevitably, a flexible system will undergo reliability, capacity, and performance upgrades, typically every two years. These must be estimated and included.

6.7.3 PHM System Maintenance

The costs of server leasing, troubleshooting and “help desk” labor, software licenses and fixes, etc., must be estimated and included.

6.8 Aftermarket Impact on Costs

Implementing a PHM system has an impact on the aftermarket services and business models. Depending on the suite of benefits that the PHM system brings to the end user, there will be a direct financial impact on the supplier of the component being monitored by the PHM and the expectation is that it will result in lower sales of aftermarket components. But there are other aftermarket impacts as discussed below.

6.8.1 Increased On-wing Component Life

Keeping components on wing longer because of PHM will impact the aftermarket model of the supplier. While the intent is always to have the most reliable component on wing, the fact that components require scheduled overhaul or have a pre-defined life, and will require routine replacement, is part of the overall business case for the supplier. If PHM analysis changes that figure, then it needs to be taken into account at the outset. Note however, that the “pre-defined life”, probably determined during the component’s design and initial deployment onto a platform, can be responsibly adjusted (be it an increase or decrease) based on what should be excellent performance data of the component across the fleet of platforms. This consequence should be seen as a positive by the component manufacturers as it would increase their confidence in the product they are offering to the platform OEM and down the line customers/end users.

6.8.2 Removing Components Before They Actually Fail

One of the main benefits of PHM is to be able to identify a faulty component before it fails. However, this brings several and inter-related aftermarket issues such as:

6.8.2.1 Warranty Management

How will the OEM manage warranty on components removed based on PHM analysis? In the absence of clear failure of a component, some means of determining degradation to the point of incipient failure will be necessary as opposed to a mere pass/fail criteria. Assuming that a warranty manager requires evidence for “reasonable justification of removal” as opposed to 100% acceptance of the PHM system’s reasoning, some thresholds defining reasonableness will need to be created. There are likely to be costs associated with creation of a workable system to accommodate this change.

6.8.2.2 Mean Time Between Failure (MTBF) Calculation

How will components removed, based on a PHM analysis, be considered in fleet MTBF calculations since they have technically been removed before they failed? As discussed in 6.7.2.1, a means to address this disruption to the well-established procedures will most likely be needed. If remaining useful life (RUL) has been calculated by the PHM system, then this estimate could be used as “best evidence” and the RUL added to the hours at which the component was removed so as to provide appropriate credit, although the RUL should be a low number (e.g., a few 10s of hours at the most as opposed to 100 or more). If it turns out that the PHM system generated a false alarm and caused a “still very serviceable” component to be removed and replaced, then the statistics department might need to be called in to create fractions of removals (e.g., counting a serviceable component removal as “half a removal”). As long as false positives can be ensured to be low (<10%), there is no extra cost burden since the component truly will be failing anyway. In some cases, the prognostic repair direction can actually reduce total maintenance costs because the repair is being done before a much more expensive repair would be caused by inaction. This is another example of a benefit that is “complex” and needs to be addressed depending on the outlook and mindset of the customer or the decision maker.

6.8.2.3 Acceptance Test Procedure (ATP)/Bench Testing

Most components removed based on PHM analysis would most likely pass a standard ATP when returned to the supplier. If not addressed properly, this could increase No Fault Found (NFF) rates and cause a rise in failures shortly after being re-installed on the aircraft, thus causing increased cost to the end user instead of reducing them. For the purposes of cost benefit analyses, it would be prudent to check that the maintenance repair and overhaul (MRO) system can cater adequately for this paradigm change.

While the above elements will have wider business implications affecting more parties than just the implementer or user, the effects on the overall domain need to be considered. For instance, if say the MTBR for a component increased by a factor of 2, then the supplier of the component might now deem its value (and therefore its price to the customer) to be higher than before the PHM system were introduced even though its design and method (and cost) of manufacture is unchanged. Imprecise cost estimating is probably the only tool that could help address the prediction of these possible subsequent effects.

7. BENEFITS FOR CONSIDERATION IN AN AIR VEHICLE PHM COST BENEFIT STUDY

7.1 Fuel Savings

As discussed in 6.5.3., the fuel impact can be positive or negative depending on the stage at which a PHM system is being considered and how it is being used. However, there are other benefits associated with fuel, and therefore cost, that can be considered.

