



AEROSPACE RECOMMENDED PRACTICE

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Superseded by ARP6275

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

RATIONALE

Cancellation of document ARP4176, "Determination of Costs and Benefits from Implementing an Engine Health Management System," authored by the E-32 Aerospace Propulsion Systems Health Management Technical committee and issued on 5 Feb 2013 is being requested. Upon subsequent creation of the HM-1 committee, Integrated Vehicle Health Management, a corresponding vehicle-level cost - benefit document was deemed necessary. Consequently, ARP6275, "Determination of Cost Benefits from Implementing an Integrated Vehicle Health Management System" was authored and issued on 7 July 2014. ARP6275 was closely based on ARP4176 (and led by the same individual) but enhanced to reflect vehicle level decisions, to include the propulsion system level. It was also expanded somewhat to address learnings since ARP4176 was issued. The result is that ARP6275 is a superset of ARP4176, making the latter redundant and adding unnecessary work to keep the status and content of both aligned. Thus, the E-32 TC respectfully requests cancellation of ARP4176 in favor of the more recent and in-depth ARP6275.

CANCELLATION NOTICE

This Technical Report has been declared "CANCELLED" as of April 2020 and has been superseded by ARP6275. By this action, this document will remain listed in the respective index, if applicable. Cancelled Technical Reports are available from SAE.

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TABLE OF CONTENTS

1.	SCOPE.....	4
1.1	Purpose.....	4
1.2	Approach.....	4
2.	REFERENCES.....	4
2.1	Applicable Documents	4
2.1.1	SAE Publications.....	4
2.1.2	Other Documents.....	5
2.2	Abbreviations	5
3.	INTRODUCTION.....	6
3.1	Motivation for Implementing a Prognostics and Health Management System.....	6
3.2	Fundamental Considerations Preceding the Cost Benefit Analysis	7
4.	FACTORS INFLUENCING COST BENEFIT STUDIES AND ANALYSES	8
4.1	PHM System Complexity	8
4.2	Usage: Military versus Commercial	8
4.3	Legacy versus New Platforms	9
4.3.1	Impact on Design	9
4.4	Performance versus Reliability or Sustainment.....	10
4.5	Cost Savings versus Cost Avoidance.....	10
5.	COSTS FOR CONSIDERATION IN AN ENGINE PHM COST BENEFIT STUDY.....	10
5.1	PHM System Scope and Overview.....	10
5.1.1	Data Generation and Acquisition	10
5.1.2	Data Capture	11
5.1.3	Vehicle/Platform Integration.....	11
5.1.4	Communications (including Satellite and Other Relay Provisions)	11
5.1.5	Ground Station	11
5.1.6	Information Delivery	11
5.1.7	Data Storage and Archiving	11

