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

RATIONALE

This Aerospace Recommended Practice (ARP) provides insight into how to create a cost benefit analysis to determine the justification for implementing a propulsion/engine health management system. The considerable advancement of health management (HM) tools and capabilities in the past 10 years, coupled with some successful applications to legacy and new engines drove the need to re-write the original AIR and provide more specific guidance, thus creating the need for an ARP. Moreover, there has been increasing requests in recent years by potential implementers, both commercial and military, to better understand how to make a convincing business case within their organizations, This, for many, has become the stumbling block that prevents implementation of an Engine Health Management System.

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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.

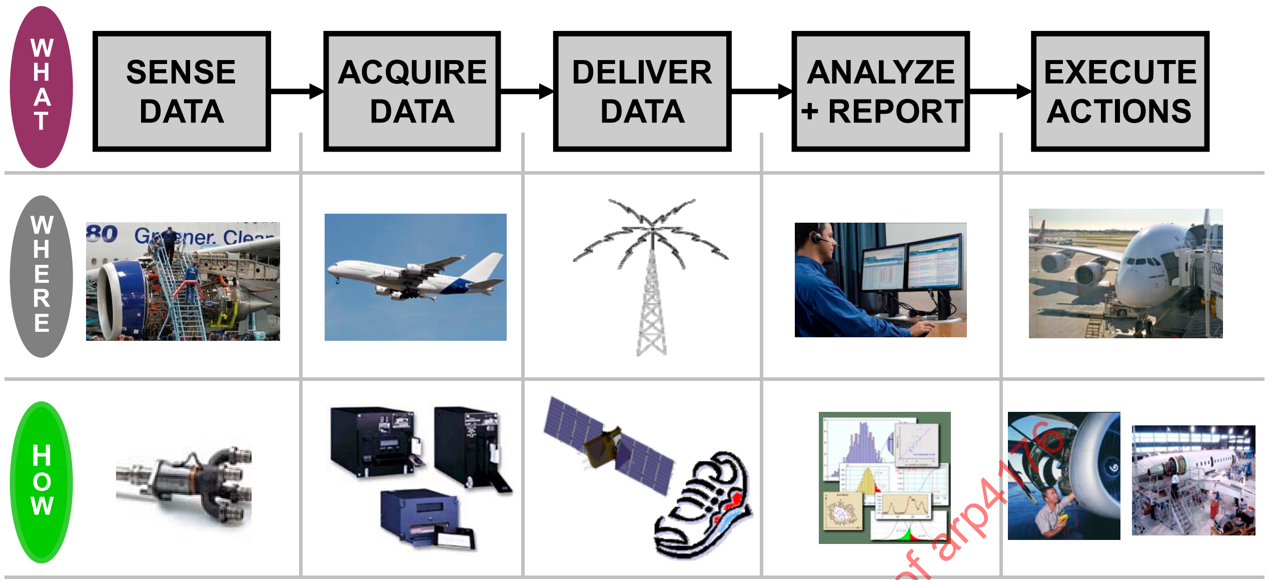

FIGURE 1 - BASIC PHM PROCESS FLOW

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.

5.1.2 Data Capture

Is it adequate to capture periodic "snapshots" of data or should the entire flight be recorded? Are all available parameters required or will a smaller subset suffice? 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?

5.1.3 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 host system (e.g., the engine) and what are the effects on the higher level system (i.e., the air vehicle)? For example, it is recognized in the industry that for every kilo of weight added to an engine, the aircraft weight increases by four kilos.

5.1.4 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-boarded? 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.

5.1.5 Ground Station

What hardware and software will be needed to receive, validate, decompress, decrypt, and analyze the data? The cost of acquisition, training, verification/validation and sustainment of the ground based system needs to be determined and included.

5.1.6 Information Delivery

How will the processed and analyzed data, and 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 a pull approach?

5.1.7 Data Storage and Archiving

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. The development time will have an impact on these calculations. The cost of electronic hardware is constantly falling, and the development time for aerospace systems can be quite large; so the CBA can be favorably affected by these lead times. These should be taken into consideration.

5.1.8 Software (including Software Maintenance)

Health management hardware (sensors, recorders, storage, processors, etc.) is readily available off-the-shelf although their certification or qualification typically makes these components relatively expensive.. The software system(s) to analyze the data and seamlessly deliver reliable answers is generally *not* available off the shelf. Robust, enterprise-class, PHM software is very difficult and expensive to develop yet, without it, the system will be useless. Software for acquisition, data processing, storage and analysis may be included for on-board and/or ground-based solutions. Partitioning/protection architectures for integrated systems can reduce the impact of future enhancements and prevent unsafe conditions in engine control and display systems.

5.1.9 Technical Support for Users

This is a piece of the sustainment costs of an implemented PHM system and needs to be included in the cost equation.