7.1.1 Fewer Mission Aborts, Air turn-backs, Diversions

In military operations, a significant number of sorties are lost, sometimes at start-up or during the mission itself, because of a “surprise failure” of a system on the platform. There is a calculable fuel cost to the loss of a mission (e.g., fuel consumed and/or dumped to reduce weight for landing). Similarly, commercial operators experience air turn-backs or diversions for unanticipated failures which consume substantial fuel (and have other large costs associated with them) for no generated revenue (i.e., the mission was not accomplished). Sometimes, if a system fails, even with built-in redundancy, then it is a red-fail on the minimum equipment list (MEL) but the single remaining system might also be degraded which subsequently causes a turn-back.

7.1.2 Increased Propulsive Efficiency and Reduced Platform Drag

Specific fuel consumption is a prominent parameter in both military and commercial operations and so a hidden but significant cost saver lies within more efficient operation of a fleet of vehicles. PHM systems can inherently provide engine and airframe performance rankings from best to worst in a fleet and thus show which engine(s) are “worth” fixing to restore efficiency. The airframe’s aerodynamic qualities also degrade over time. Structural repairs and leaking door/panel seals increase drag as do asymmetries of flight control surfaces. A comprehensive PHM system can correlate airframe and system deterioration to fuel burn increases. The extent of cost savings can be determined by either measuring the achievement of a plausible goal compared with the current fleet status or by assuming a level of improvement and, calculating the cost savings based on the price of fuel, annual miles flown, etc.

7.2 Increased Accuracy in Identifying Faulty Components

Better diagnosis of potentially faulty components means fewer removals, which reduces the number of “re-test OK” or “no fault found” (NFF) components. Several savings cascade from this and include reduced aircraft maintenance, reduced aircraft downtime and greater availability, less work at the “back shop” to test components, and, potentially, a reduced pool of rotables because the remove and replace rate has been reduced. Each of these factors should be considered on its merits and its applicability and a cost estimate applied. As stated earlier, if a PHM system enables dual redundancy to be removed from a platform, then the savings are significant because it’s one component saved per platform across the entire fleet. But it might also be significant if a pool of expensive LRUs can be reduced by five to ten percent across the fleet. The challenge for the CBA is to determine how many components can be benefically impacted by a PHM system (possibly determined from the FMECA) and compute the savings based on the purchase price of the components and by how many the pool can be reduced.

7.3 Trending of Performance Degradation and Early Corrective Action

The benefits from monitoring system performance such as engines, or brakes or pumps and plotting the inevitable degradation are well understood. The results of the monitoring can then be associated with avoidance of the depth and cost of maintenance that would have been carried out if the failure had been allowed to manifest itself. Early detection increases the likelihood of keeping components on wing or in service for a longer period and thus utilizing their full useful life through timely intervention and maintenance actions. It also leads to many other benefits such as reducing the amount of secondary damage as well as the remedial maintenance necessary after the failure has occurred. To put quantitative estimates to these savings is clearly a challenge and some assumptions would need to be made such as estimating a percentage of the fleet that is saved from secondary damage and assigning an estimated cost to the maintenance and parts usage that has been or would be avoided. Using past maintenance history and statistics would provide data and insight for the calculations.

7.4 Business Benefits

7.4.1 Warranty/Guarantee Mitigation

In commercial sales and in military sales handled commercially (e.g., F117 engines for the C-17 aircraft), most deals include extensive reliability, performance, and fuel burn guarantees. A competent PHM system has been shown to reduce costs associated with many of the guarantees, allowing lower cash reserves to be carried by the guarantor organization.

7.4.2 Reduced Support Services Costs

Increasingly, new commercial and military vehicle sales include services and support contracts by the OEM. While engine OEMs have implemented “Power-By-The-Hour” ™ programs, which shifts ownership of both the failure and maintenance cost risks from the operator to the OEM, taking that step for an entire airframe is a much more complex proposition. Comprehensive support and services contracts for military platform programs are becoming common in the military and commercial airframe arena. As in engine support programs, airframe PHM capability is seeing an expansion and PHM systems have been shown to directly reduce costs per flight hour. Typical savings are reported by providers and users as being in the 3 to 8% range and are significant when associated with billion+ dollar deals. Thus, a capable PHM system can directly generate revenue through sale of service to entities not wishing to take on this burden themselves, be it any of the military or commercial categories of operations. Monitoring fleet data from a PHM system is one thing; conducting traditional maintenance without the interpretation of the PHM system information is another. So for a carrier that incorporates PHM, it might be prudent to consider outsourcing the review and analysis of the data to a third party.