5.1.8	Software (including Software Maintenance)	11
5.1.9	Technical Support for Users	12
5.1.10	Data Analysis and System Upgrades to Address Emerging Fault Modes and Evolving Needs	12
5.1.11	Electronic Component Obsolescence.....	12
5.1.12	Discussion.....	12
5.2	Development Costs.....	13
5.2.1	Requirements Definition.....	13
5.3	Design and Development.....	13
5.3.1	Build and Qualification	13
5.4	Production Costs.....	14
5.5	Operational Costs	14
5.5.1	Labor for Data Handling, Analysis, Storage, and Transmission	14
5.5.2	Data Transmission and Storage Costs	14
5.5.3	Additional Fuel Costs	14
5.5.4	Unnecessary Maintenance due to PHM System “False Alarms”	15
5.6	PHM System Sustainment Costs.....	15
5.6.1	PHM System Training	15
5.6.2	PHM System Upgrades	15
5.6.3	PHM System Maintenance	15
5.6.4	Component Obsolescence.....	15
6.	BENEFITS FOR CONSIDERATION IN AN ENGINE PHM COST BENEFIT STUDY	17
6.1	Fuel Savings	17
6.1.1	Fewer Ground Runs for System Checks or Diagnoses.....	17
6.1.2	Fewer Mission Aborts	17
6.1.3	Increased Propulsive Efficiency through More Systematic Monitoring of Degrading Engines.....	17
6.2	Planning and Anticipating Engine Changes.....	17
6.3	Identification of Faulty Components Such As Control Valves and Air Bleeds.....	18
6.4	Trending of Performance Degradation and Early Corrective Action	18
6.5	Business Benefits.....	18
6.5.1	Warranty/Guarantee Mitigation	18
6.5.2	Power-by-the-hour Cost Reduction	18
6.5.3	Service Sales	19
6.5.4	Life Extension of Life-limited Parts (LLP).....	19
6.5.5	Increased Residual Value	19
6.6	Reduced Weight of Propulsion System through Reduced Redundancy and Conservatism.....	20
6.7	Maintenance Savings.....	20
6.7.1	Reduced Line Maintenance Labor-hours/Staffing	20
6.7.2	Reduced Shop Maintenance Labor-hours/Staffing.....	20
6.7.3	Reduced Number of LRUs Returned For Bench Check/Overhaul and Reduced “Back Shop” Labor-Hours/Staffing.....	20
6.7.4	Reduced Secondary Damage from Early Detection of Incipient Failures	20
6.7.5	Improved Parts Life from Early Detection and Correction of Component Performance Degradation.....	21
6.8	Operational Savings.....	21
6.8.1	Fewer In-flight Shut Downs (IFSD) and Unplanned Engine Removals (UER).....	21
6.8.2	Greater Platform Availability	21
6.9	Capital Investment	21
6.9.1	Fewer Mission Aborts Prior to Takeoff and After Dispatch.....	21
6.9.2	Reduced Spare Equipment, Parts and Material Stocks	22
6.9.3	Reduced Maintenance Facilities and Equipment at All Levels	22
6.9.4	Reduced Investment in Equipment and Facilities Due To Lower Demand for Vehicles, Spares, and Material	22
6.10	Incidental Costs.....	22
6.10.1	Marginally Reduced Dependence on Strategic Materials and Obsolete Components	22

7.	CHALLENGES ASSOCIATED WITH COMPLETING A COST BENEFIT STUDY	23
7.1	Qualitative Values	23
7.2	Desired Fidelity	23
7.3	PHM System Confidence	24
7.4	Is a Cost Benefit Study Really Necessary?	24
7.5	PHM is Too Good to Be True.....	24
8.	EXAMPLES OF PHM IMPLEMENTATION AND ASSOCIATED COST ANALYSIS MODELS	25
8.1	U.S. Army Helicopters.....	25
8.1.1	Implementation of CBM	25
8.2	Financial Tools	26
8.2.1	Real Options Analysis (Reference 2).....	26
8.2.2	Actuarial Science (Reference 3):	26
8.3	Integration of a PHM model (Reference 4)	26
8.4	System Dynamics Approach/Perspective	27
8.4.1	Business Case Scenarios using System Dynamics Modeling (Reference 5)	27
9.	SUMMARY	34
10.	NOTES	34
FIGURE 1	BASIC PHM PROCESS FLOW	7
FIGURE 2	A GENERALIZED PHM VALUE MODEL	23
FIGURE 3	U.S. ARMY HELICOPTER FLEETS ARE LEADING THE WAY FOR ON-BOARD PHM APPLICATIONS	25
FIGURE 4	BUSINESS CASE 1	29
FIGURE 5	BUSINESS CASE 2	30
FIGURE 6	BUSINESS CASE 3	31
FIGURE 7	BUSINESS CASE 4	33
TABLE 1	PHM SYSTEM IMPLEMENTATION RELATIVE COST AND WEIGHT IMPACTS (ESTIMATED)	16
TABLE 2	ASSUMPTIONS	28
TABLE 3	ESTIMATED PHM COSTS	28
TABLE 4	BUSINESS CASE 1: ROI AND NEW SAVINGS BASED ON A 10-YEAR PERIOD	30
TABLE 5	BUSINESS CASE 2: ROI AND NEW SAVINGS BASED ON A 10-YEAR PERIOD	31
TABLE 6	BUSINESS CASE 3: ROI AND NEW SAVINGS BASED ON A 10-YEAR PERIOD	32
TABLE 7	BUSINESS CASE 4: ROI AND NEW SAVINGS BASED ON A 10-YEAR PERIOD	32
TABLE 8	OVERALL ROI AND SAVINGS BASED ON A 10-YEAR PERIOD	33