5.1.10 Data Analysis and System Upgrades to Address Emerging Fault Modes and Evolving Needs

Again, this is a necessary piece of sustaining an implemented system and ensures that the system does not become outdated as the fleet ages.

5.1.11 Electronic Component Obsolescence

This is an important issue that can negatively impact the life-cycle costs and should therefore be considered.

5.1.12 Discussion

The above elements can also be assigned within the categories of development, production, and sustainment costs (see below) and while these elements do not constitute an exhaustive list, many 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 platforms and their systems are seldom delivered into service with all, or even most of, the failure modes already identified. Most failure modes 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 anticipated and 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. Few current PHM systems provide for explicit integration of information from shop floor (or MRO) and incident investigation findings (formally outside the scope of this document) but proactive management of this information source will inevitably drive PHM system change and cost.

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.

5.2 Development Costs

5.2.1 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 Failure Modes, Effects, and Criticality Analysis (FMECA), and determination of specifications such as size, weight, power, false positive and false negative rates, robustness to the expected operating environment, and certification requirements. 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. The key requirement, particularly in commercial applications, is determination of the end use of the output: will it be used to make solely economic decisions (when should I do maintenance to minimize my costs) or safety-related decisions (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. Setting aside some critical components such as the Engine Vibration monitoring unit which are certified to Level C, most typical on-board PHM systems have Level E software whereas to use the system for maintenance credit or safety mitigation would require higher assurance levels depending on use. Clearly this is much more expensive to accomplish and may also require ground system certification.

In summary, where PHM systems are used for economic decisions, (which has historically been the predominant driver for their use), and not safety related decisions, then Level E software is sufficient and the ground HM processes are *approved* through operators’ maintenance plans. But, if PHM systems become considered or used for safety related and life extension purposes then regulatory approval and *certification* at some appropriate level will be needed.

5.3 Design and Development

These costs will be based on the above requirements definition.

5.3.1 Build and Qualification

While building a well-defined PHM system is relatively straightforward, its qualification is much more complex and undefined, and realistically extends well past its initial entry into service. In fact, it is understandably believed by many that qualification of a PHM system never ends. This is because the propulsion system being monitored will be constantly changing, somewhat like the aging of a human being, so the degradation and ailments change throughout the life cycle and thus the PHM system must always adapt to accommodate the slow but continual changes of the system. The big unknown is the degree of verification and validation required at the outset to satisfy initial implementation. Reference 1 provides insight into how to claim maintenance credits from a Condition-Based Maintenance (CBM) system and the Verification and Validation (V&V). Clearly, the thorny issues cited above and the questions below are plentiful and the cost to answer them is significantly high, yet hard to accurately estimate. For instance, what accuracy is required (i.e., the number of false positives (“the system cried wolf”) and false negatives (“the system was not sufficiently competent and missed a fault”) that are tolerable)? How will accuracy be tested and validated? One approach is to capture a number of data sets containing real world failures of all types the system is expected to detect and run the data through the system to see how quickly and accurately it triggers. How well does the system learn from its own experience as well as from its “siblings” on like platforms in the fleet? Does the PHM system degrade with age or does it actually improve (become older and wiser)? What is the metric of acceptability and to what is it compared (since the accuracy of the human maintainer is not only not documented but also extremely variable from person to person and therefore very difficult to define)? Employing probabilistic risk management tools and starting with some initial, provisional PHM system qualification with an ability to accommodate component life extension is seen as inevitable and will impact PHM system engineering support and configuration change. The recommendation is to consider these “difficult” aspects cited above and show in a CBA that they have been considered, even if the costs assigned are estimates as opposed to precise computations.

5.4 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 (including integration with other ground systems and processes) and its operation, maintenance, and training documentation needs to be included.

5.5 Operational Costs

5.5.1 Labor for Data Handling, Analysis, Storage, and Transmission

This is self explanatory and needs no embellishment in terms of how to calculate them; it should be a simple product of the manhours estimate and labor rates. How these costs are accounted for depends on the specific organization; they are likely to be “someone else’s” (e.g., a support function) area or department, but irrespective, they are still a cost for the company to accept.

5.5.2 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 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 like China 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 will not be) universally deployed.

5.5.3 Additional Fuel Costs

It is probable the PHM 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 stated in an article 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 over time, 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 exponential and closes towards zero but the elements are not only the fuel to carry the additional PHM system weight but also the “fuel for the (extra) fuel” and potentially extra structure or strength to carry the additional load. However, if a system is being introduced at the design stage of a platform, then it might be that the addition of a PHM system actually *reduces* overall platform weight because of redundancy that might be designed out at the outset (see 4.3.1). As discussed in 3.1, the U.S. Navy adopted PHM based on the fact that the redundancy of two engines could be eliminated, yet maintain equivalent safety.