7.4.3 Life Limited Parts

Components such as landing gear can be beneficially impacted by HM systems although there are two sides to the equation. Possible overstressing of a landing gear from, say, a heavy landing, is often subjective and is up to the pilot/captain to report. Obviously, the occurrence is opinion-based unless there are actual data recording devices in place. If a pilot reports the heavy landing, the operator typically contacts the OEM who will likely ask for the landing gear to be removed and quarantined while an inspection of the gear, or an analysis of the captain’s reported conditions, or severity of the heavy landing can be analyzed. The operator has thus suffered the expense of changing a landing gear assembly (or the aircraft suffers an aircraft on ground (AOG) event while the OEM determines the next course of action), and the associated costs can be computed. Some weeks later, the decision from the OEM as to the condition of the landing gear becomes available and one possibility (which for “mild” heavy landings is often the case) is for the assembly to be released back into service. However, an HM system fitted to the landing gear assembly would reveal every occasion that the OEM’s maximum limits were exceeded. In all likelihood, this scenario will increase the number of detected heavy landings (because there will be a clinical assessment as opposed to a human in the loop, opinion-based, assessment). One could argue that a HM system on a landing gear assembly will increase costs for the operator. The answer, in the short term, is yes but, by the OEM and operator being able to pair the severity of the heavy landing (from the known recorded data) with the actual determined condition of the landing gear assembly, the conservative limits typically set by the OEM are likely to be relaxed, based on an expedited understanding of how the equipment withstands hard usage. Additionally, the opportunity exists to extract a full (and most likely longer) installed life from the gear as opposed to being removed at some conservative life limit for overhaul. Finally, the operator can be comforted from the safety perspective of heavy landings possibly not being reported by the pilot/captain being eliminated. Once again, the benefit is qualitative until an actual landing gear failure occurs; then the costs become real and are suffered by the operator along with the inevitable news coverage and damage to reputation. One approach is to compute the likely costs of a landing gear failure and multiply by the (probably assumed or estimated) probability of occurrence to determine how the HM system, if fitted, would ensure against such an eventuality. The above scenario, using landing gear as an example, can be applied to any significant component or assembly on the airplane.

7.4.4 Increased Residual Value

Commercial aircraft with PHM data collection and transmission capability, combined with PHM-driven maintenance plans and/or health monitoring, can be shown to retain greater value relative to one not so equipped and maintained. All aircraft in the hands of mainline operators are eventually sold, and residual value is a major consideration. Aircraft financing and leasing organizations have tables of residual value data to provide cost differences that will help in determining the cost benefits.

7.5 Reduced Weight of Airframe Systems through Reduced Redundancy and Conservatism

This was also addressed in 6.6.3 and, if a thorough CBA is being performed, the weight savings might beneficially impact other related systems on the platform. Weight is a major concern for all types of operators be it a potential mission limiter for military platforms or a cost factor for commercial or business operations.

7.6 Maintenance Savings

This element is potentially huge because of the plethora of issues that can emanate from routine maintenance activities, such as inspections. Without a Condition Monitoring system of some form, routine, scheduled inspections of various parts of every platform in the fleet are required irrespective of specific evidence of need. Similar to someone crossing the road, every maintenance activity has a risk associated with it, be it a screwdriver slipping and gouging an adjacent surface or a human body part unknowingly putting undue pressure on a wiring harness or hydraulic pipe. In addition to causing accidental secondary damage, there might be a need to remove other components or fixtures to reach the inspection area, or other issues are discovered, which need to be corrected even though the system on the platform was operating satisfactorily beforehand (although “finds” like these can sometimes avoid an impending serious or catastrophic failure). The above scenarios encompass maintenance at all levels, (i.e., line (O-level) and shop (I-level and depot) labor), as well as materiel labor, including rework. With a PHM system, emerging problems should be detected earlier which thus reduces the issues cited above (reduced disassembly leading to reduced replacement of parts necessarily exposed (“sunshine”) during the tear down process) and also catch those fortuitous “finds” of impending failures. Because of the interlinked nature of these consequences of maintenance activities, the cost savings associated with them are hard to quantify, yet the savings are real. Some of the factors to consider are expanded upon below but each CBA undertaking is likely to identify others.

7.6.1 Reduced Line Maintenance Labor-Hours/Staffing

The PHM system should determine the root cause of problems more precisely and accurately than the human in the loop, so there should be a reduction in maintenance activities at the flight line. Typically, there will be a fewer scheduled and routine inspections and removals, and fewer unscheduled removals. If the direct labor savings are admissible in the analysis, then there is a simple and accurate calculation based on labor-hours saved and hourly rate. Determining by how much the PHM system will exceed the human decision making efficiency is hard to quantify and will vary between operating location so a conservative, reasonable estimate should be made and used as an assumption in the CBA to determine the savings. As discussed earlier, the benefits trickle down to “back shop” maintenance, transporting of components for functional testing, and the size of spares pools as covered below. If a particular inspection capability is too expensive to implement throughout the airplane, then maybe some form of limited implementation to focus on the most inaccessible area or those most expensive in terms of maintenance to inspect manually, might be the optimum approach.