1. SCOPE

This ARP provides an insight into how to approach a cost benefit analysis (CBA) to determine the return on investment (ROI) that would result from implementing a propulsion Prognostics and Health Management (PHM) system on an air vehicle. It 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 PHM systems but want to either quantify or understand the economic benefits (i.e., the value proposition) that a PHM system could provide.

1.1 Purpose

This ARP is not intended to be used as a standard or legal document but is compiled to help the increasing number of people who want to compute a PHM Cost Benefit Analysis 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 engine manufacturers and the U.S. Department of Defense (DoD) to identify effective tools and techniques. The various methods were assessed by an E-32 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.

ARP1587	Aircraft Gas Turbine Engine Health Management System Guide
AIR1828	Guide to Engine Lubrication System Monitoring
AIR1839	A Guide to Aircraft Turbine Engine Vibration Monitoring Systems
AIR1871	Lessons Learned from Developing, Implementing, and Operating a Health Management System for Propulsion and Drive Train Systems
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
ARP4761	Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment

AIR5317 A Guide to APU Health Management

AIR5871 Prognostics for Gas Turbine Engines

2.1.2 Other Documents

Reference 1: AHS2011-000291, Verification and Validation Process for CBM Maintenance Credits dated 24 Feb 2011

Reference 2: "Real Options Analysis as a New Economic Tool Linking CBM Investments to Business Strategy". Presented by Fred Discenzo, PhD, Rockwell Automation, at the 56th Meeting of the MFPT Society, April 2002. Available from Society for Machinery Failure Prevention Technology, 5100 Springfield St., Ste 420, Dayton OH 45431-1264 (937)-256-2285, www.mfpt.org

Reference 3: "The Business of PHM: An Actuarial Engineering Perspective," Keynote address by Sameer Vittal at the PHM Conference, Portland, OR, (www.phmsociety.org/sites/phmsociety.org/files/PHMconference2010_SameerVittal.pdf) Oct, 2010

Reference 4: "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

Reference 5: "Economic Modeling for Prognostic Health Management", Presented by Ron Shroder and Nick Frankle, Frontier Technology Inc, at the 2009 conference of the Society for Machinery Failure Prevention Technology, Dayton OH. Available from Society for MFPT, 5100 Springfield St., Ste 420, Dayton OH 45431-1264 (937)-256-2285, www.mfpt.org

2.2 Abbreviations

ACARS	Aircrew Communications Addressing and Reporting System
AIR	Aerospace Information Report
ARP	Aerospace Recommended Practice
ATO	Aborted Take Off
CBA	Cost Benefit Analysis
CBM	Condition-Based Maintenance
CEDU	Central Engine Diagnostics Unit
DoD	Department of Defense
DSC	Digital Source Collector
ETOPS	Extended (Twin Engine) Operations
EFH	Engine Flight Hour
EKG	Echo Cardiogram
FADEC	Full Authority Digital Engine Control
FMECA	Failure Modes, Effects, and Criticality Analysis
HM	Health Management
IFSD	In-Flight Shutdown
JSF	Joint Strike Fighter
LCC	Life Cycle Cost
LLP	Life-Limited Part
LRU	Line-Replaceable Unit
MRO	Maintenance, Repair, and Overhaul
MTBR	Mean Time Between Removals
NFF	No Fault Found
OEM	Original Equipment Manufacturer
PHM	Prognostics and Health Management
PHMU	Prognostics and Health Management Unit
PTCRB	PCS (Personal Communication System) Type Certification Review Board