5.5.4 Unnecessary Maintenance due to PHM System “False Alarms”

As no system is perfect, an element of “false positives” can be expected from a PHM system (5.3.1). But, against what baseline 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 a separate 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 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 PHM 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. 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 baseline from which to try and compare against the status quo. In any case, a PHM system that exceeds some perceived or real threshold of false detections runs the risk of being ignored or marginalized such that it is no longer utilized by the decision-makers. For instance, on earlier engine models there have been occurrences of maintainers permanently disconnecting accelerometers due to repeated false vibration alarms.

5.6 PHM System Sustainment Costs

Some of the elements shown below were also included in the operational cost section (5.5) as there is a degree of unavoidable overlap between operations and sustainment activities.

5.6.1 PHM System Training

In a well-designed system, usage should be nearly intuitive, minimizing the need for training. However, this ideal is difficult to achieve and training will be required. A well-designed training program, probably Web-based, needs to be estimated and included.

The impacts of relative cost and weight to implement a new PHM system were estimated and are illustrated in Table 1.

5.6.2 PHM System Upgrades

Inevitably, a flexible system will undergo reliability, capacity, and performance upgrades no less often than every two years. These must be estimated and included.

5.6.3 PHM System Maintenance

Cnsideration should be given to the costs of implementing enhancements or corrections to the on-bard systems that support the PHM system. The costs of server leasing, troubleshooting and “help desk” labor, software licenses and fixes, etc. also need to be estimated and included.

5.6.4 Component Obsolescence

This can have a negative impact on the repair and maintenance of the PHM system itself. Provision must be made to either buy and maintain long-term spares inventory, or for future investment in component redesign based on new components.

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

		ELEMENT	SUB-ELEMENT	WEIGHT IMPACT	COST IMPACT Civilian or Military Retrofit Non-Recurring	New Dev. 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
			Casting	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. BENEFITS FOR CONSIDERATION IN AN ENGINE PHM COST BENEFIT STUDY

6.1 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.

6.1.1 Fewer Ground Runs for System Checks or Diagnoses

Connected with the discussion in 6.5.4., one approach is to estimate a percent reduction in the number of diagnostic ground runs based on historical data and on the PHM system's ability to correctly predict impending failures. Making a conservative but theoretical assumption is the easier option; otherwise scrutiny of the number and frequency of engine ground runs on a fleet of aircraft and determining which ones could be avoided if a PHM system were in place, would be more quantitative but also more time-consuming and would still require a degree of theoretical assessment.

6.1.2 Fewer Mission Aborts

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. Hot weather engine surges, engine vibration, low oil pressure, and stuck bleed valves are some of the typical defects. 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 aborted takeoffs (ATO), in-flight shutdowns (IFSD), and air turnbacks or diversions for unanticipated failures which consume substantial fuel (and have other large costs associated with them). Some of these are considered in greater detail below.

6.1.3 Increased Propulsive Efficiency through More Systematic Monitoring of Degrading Engines

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 an engine fleet. PHM systems can inherently provide engine performance rankings of one to N in a fleet and thus show which engine(s) are "worth" fixing to restore efficiency. Whether it's a compressor wash or something more significant and costly such as changing of a rotating module, the PHM system can help to lift the overall efficiency of an engine fleet by as much as the person in charge of performance monitoring is motivated to do or economic viability allows. Determining 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, in either case, calculating the cost savings based on the price of fuel, annual miles flown, etc.

6.2 Planning and Anticipating Engine Changes.

For commercial avaiation, and to a lesser extend military operations, health monitoring is one of the tools that helps determine a schedule for engien changes. Natural degradation in engine performance over time (measured by parameters such as exhaust gas temperature "margin") helps operators determine when an otherwise serviceable engine will need to be removed and replaced and thus ensure that the necessary resources and the aircraft's location (i.e., a suitable maintenance center) is pre-planned. This clearly minimizes the adverse impact on operations but it can be seen by a some as a natural efficiency and planing measure as opposed to a real cost saving. In this case, the recommended approach is to consider how many engine changes are pre-scheduled in a year based on advance warning of a health management system and compute the costs that would have otherwise been incurred if those egine changes had happened radndomly with no forewarning. Some assumptions will need to be made such as where the airplane might have been at the time of the engine change but a reasonabe comparitive calculation could be obtained to measure the cost benefit.

6.3 Identification of Faulty Components Such As Control Valves and Air Bleeds

Better diagnosis of potentially faulty components means fewer removals, some of which are subsequently found to be “re-test OK” or “no fault found” (NFF). 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 inventory of rotables or spares 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 rotables (e.g., fuel control unit, fuel pump, etc.) can be reduced by five to ten percent across the fleet. The challenge for the CBA is to determine how many components on the engine 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.

6.4 Trending of Performance Degradation and Early Corrective Action

The benefits from monitoring engine performance and plotting the inevitable degradation are easily 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 the engine on wing or in service for a longer period 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 on reasons for engine rejections would provide data and insight for the calculations.