7.6.2 Reduced Shop Maintenance Labor-Hours/Staffing

As noted in 7.5.1, the savings at the component test and repair organizations will be generated from reduced maintenance labor hours based on reduced throughput of line-replaceable units (LRUs), and reduced number of false removals and subsequent NFF. Once again, if the direct labor savings are admissible in the analysis, then there is a simple and accurate calculation based on labor-hours saved and hourly rate.

7.6.3 Reduced Number of LRUs Returned for Bench Check/Overhaul and Reduced “Back Shop” Labor-Hours/Staffing

This benefit leads to a smaller pool of spares but computing a true monetary figure will be difficult. One approach is to estimate the improvement over the current base-line (if there is one for a legacy system, or if one has been computed for a new system), and use the cost of the LRU multiplied by the percentage savings envisioned as the cost benefit. For completeness and greater accuracy, apply the same approach to the components that experience the benefit of a HM system. One might also consider the “installed” value of an LRU that’s just been fitted and has a full life ahead of it versus one about to be removed for scheduled or other maintenance which has a diminished “installed” value.

7.7 Operational Savings

The following factors would help to improve operational availability and reduce direct and indirect operating costs.

7.7.1 Fewer Delays, Diversions, Air-Turnbacks and Unplanned Component Removals

While the fuel savings associated with a reduced number of air-turnbacks was discussed in 7.1.1, the primary benefits of airframe PHM systems are the reduction in schedule interruptions, including departure/arrival delays as well as more costly, but less frequent, diversions/air-turnbacks. In the commercial area, the largest benefit impact is on delay reductions, which can have ripple effects throughout an operator’s network. For commercial operators, the cost of a diversion is immense because of passenger re-routing and accommodation. The diverted plane is no longer generating revenue, and the dispatch of a maintenance crew and associated replacement parts to recover the aircraft is very expensive and time-consuming. Once again, the adverse effects on the operator’s on-time statistics, passenger inconvenience and discontent, and unwanted publicity are some of the factors to which a cost could be assigned. It is important to factor in the impact of the length of a delay as well. For example, a 1 hour delay might be made up within an 8 hour flight, whereas a 4 hour delay has more significant ripple effects for connecting flights and missed maintenance opportunities. In the military, the cost of a lost sortie can include incalculable elements such as failure to engage a time-critical target, loss of training value to other members of the formation, or diverted or canceled missions of other aircraft (e.g., if the affected platform was a refueling tanker). The military tracks non-mission capable hours and this can be used as a meaningful metric for calculating the benefits. Putting specific cost numbers on these elements is difficult but, at the very least, these factors should be listed and presented so that the decision-makers can put their own weighting on them. In short, an PHM system can help to minimize the amount of maintenance conducted, and also help to perform the maintenance at the most opportune moments (i.e., overnight in a hanger as opposed to during the daytime at a remote or non-hub location) and avoid any secondary effects of failures that were not pre-empted.

7.7.2 Greater Platform Availability

This is sometimes translated as a “force multiplier” in that “y” PHM equipped airplanes with 10% greater availability (for example) are equivalent to “y+10%” non-PHM equipped planes. If, for a new platform, where a PHM system is being implemented from the outset, the initial purchase quantity can be reduced by this calculated force multiplier factor, and the cost benefit can be computed directly in terms of reduced initial costs and any reduction in operational and sustainment costs from operating a smaller fleet size. By contrast, where PHM is introduced on a legacy fleet, as is the case with the U.S. Army (see 9.1), they have proved, with operational data, the availability increases associated with its CBM+-equipped platforms. But, the cost benefit will only manifest itself when the fleet size is reduced by retiring selected platforms. Here, the cost benefit is less apparent as the original purchase of the platforms is a sunk cost and so the benefits now emanate from reduced operating and maintenance costs of a reduced fleet. On the plus side, the “force multiplier” effect is known, based on real data, compared with the scenario of a theoretically predicted reduced fleet size for a new fleet. In the commercial world, increasing platform availability across the fleet will allow an operator to either fly more revenue generating flights per day or reduce the size of the fleet to meet the same flight schedules. These costs are directly visible and calculable to the operator.