ROI	Return on Investment
SER	Scheduled Engine Removal
TAC	Total Accumulated Cycles
TOW	Time on Wing
UAV	Unmanned Air Vehicle
UER	Unscheduled Engine Removal
V&V	Verification and Validation
WIP	Work in Progress

3. INTRODUCTION

3.1 Motivation for Implementing a Prognostics and Health Management System

While engine condition monitoring has been utilized in various forms since the late 1960s and with steadily increasing capability since the 1970s, prognostics and health management (PHM) tools and capabilities have come from their infancy in the early 1990s to now being sufficiently mature to implement on airborne systems. This rapid progress in technology was mainly the result of the pull by the DoD's Joint Strike Fighter (JSF) Program. With affordability at the core of the program, the U.S. Navy agreed, for the first time in recent history, 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 (Reference 1) but now, a stated program created a requirement as opposed to a serious desire. To many, the ability to predict the need to 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. The reason for considering a PHM system is the place at which 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 conservatism. In contrast, the commercial aviation world sees the benefits of a PHM system primarily in terms of *economics*. Most commercial airline 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. However, where safety can be improved as an associated benefit from some other action, then clearly this will be exploited by operators and manufacturers. When Extended (Twin Engine) Operations (ETOPS) was introduced in 1997 (and redefined by the FAA in 2007), commercial operators recognized Health Monitoring as a major tool to ensure that the regulatory imposed requirements could be met. So, even though the military and commercial entities are broadly separated by the fundamental difference of safety over economics, there are many common aspects when considering implementation of a PHM system on a platform, and the high level process flow is illustrated in Figure 1. Looking at the three rows, the "What" row is self explanatory and represents the infrastructure necessary to establish a PHM system (remove any one of the elements from the chain and the PHM system would be unable to function). The "Where" row represents the locations that those essential elements would be conducted. For instance the sensors will typically be on the engine and hopefully the maintenance actions will be performed at the flight line or the dispatch gate. Finally, the "How" row shows the ways and means of performing the essential elements, be it one of the plethora of sensors available to generate the data, to maintenance performed by engine overhaul technicians or maintenance teams overnight in the hangar. The first issue, irrespective of operator or platform is to define what the PHM system is required to detect and manage (3.2); thereafter, the other motivational drivers for PHM system installation include higher affordability, increased equipment usage, enhanced reliability, reduced spares holdings, etc., which are described later (Section 6) and will have differing priorities depending on the specific user or implementer of the system.