6.5 Business Benefits

In this section, the benefits can be in the eye of the beholder. For instance, if the PHM system allows a component to be maintained on-wing until after the warranty period, and then fails, who is the beneficiary? With the increasing move towards “power by the hour” (6.4.2), are the benefits enjoyed by the service provider or does the concept reduce engine-related maintenance costs for the operator? A similar situation aplies to 6.4.3, service sales. The crucial point unerlying all these observatons is that considrable benefits can be enjoyed by OEM, operator and maintenance service provider. The business skill is in determining where the benefits lie for the individual party and how to optimize or maximize them in a manner that is acceptable to all parties involved. This is nothing new, it is fundamental business practice, but it does underscore the basic premis of this document that determining the cost benefits is a complex issue and ultimately is whatever the compiler of the case wants it to be.

6.5.1 Warranty/Guarantee Mitigation

In commercial engines sales and in military sales handled commercially (e.g., F117 engine 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 organization.

6.5.2 Power-by-the-hour Cost Reduction

Most new commercial and military engine sales include contracts for the OEM to maintain the engines under some type of fixed price dollar-per-flight-hour program. This business model shifts failure and maintenance cost risk from the operator to the OEM. The fairly recent expansion of OEM PHM capability is directly tied to this risk shift; PHM systems have been shown to directly reduce $/EFH costs under programs that require a PHM system to be used. These savings can be in the 3 to 8% range; this is significant when associated with aerospace system contracts that can run into billions of dollars.

6.5.3 Service Sales

A capable PHM system can directly generate revenue through sale of service to entities not wishing to take on this burden themselves, both military and commercial. Many legacy commercial operators are reducing powerplant engineering staff, and many low cost carriers never provision for the labor in the first place, instead choosing to outsource this monitoring capability. The revenues from this type of service are relatively low and the available market is shrinking due to retirement of older engines and the prevalence of dollar-per-flight-hour programs which include “free” PHM services as part of the contract. A new opportunity involves bundling engine PHM with other health-related services such as aircraft fuel burn reduction, APU health monitoring, etc.

6.5.4 Life Extension of Life-limited Parts (LLP)

Life-limited parts (LLPs) are those (generally rotating) parts in gas turbine engines with explicit life limits usually based on cycles. These parts cannot be flown to failure due to the catastrophic consequences, nor can they be replaced “on condition” since they are typically inaccessible and the flaws or material degradation that could cause failure are buried. Military cycle counting is rudimentary but commercial counting is even more so: one flight equals one cycle. Of course, no two flights are identical but each is currently treated in the same way for LLP cycle counting. Recent military programs are building more robust “damage accumulation” algorithms into on-board or off-board systems to replace the basic capabilities of the past. An LLP life extension system will use the same basic control process sensors as the larger PHM system but will look at them or record them continuously throughout the flight. Life usage algorithms will be applied to the peaks and valleys of temperatures and rotor speeds to calculate an effective life consumed in that flight. There is a considerable configuration management challenge in that each part number will have a different algorithm based on its geometry and properties, and each serial number will consume life at a different rate. So each of the 30 to 50 LLPs in every engine must be individually tracked and managed. Since most OEMs’ certified lifing systems are very conservative and assume that many or most flights occur at elevated outside air temperatures and with minimal thrust de-rate, actual operation using an LLP life tracking system may result in more flights between LLP changes than with current cycle counting methodologies.

LLPs typically constitute the most expensive part of a full engine overhaul when they are replaced. As engines become ever more reliable, replacing LLPs will become an increased cause of shop visits. Depending on the business model and who captures this value, it can result in lower OEM costs in $/EFH maintenance agreements, reduced LLP costs for operators, extended TOW, or at least flexibility for bringing in an engine for LLP replacement. Calculating benefits will be on a case-by-case basis and depends on the business model employed. The calculations will clearly be complex and dependent on the degree of fidelity sought, and thus the number of associated parameters used in the calculations.

A slightly different scenario is one in which an OEM finds itself with a life shortfall on one or more LLPs in an engine model. An LLP life extension system may allow the OEM to manage the shortfall while reducing the adverse financial or availability impact both to them and the operators. In this case, the benefit is huge and directly calculable, replacing the cost of bringing every engine in early with the much lower cost of the PHM/LLP system.

Finally, some commercial carriers, especially outside the USA, tend to have either full fleet monitoring of critical parts using either on-board cycle counters or data collection for off-board analysis. The algorithms are typically very complex and use many performance parameters in their calculations as opposed to, for instance the square of speed or counting TAC’s. There has thus been a move away from the “one cycle per hour” relationship, and an effort to employ more advanced cycle counting methodologies, which is a step towards more comprehensive engine health management.

6.5.5 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 equiped 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.