7.8 Savings from Reduced Capital Investments

An PHM system can generate a plethora of capital investment savings as itemized below. These elements need to be segregated from the above cost elements as it is treated differently in financial analysis.

7.8.1 Reduced Spare Equipment, Parts and Material Stocks

The cost of establishing the spares pool compared with that of a reduced pool, because of more accurate forecasting and reduced usage rate/turnover, can be calculated using the price of each component. Note that, occasionally, and because of “full disclosure” capabilities of a PHM system, the holdings of a particular component might need to be increased, but while this is an increased cost, it is justified by the benefits of knowing a more accurate forecast consumption rate, which will reduce the number of delays or no-notice maintenance fixes required. Thus, while there is a specific component cost increase, there is an overall cost savings to the fleet/platform because not having to wait for parts generates higher platform availability. The harder parameter in the equation is to determine by what factor the spares pool and reduced usage will be reduced. Once again, a conservative figure can be assumed or estimated, or a model developed to “fly the fleet forward” and determine what savings are conceivable. Typically, this is a cost benefit that needs to be remembered but not necessarily included at the outset. The most accurate answer will come from monitoring the change in this element *after* a PHM system is introduced and will be something to add to the refined cost benefit analysis some 12 or 24 months after fleet embodiment. It is presumed that the operator appropriately provisions spare capacity and stocks to maintain an optimal or given level of mission performance or customer service. In reality, the additional capacity and spares levels are more likely set at levels that minimize the costs to compensate fare-paying passengers for delays and cancellations, or, in the military, to ensure adequate war-fighting capability. This may be usefully addressed qualitatively, but is not a required element of a cost benefit analysis.

7.8.2 Reduced Maintenance Facilities and Equipment at All Levels

Consider the impact on maintenance facilities and the associated equipment, especially at non-hub or non-MRO locations for the operator. It might be that the best insight into this factor and a true cost benefit is unearthed after one to two years of operation with the PHM system installed and reduced maintenance is a reality and measurable. For example, being able to eliminate a test cell at a maintenance facility or reduce the workforce to one shift instead of two are all “step” improvements that might subsequently be accomplished from implementation of a PHM system. The recommendation is to list these potential savings at the outset in the CBA and possibly compute what it would take, in terms of PHM impact, to achieve these “step change” savings, and then decide if it is feasible a year or two after PHM system implementation.

7.8.3 Reduced Investment in Production Equipment and Facilities due to Lower Demand for Vehicles, Spares, and Material

This is more pertinent when introducing a new platform into service and being able to reduce the initial provisioning over what would have been provided without a PHM system. It’s possible that maintenance and support facilities won’t be built or purchased from the outset, as opposed to savings generated by closing existing facilities.

7.9 Other Miscellaneous Costs

7.9.1 Marginally Reduced Dependence on Strategic Materials and Obsolete Components

Many parts in modern vehicles, commercial and military use rare earth elements and other exotic materials be it in their initial manufacture or in coatings. Avionics use electronic components that have short technology half lives. If the PHM system can extend the useful lives of system components, then the dependency on these materials is reduced. Similarly, the PHM system may allow extended use of out-of-production or obsolete components. Actual costs associated with these benefits are probably small and difficult to determine. This benefit should be identified in the CBA but not necessarily included in the calculations.

Figure 2 summarizes the flow of value creation for the customer and provider.