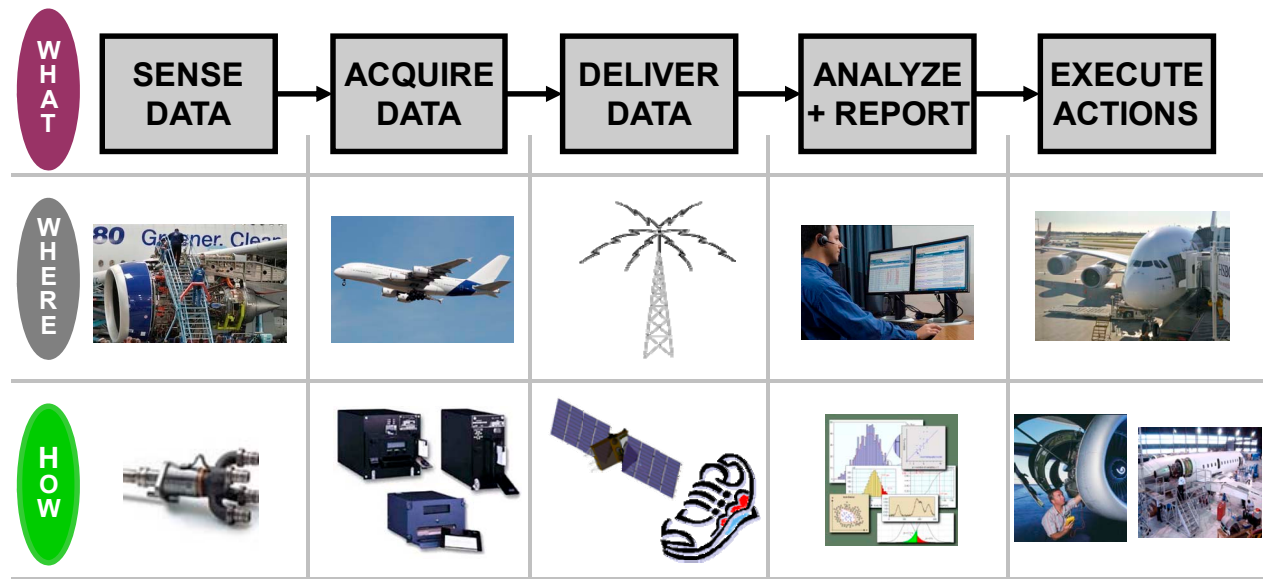


FIGURE 1 - BASIC PHM PROCESS FLOW

3.2 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 the specific failures or modes of failure that need to be detected. The PHM system will thus be configured to identify system 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 (too dangerous), and unscheduled engine changes in remote operating bases (costly for the operator and major inconvenience incurred by the customers, usually resulting in increased costs to the operator and long-remembered customer dissatisfaction). There are a great many other failures which could be termed innocuous in that they are easily repairable, don't pose an unsafe condition or in-flight hazard, or are inexpensive to fix (although it is recognized that some of these, if left unattended, could lead to larger costlier issues in the future). Many airline passengers experience such failures with overhead seat lighting, personal entertainment malfunctions, etc. 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. It is proffered that any failure can be detected in its incipient phase provided the parameters associated with the degradation that precedes 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 cost effective or worthwhile (although how this decision is reached can involve a large amount of subjectivity). However, during the operating life of a fleet of engines, different failure modes come to light, or regulations change to effect maintenance and inspections, or the modus operandi of the platform/system changes that, in turn, change the ways that components are monitored. In other words, PHM on a system is a living thing (see 5.3.1) and needs to be flexible, adaptable, and easily updated to accommodate these continuous changes. Nonetheless, the common starting point is to define the failures in the system that need to be mitigated (for whatever reason). This is typically accomplished with a System Safety Analysis (ARP4761 and/or ARP4751A for commercial applications). Once identified, how those failures can be anticipated at a sufficiently early stage (from data generated during system operation), and which sensors and analytical tools (PHM) will reliably provide the necessary information can be determined. From that point, a cost benefit analysis can be initiated. Note that the ideal situation is for system design engineers to work hand in hand with PHM and reliability and safety engineers throughout the design process, including preliminary design. This would allow the designs to be optimized so that failures that can be economically eliminated or ameliorated by design changes could be handled at the outset, whereas those failures that need monitoring would be taken care of with monitoring systems integrated into the design at the very beginning. This will lessen the need for add-on systems whose post-design installation is invariably more difficult to justify.

4. FACTORS INFLUENCING COST BENEFIT STUDIES AND ANALYSES

4.1 PHM System Complexity

Nowadays, a PHM system can be as complex as a customer requires. Traditionally, monitoring and managing engine gas path performance (temperatures, pressures, speeds, etc.) constitute the underlying baseline, but modern systems can determine blade “time of arrival” to detect blade distress, bearing degradation using on-board oil debris detection and analysis, ingestion of foreign objects, failure of internal components, disk cracks. On-board oil quality monitoring is also possible, as is extensive vibration analysis, and even health management of external components such as fuel control units, pumps, shut-off valves, and actuators. The cost benefit analysis is thus highly dependent on the requirements of the end customer. While a PHM system may be supposedly available “off the shelf,” the reality is that the PHM tools and capabilities will need to be customized to meet not only the specific application but the customer’s defined needs. 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 baseline. 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.