6.6 Reduced Weight of Propulsion System through Reduced Redundancy and Conservatism

This was addressed in 5.5.3, and, if a thorough CBA is being performed, the weight savings might beneficially impact other related, non-propulsion, systems on the platform.

6.7 Maintenance Savings

These include line (O-level) and shop (I-level and depot) labor and material, including rework. Note that more effective PHM will detect emerging problems earlier which opens up a plethora of benefits (reduced disassembly leading to less sunshine parts, etc., see 6.3) whose associated cost savings are, for the most part, hard to quantify, yet are real savings.

6.7.1 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 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 locations. Thus, 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.

6.7.2 Reduced Shop Maintenance Labor-hours/Staffing

As noted in 7.6.1, 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.

6.7.3 Reduced Number of LRUs Returned For Bench Check/Overhaul and Reduced "Back Shop" Labor-Hours/Staffing

This in turn means a smaller pool of spares (from the number of spare engines to the number of spare fuel pumps, blades, disks, actuators, etc.). This factor can become significant, especially in the case of high value spares, because a PHM system would create the potential to position these items at the location of anticipated need as the indications of degradation in the installed component become evident. Computing a true monetary figure will be difficult. One approach is to estimate the improvement over the current baseline (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 PHM system.

6.7.4 Reduced Secondary Damage from Early Detection of Incipient Failures

While this is related to 7.3, it also encompasses the savings in materiel and parts usage. Again, make a conservative but sensible estimate of the damage that could be saved if one engine per unit per year did not suffer secondary damage because an incipient failure was caught early and rectified. The "damage" has both quantitative and qualitative elements. Assuming the organization isn't a start-up, it should have maintenance histories that can be mined to estimate and validate savings from the reduction of secondary damage. Consider also the associated beneficial effects of increased readiness, availability, and safety. Secondary damage could invoke a serious in-flight incident; consider the likelihood, albeit remote, and the cost that could typically be assigned to such an unwanted incident. If more complexity is sought, consider the damage to the airline operator's name in terms of perceived customer satisfaction? These questions are posed for completeness, especially if the complier of the CBA has ascertained that the decision-making management will be receptive to factors such as customer satisfaction or wish to avoid being at the bottom end of market surveys for reliability, safety, on-time performance etc.

6.7.5 Improved Parts Life from Early Detection and Correction of Component Performance Degradation

By more active monitoring and management of performance, engines can be kept operating at or near their optimum operating condition, thus avoiding premature hot section burn out and increasing time-on-wing (TOW) or mean time between removals (MTBR). Again, there are at least two approaches when trying to measure this benefit. A "clinical" linear value can be calculated from TOW, e.g., removal and maintenance/overhaul cost divided by number of hours installed, or the benefit can be seen from a reducing "residual" value as TOW for an engine increases. For instance, a brand new engine just fitted on wing represents a much greater "value" to the operator than say the other engine on the same platform that might be just a few hours from scheduled removal or is close to not meeting its performance margin and in need of overhaul. If the latter engine suffers a blade failure or overtemp, then the "cost" of that event could be regarded as much less compared with the former engine whose "investment" is only just beginning to be amortized. The ultimate value, however, is that increasing time on wing is a measure of goodness; how the operator wishes to account for that benefit is up to the individual.

6.8 Operational Savings

The following factors reduce direct and indirect operating costs.

6.8.1 Fewer In-flight Shut Downs (IFSD) and Unplanned Engine Removals (UER)

Fewer IFSDs leads to fewer diversions and less remote maintenance effort and costs. 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 (probably an engine) to recover the aircraft is very expensive and time-consuming. A modern high-bypass high thrust engine may require leasing an Antonov 124 or 225 to deliver a replacement engine. 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. 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). 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. The organization should have IFSD data and maintenance history that can be mined to estimate and validate reductions in IFSDs and UERs, and the associated costs emanating from a PHM system's ability to detect specific causes. Note that there are a number of failure categories which current practical PHM systems cannot directly detect such as high cycle fatigue, embedded cracks, mechanical failures of engine external elements, and others.

6.8.2 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. The cost benefit can be computed directly in terms of "airplane costs." The U.S. Army, with its CBM+ initiative for its rotorcraft fleet, have calculated availability increases associated with its CBM-equipped platforms which can be translated into a cost benefit by applying the percentage increase to the cost of the platform. In the commercial world, increasing platform availability across the fleet might enable the fleet to fly some percentage more revenue generating flights per day. These costs are directly visible and calculable to the operator. This is one of the few parameters where the cost calculation can be clearly defined for commercial and military operations.

6.9 Capital Investment

This cost needs to be segregated from the above cost elements as it is treated differently in financial analysis. It affects the calculations of return on investment, while the above costs affect the returns to the investment. It is, however, still a cost element applied to the CBA/business case.

6.9.1 Fewer Mission Aborts Prior to Takeoff and After Dispatch

These costs were mentioned in 6.1.2 and they apply to both the operational and maintenance aspects of aircraft operations.