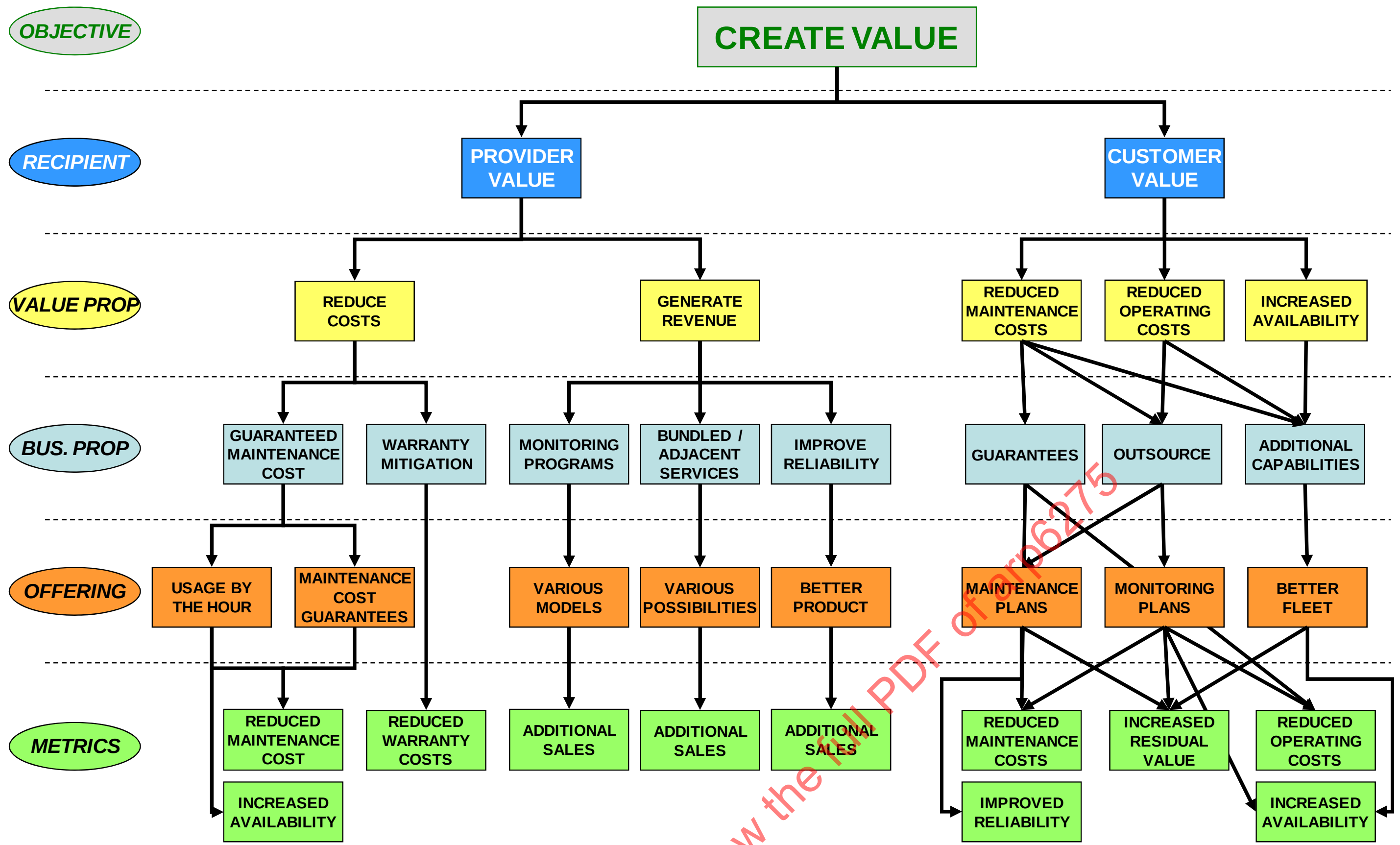

FIGURE 2 - A GENERALIZED PHM VALUE MODEL

8. CHALLENGES ASSOCIATED WITH COMPLETING A COST BENEFIT STUDY

8.1 Scope of Cost Benefit Study

The initial challenge, as discussed in earlier sections, is to determine how deep an analysis is needed and the parameters that can be assessed and included. This will depend on a plethora of circumstances that are unique to the specific case.

8.2 Data Availability

Typically, organizations encounter difficulties in obtaining sufficient data to begin the cost benefit analysis. In some cases, data on a crucial parameter might not exist at all. Other difficulties include insufficient data being available or access to the data or its retrieval is difficult. The following challenges then exist even if a sufficiency of data is available.

8.3 Qualitative Values

There are elements that are ultimately unquantifiable or sufficiently intangible which means that their estimation of worth is either based on emotion or "priority" to the specific operator or customer. For example, it is difficult to put a value on asset availability. But availability is critical for commercial operators, especially low cost carriers whose business model requires maximizing flights per day with turn times of 20 to 30 minutes. Maintenance required during the day has a huge negative impact. A PHM system which flags preventive maintenance that can be accommodated overnight with no impact on the daily flight schedule is of substantial value. And if the plane in question is a military combat asset, then availability is even more important and valuable, especially if the only mandatory or unavoidable down time is to refuel and rearm.