4.2 Usage: Military versus Commercial

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 missions on a normal basis until a major exercise or combat/war scenario arises, 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 are often less than 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 5 to 10 for military) because of the higher usage rate and the longer flight durations. If the metric of number flights is used as a detection window, then parity (i.e., five or less flights to maintenance) between the military and commercial operations is more likely. 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. 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. As such, many cost benefit models are needed so that one best suited to the specific circumstances can be utilized.

4.3 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. 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 an operational fleet of engines. While one can sense that the qualitative cost benefits are reduced by just the thought of fleet modification, the PHM system could be specifically designed to address the failure modes of the engines 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 the optimum time, both from ease of embodiment and ROI. However, there is likely to be no operational data on which to help base the PHM system design or 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 not only more difficult to compute but also harder to generate a justifiable fidelity. Moreover, it is unlikely that all the failure modes or problems with a new fleet of equipment will be predicted at the outset. As mentioned in 3.2, and later in 5.2.1, a PHM system needs to be a “living thing” as opposed to a “fit and forget” capability be it on a new or a legacy system. The sustainment of the PHM system is therefore a cost element that needs to be included in the CBA for both.

4.3.1 Impact on Design

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 duration 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, then the downside is the reduced number of minutes that the UAV can loiter at the area of interest and 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 (albeit more likely for a military platform than a commercial one) and possibly cost of manufacture and *increases* platform capability and performance (such as time on station). Additionally, building in capacity at the outset for introducing smart software updates that would increase EHM 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. This rationale is equally applicable to reliability, where the addition of a PHM system has the potential to reduce conservatism in the design.

4.4 Performance versus Reliability or Sustainment

For commercial platforms, increasing performance and capability is not usually a prominent issue compared with sustainment of a reliable fleet throughout the life cycle. For military systems however, technology upgrades and increases in performance usually trump fleet modifications, even if those modifications would have greatly benefited life cycle costs. Such an example is fleet implementation of a new radar for the F-15E in the 2000 to 2010 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, etc. As discussed in 3.1, 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. On the other hand, intense business competition in the commercial airline world drives the desire for increased availability, but the same difficulty exists of how to determine and justify the investment of a PHM system to achieve the anticipated increase and the likelihood of the increased availability being achieved. Calculating or assigning a cost benefit to, say, a one percent increase in platform availability, readiness, or mission success is far from objective.

4.5 Cost Savings versus Cost Avoidance

When calculating all the total benefits (termed in this paper 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. The military does not recognize maintenance or labor-hour reductions as monetary savings, but they can be book-kept as cost avoidance. Thus, what can be claimed as an accountable "benefit" is not necessarily set in stone and needs to be determined and agreed upon ahead of time by the compiler and the reviewers of the business case. As will be discussed in the subsequent sections, 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.

5. COSTS FOR CONSIDERATION IN AN ENGINE PHM COST BENEFIT STUDY

For a comprehensive 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:

5.1 PHM System Scope and Overview

5.1.1 Data Generation and Acquisition

Data invariably comes from sensors so, having determined which failure modes need to be anticipated, it needs to be determined how the required data will be obtained. Are additional sensors needed in the system? Adding sensors adds weight, be it from the sensor, its mounting provision, the associated wiring/plumbing, the interface to the recording device, etc. It can also reduce system reliability and increase maintenance costs since some sensors are less reliable than the equipment they are mounted on. The best scenario is to mainly rely on the sensors that are necessary to manage and ensure the process of safely operating the engine and minimize the introduction of additional sensors for purely PHM purposes. Lastly, retrofitting additional sensors on legacy fielded engines 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 engine is in service.