6.9.2 Reduced Spare Equipment, Parts and Material Stocks

The purchase price of the spares pool compared with that of a reduced pool because of more accurate forecasting and reduced usage/turnover can be calculated using the price of each component. The harder parameter in the equation is to determine by what factor the spares pool and 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 required to be a viable element of a cost benefit analysis.

6.9.3 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. As discussed in 6.6, 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. 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’s feasible a year or two after PHM system implementation.

6.9.4 Reduced Investment in Equipment and Facilities Due To Lower Demand for Vehicles, Spares, and Material

This is more pertinent when introducing a new engine into service and being able to reduce the initial provisioning over what would have been provided without a PHM system. It is similar to the savings cited in 6.6.3 but is the inverse in that the facilities won’t be built or purchased from the outset, as opposed to savings generated by closing or reducing existing facilities.

6.10 Incidental Costs

6.10.1 Marginally Reduced Dependence on Strategic Materials and Obsolete Components

Many parts in modern gas turbine engines utilize rare earth elements and other exotic materials either in their initial manufacture or in coatings. To whatever extent the PHM system can extend the useful lives of engine components, dependency on these materials is reduced. Similarly, the PHM system may allow extended use of out-of-production 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.

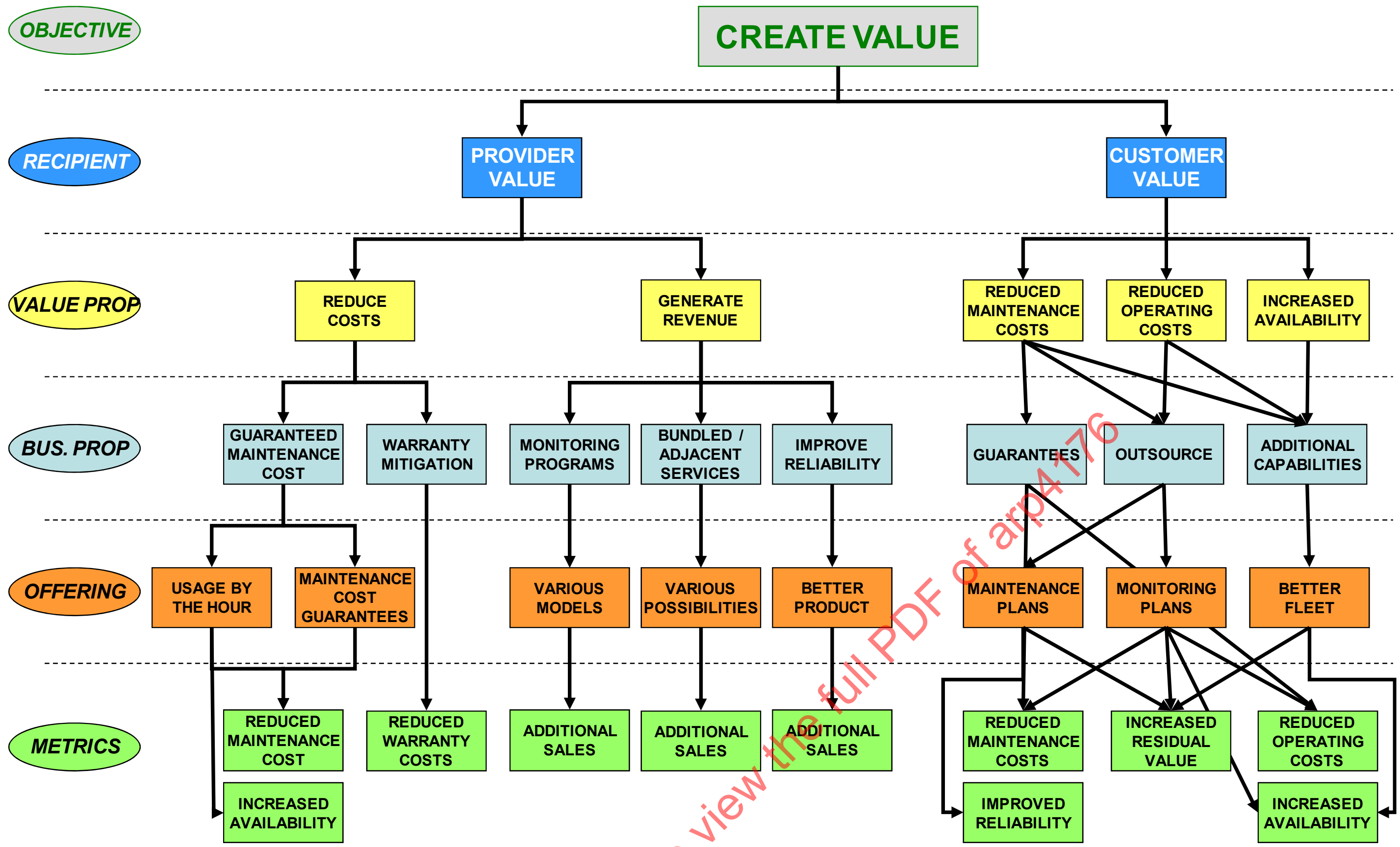

FIGURE 2 - A GENERALIZED PHM VALUE MODEL

7. CHALLENGES ASSOCIATED WITH COMPLETING A COST BENEFIT STUDY

7.1 Qualitative Values

Even with the above elements identified and some assumptions or estimates made to generate a “bottom line” figure, there are elements that are ultimately unquantifiable or sufficiently intangible 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 min. Maintenance required during the day has a huge negative impact. A PHM system which flags preventative 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.

7.2 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. In the end, 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.

7.3 PHM System Confidence

Basic health management capability has been available for 30-plus years in the form of free trending software provided by OEMs to operators of commercial engines. Military health management trending was generally limited to periodic oil analysis and inspections such as engine oil filters and chip collectors. Neither of these approaches resulted in quantifiable data being aggregated to determine effectiveness. The last decade brought the rise of power-by-the-hour maintenance agreements in both commercial and military applications, which prompted the introduction of much more comprehensive OEM PHM systems. While specifics are treated as proprietary by the OEMs, there is a general belief that a comprehensive gas path monitoring system can reduce maintenance costs by 3 to 8%. The other benefits are much harder to achieve consensus on, and estimates of cost and time to implement new capabilities or improvements have been highly unreliable. A data-based cost/benefit analysis will greatly enhance credibility when trying to convince others.

7.4 Is a Cost Benefit Study Really Necessary?

There are some (usually advocates) who question how a PHM system could possibly provide a return on investment (ROI) that would be worse than a system with no PHM system. Other advocates maintain 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 8.

7.5 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 ameliorate the skeptics.