8.4 Desired Fidelity

The outcome of the cost benefit study has an indeterminate “error” based on the degree of fidelity sought, which is dependent on the complexity of the analysis conducted, which is further dependent on the quality or accuracy of the data used. Additionally, the fidelity will be influenced by the questions being asked by the recipient. For example, “What is the value of implementing a HM system on my fleet?” will require a different level of analysis than the question “What is the value if implementing a prognostic approach to this failure mode?” Addressing the first will most likely be a top-level analysis that might involve fleet level approximations of some of the larger and more coarser elements of the CBA equation whereas the approach to the second question will probably involve a very detailed analysis for which the very specific data and accurate answers are more germane. While there are separate but related tools available to address both of these scenarios, the inevitable question in the end is, “How believable is the bottom line figure?” A sensitivity analysis by conducting a few “what if” exercises could quickly identify the parameters that have most influence on the outcome but, in practice, each organization will have their own value or priority on the multitude of elements. Ultimately, a qualitative assessment could dominate the analysis. The general advice is not to be too focused on the absolute accuracy of the individual parameters unless the parameter has a large influence on the outcome, but be aware of the accuracy of the overall outcome. Consider also the parameters that can vary over time (e.g., fuel, whose price has become much more variable in recent years than previously) and their influence on the final outcome of the analysis.

8.5 Perception of PHM System Value

Basic health management tools have been available for 40-plus years in the form of trending software provided by OEMs to both commercial and military operators. The propulsion-related systems tended to lead the use of these tools and have provided most of the pull for better and more sophisticated capabilities. One example of how health management has progressed from a qualitative (e.g., chip detector) to a quantitative assessment is in lubrication systems. The introduction of real-time oil debris analysis by counting and sizing particles as they flowed through the oil stream has helped users to identify impending bearing or gear failures in the propulsion or transmission systems and create a true prognostic capability. Such a capability was introduced on the F-22 airplane in the mid-1990s and has subsequently been adopted by other platforms. The last decade has seen the introduction of “Power-By-The-Hour”™ maintenance agreements for the propulsion systems in both commercial and military applications, which prompted the introduction of much more comprehensive OEM PHM systems. This performance based concept has in turn expanded to platform availability. While specifics are treated as proprietary by the engine OEMs, the general belief that a comprehensive engine gas path monitoring system has reduced maintenance costs by 3-8% and it is reasonable to assume that expansion of the concept will yield similar savings across the entire platform. As health management becomes implemented on airframe and other sub-systems on air vehicles, a better perspective on how the tools help generate savings (thus providing more insight into the overall value of such tools) will become available. A data-based cost/benefit analysis will greatly enhance credibility when trying to convince others.

8.6 Is a Cost Benefit Study Really Necessary?

A cost benefit analysis could be generated internally by an end user (e.g., an airline operator) or it could be initiated by the provider of the equipment to the user or initiated by a third party service provider. The determination of how detailed an analysis to perform ranging from “almost none at all”, (especially if the end user is initiating the analysis), to a very thorough analysis if the equipment provider is trying to convince the user is a fundamental consideration. But, in almost all cases, the customer (end user) will tend to lead that decision. There are some (usually PHM advocates) who question how a platform equipped with a PHM system could possibly provide a return on investment (ROI) that would be worse than a platform with no PHM system. Other advocates might maintain that it is not worth conducting an ROI analysis; the benefits can be “felt” (qualitatively), especially if the driving force is safety. Some believe there is an unjustified insistence that a cost benefit or ROI analysis is required for *every* decision, even when the benefits are well understood and the proposed way forward is clearly “the right thing to do.” One prominent example of this scenario is the recent adoption of Condition Based Maintenance (CBM) by the U.S. Army for all its helicopters which necessitated fitment of Digital Source Collectors (DSC) to all its legacy platforms, as is discussed in Section 9. The point being made here is for the person tasked with, or motivated to undertake, a cost benefit assessment should consider from the outset the scope of the study (i.e., what depth of PHM ability is required or worth doing) and how much time and effort should be spent undertaking the study. The complexity of the combination of systems being monitored, the technologies to be implemented, and the failure mechanisms to be detected are generally more than can be evaluated and prioritized by following a “feeling.” It’s also important to address two other issues that could be encountered. First, contract awards typically go to the lowest bidder based on delivery price, not life cycle cost. Hence supportability analysis and developmental programs are generally not included in the proposal or program plans; the F-35 (formerly JSF) was one of the last, albeit recent, programs to use LCC as a competitive metric in the proposal phase. Secondly, program managers on new and existing programs (where upgrades are being considered) typically only consider fly-away costs; the development cost of HM capabilities merely adds to that bottom line; hence it is difficult to make the case that LCC benefits are important unless, of course, there is customer pull.