8. EXAMPLES OF PHM IMPLEMENTATION AND ASSOCIATED COST ANALYSIS MODELS

8.1 U.S. Army Helicopters

8.1.1 Implementation of CBM

Around 2004, the U.S. Army decided to implement Condition Based Maintenance (CBM), 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 consumed many maintenance man-hours and risked incurring secondary damage to the platform especially where panels needed to be removed for access. 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. 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 EKG 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 are stark comparisons between the maintenance carried out within units that are “DSC equipped” versus “non DSC equipped” units. Cost savings of $112 million over a 26 month period have been determined between the two categories of units and this does not include maintenance man-hours which, in the DoD, are “sunk costs” and are not admissible for credit in a cost benefit analysis. As more helicopters become DSC equipped, the cost savings are expected to rise exponentially. When asked by one of the SAE E-32 committee members how the Army had justified the initial investment, the answer from a General Officer was that it was all about “Having a vision and staying with it.” The Army pulled working capital funds forward from future year budgets to pay for an investment that the General Officer “just knew” would make sense and provide a very high ROI, so the future year operating budgets are depleted but will not be needed at their prior levels because of the reduced operating and maintenance costs in the out-years. The initiative was thus embarked upon in the absence of a strong, prior CBA, and was justified by a group of people who believed that it was the right thing to do and that the benefits would subsequently be seen, measured and quantified, thus providing a template for others, both military and commercial to adopt.

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

In March 2010, the following benefits were being briefed to the aerospace and military community, backed up by raw data directly from operating platforms.

- Nine percent greater availability on helicopters fitted with DSCs compared with those not fitted with DSCs.
- Three "Class A" (i.e., loss of aircraft, damage greater than $2 million, or loss of life) incidents avoided, a savings of $49 million.
- 57 engine removals avoided on UH60/AH64 fleets, a savings of $27 million.

This is an enlightening example where no clinical or detailed CBA/ROI was performed prior to embarkation but was backed by a strong belief of Army senior leadership, and one individual in particular that adopting a CBM strategy for the U.S. Army's entire helicopter fleet was the way to go to address the major challenges facing the Army's maintenance and sustainment activities.

8.2 Financial Tools

8.2.1 Real Options Analysis (Reference 2)

A model derived from options in financial markets ("puts" and "calls" on shares or currencies) has been used to help capture the unique and important benefits of PHM systems. A PHM system and the CBM activities that emanate from it, inherently provide future decision and investment options enabling maintenance personnel to avoid a future failure by making these near term investments (exercising the option). Future options enabled by an initial PHM investment provide economic benefits that are difficult to capture with traditional capital asset pricing models. Real options valuation methods are designed to capture the benefits of future investment and strategic options such as those enabled by a PHM system. Augmenting existing economic analysis methods with an option value pricing model can capture, in financial terms, the unique and important business benefits provided by PHM investments.

Similar to financial investment models, a PHM investment does not prevent a failure or automatically generate profit; instead it affords an option to take action in the future to realize a financial or operational benefit. The option to make future investment decisions may be captured in an economic model called real options valuation. Some believe that applying a real options valuation model provides a more accurate picture of the financial and strategic benefits that are enabled by PHM investments.

8.2.2 Actuarial Science (Reference 3):

One way to view PHM systems, is to consider them as insurance against future failures. A rich tradition exists of pricing insurance contracts based on historical failure statistics; primarily in the area of life, medical, and liability insurance. Actuarial science provides the necessary tools to assess the risks associated with each field so that the premiums can be set in an objective manner. As described by a leading researcher in this area (Reference 3), these analysis tools are now being used to model the financial risks associated with managing large fleets of industrial assets such as gas turbines, and lead to a more effective means of pricing long term service agreements.

8.3 Integration of a PHM model (Reference 4)

The integration of a PHM model, within a larger logistics analysis model, is still uncommon and not well documented. Overall categories for identifying and understanding the different types of impacts and benefits that a HM system can have from a logistics support perspective are: *Reduced Lead Time*, *Avoided Consequences of Failure*, *Extended Life/Reduced Maintenance Frequency*, and *Optimized Resource Use*. A method to assess prognostics by a modeling capability that is implemented in discrete-event simulation models has been developed.

In the *Avoid Consequences of Failure* scenario, increasing the lead time tends to increase the number of fixes (assuming maintenance is performed at the first opportunity). Increases in lack of precision for the prediction also result in increased number of fixes, both in terms of the number of fixes for the same lead time and the longer lead time required to meet the performance goal. For the *Extend Life/Reduce Maintenance Frequency* scenario, when the predicted standard deviations and the failure standard deviations are the same, the availability will be the same; similarly, when the predicted standard deviation is less, the availability will be greater, and conversely, when it is greater, the availability will be less. As the failure standard deviation increases, availability will go down but the relationship between prediction and failure standard deviations will remain the same. Care needs to be taken in evaluating the benefits of extending life when PHM coverage is not 100 percent or involves multiple items.

In both scenarios, better precision is good if the failure variation is not well understood.

8.4 System Dynamics Approach/Perspective

This is a method for understanding the dynamic behavior of complex systems and, rather than breaking up the problem into its individual components, it looks at the whole and reveals how all the objects in the system interact with one another.

To calculate the total savings that could be generated from a PHM system, the cost elements associated with unplanned availability need to be understood. For instance, an airplane whose engine has become unserviceable at a remote location generates immediate direct (or primary) costs of obtaining the spares to repair it and the actual cost of restoring the engine to a serviceable condition. Additional direct costs might arise through the need to provide a replacement aircraft to complete the mission, and transporting a maintenance crew to the site. Secondary costs are not always easy to identify and can also be carried for as far as the operator wishes to include in his calculations and involve elements such as lodging expenses for passengers, offerings of goodwill to passengers (clothing allowance for extended delays, coupons for use on a future flight), the perceived damage of the airline's reputation in the minds of the customers, etc.). The point is that, statistically, the engine unserviceable event is just a data point but, behind the event, is a mass of variables that greatly influence the cost and impact arising from each specific event.

Net savings also need to be calculated which considers any investment involved to introduce the PHM system. Net savings is typically the difference between the Life Cycle Costs (LCC) of the current baseline system (i.e., without the PHM technology) and projected LCC based on the use of the PHM technology (which includes the cost of the introduction and use of the technology as covered earlier). While Net Savings is a good indicator of the overall value of the alternative, it does not address the time value of money, in its comparison of competing alternatives. The time value of money can be evaluated by calculating the Net Present Value (NPV) of the Net Savings at a specific cost of money known as the Discount Rate. Considering the time value of money enables decision makers to compare alternatives that have savings at completely different points in time in the system's life cycle.

Return on Investment (ROI) in its simplest form is the ratio of Net Savings to Investment Costs. Where both elements are well known, then this is a clear indicator of the financial soundness of proceeding but as discussed earlier, both elements are challenging to determine with accuracy. Moreover, the ROI does not include an evaluation of risks, particularly those that are unique to the specific equipment or systems under evaluation. These risks would need to be identified and addressed through some risk assessment process in cooperation with the ROI analysis.

8.4.1 Business Case Scenarios using System Dynamics Modeling (Reference 5)

This section provides a method for computing ROI of a PHM system for 4 different scenarios that would typically be found in aircraft operations and maintenance. It can be used for any military or commercial application but the numbers used for the categories in Table 2 assumed a single engine fighter fleet. Moreover, the numbers used are purely hypothetical and meant to help illustrate the methods of calculation. The figures in Table 3 reflect the investment costs for 10 years including acquisition, maintenance, installation, integration, and training. When considering what kind of improvement the PHM system must deliver to justify the investment, the entire engine/PHM/maintenance system should be modeled so that the impact of introducing the PHM system can be determined.