8.7 PHM is Too Good to Be True

The adage that “if something sounds too good to be true, then it usually is” is the Achilles heel of a PHM system. Budget holders and decision makers are understandably circumspect when asked to significantly disrupt a working system and expend a copious portion of their budget on a new PHM system that, despite impressive estimates, is unproven and sounds too good to be true and attracts comments such as “why is everyone else not doing it”? As stated at the outset of this document, the best CBA and ROI analysis might still not win the fight and it is one of the biggest impediments associated with introducing PHM capabilities. To somewhat mitigate this perception, use of a truly independent, unbiased, technical consultant might provide credence and impartiality to appease the skeptics. The underlying assumption is that good data were available and were analyzed in the most proficient manner. The converse can also occur, in that the analysis showed no benefit to a PHM system being adopted, in which case the rejection of the case to fit a system to a platform will presumably be an easy one for the ultimate decision maker. It is important to check that the scope of the cost benefit study matches the specific operational or financial needs of customer, i.e., what is the customer trying to achieve from the potential implementation of PHM (e.g., more time on station increased availability, reduced maintenance costs, etc.). Hopefully, the PHM CBA can justify the investment by only looking at the more easily quantified benefits and therefore not having to defend the larger but qualitative benefits.

9. EXAMPLES OF PHM IMPLEMENTATION AND COST ANALYSIS MODELS

9.1 Implementation of CBM+ on U.S. Army Helicopters

Based on the Deputy Under-Secretary of Defense for Logistics and Materiel Readiness Policy Memorandum (25 November 2002) which established the original policy for Condition Based Maintenance Plus (CBM+) and the U.S. Army Aviation CBM+ Plan (29 November 2004), the U.S. Army began implementing CBM+ on its helicopter fleets (Figure 3).

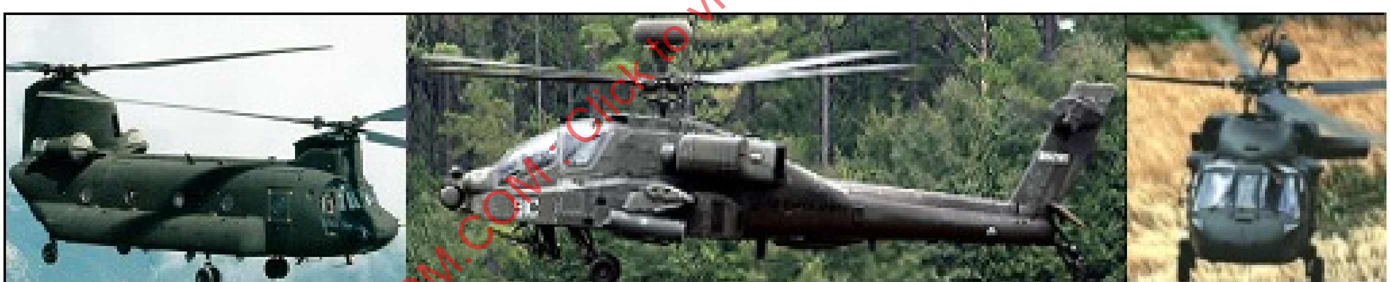

FIGURE 3 - U.S. ARMY HELICOPTER FLEETS ARE LEADING THE WAY FOR ON-BOARD PHM APPLICATIONS

CBM is a maintenance philosophy that attempts to optimize maintenance by undertaking maintenance activities on a system only when there is “evidence of necessity”. This is in contrast to the traditional approach of performing scheduled inspections *of the entire fleet* which, more often than not, find nothing untoward on the vast majority of the fleet yet consumes many maintenance man-hours and risks incurring secondary damage to the platform especially where panels needed to be removed for access. The “Plus” enhancement to the base-line CBM philosophy adds a predictive element to the components. Thus, implementation of CBM+ requires data, from each operating platform in the fleet, to be collected and analyzed to tell the picture of system or component “health” and, moreover, provide an indication of “remaining useful life” before maintenance is necessary. As stated by the Two-star General Officer who initiated the implementation, the Army pursued CBM+ because, in order of priority, they wanted to: reduce the maintenance burden on the soldiers in the field, improve asset availability, increase safety, and reduce operations and support costs. The enablers were on-board Digital Source Collectors (DSC), flight-line diagnostics, and data fusion and analysis. It could be argued that the Army’s number one desire to reduce the maintenance burden was also inextricably linked to safety in that overtaxed helicopter technicians in the field and in a combat zone was a safety issue. Indeed, none of the beneficial factors listed above is isolated from the others. CBM+ is regarded by the Army as “the Electrocardiogram of Army helicopter health” and allows the maintainers to see, first-hand, early anomalies based on greater visibility of data that CBM+ is providing. This, in the words of the Army senior management, means simple fixes triggered by condition indicators, and enables the maintenance to occur in a timely manner before an otherwise more expensive maintenance action is necessary. All 3369 Army helicopters will be fitted with DSCs by 2015; as of March 2011, 64% of the fleet was so equipped and already there